PREDICTING POTENTIAL DISTRIBUTION OF *PARTHENIUM HYSTEROPHORUS* UNDER CLIMATE CHANGE SCENARIOS IN ETHIOPIA

Abu Feyisa Dejenu [1]*, Sintayehu Workeneh Dejene [2,3], Samuel Feyisa Ayano [4]

[1]Ethiopian Biodiversity Institute, Addis Ababa, Ethiopia.

[2]Training and Research Head, Africa Centre of Excellence (ACE) for Climate Smart Agriculture and Biodiversity Conservation, College of Agriculture and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia.

[3] Research Management Coordinator, Alliance Biodiversity and CIAT, Addis Ababa, Ethiopia.

[4]Department of Natural Resource Management and Environmental Science, Haramaya University.

ABSTRACT: The high spread of *Parthenium hysterophorus* in Ethiopia had become a major threat to the various suitable ecosystems in the country. Therefore, the identification of factors facilitating its distribution and mapping of suitable habitats is vital to design future management strategies. A total of 1,352 *P. hysterophorus* occurrence records and 19 bioclimatic variables were collected from different sources. An ecological niche model was used to map the current and future (the years 2050 and 2070) habitat suitability for *P. hysterophorus*. The ensemble model revealed that 72.8%, 18.5%, 6.8%, and 1.9% of the total area were unsuitable, low, moderate, and high suitable habitats under current climate conditions respectively. The high suitability area by 2050 and 2070 under Representative Concentration Pathway (RCP) scenarios RCPs 2.6, 4.5, and 8.5 will be 8.4%, 8.5%, 9.6%, and 7.8%, 6.1%, and 16%, respectively. We found that the current predicted unsuitable area will probably be vulnerable to loss of 176.9%, 188% and 125% under RCPs 2.6, 4.5, 8.5 respectively by 2050 whereas vulnerable loss of 166.7%, 164.7%, 3,500% were predicted under RCPs 2.6, 4.5, and 8.5 by 2070. The mean diurnal range, precipitation of the coldest quarter, and annual mean temperature were identified as the most determinant of the distribution of the species. The threats of this species on native biodiversity and the economy will be high in the future unless management action is undertaken. Our study suggests that all relevant stakeholders should be organized to combat the expansion of this invasive species to new areas particularly protected areas.

Keywords: Invasion, Habitat suitability, Climate change, Species distribution models, Ethiopia.

*Corresponding author: abufeyisa151@gmail.com

INTRODUCTION

Biological invasion has become one of the key causes of environmental degradation and economic loss in most of the countries across the world (Simberloff, 2011). It is one of the main drivers of biodiversity loss (Thapa et al., 2018) and its impacts have been predicted to increase even further under global climate change (Singh et al., 2011; Bukombe et al., 2013). Climate change refers to statistically identifiable changes in the mean and/or variability of climate properties that persist over an extended period, particularly over decades (Ochieng et al., 2016). It will exacerbate the long-term distribution of invasive species (Bellard et al., 2018). Species are forced to adapt or to alter their geographical range tracking climatic changes, and many species migrations have already been documented in a variety of habitats under climate change conditions (Grimm, 2013). In comparison with native species, invasive species are more likely to adapt to new climatic conditions because they are usually abundant, tolerate a broad range of climatic conditions, cover wide geographic ranges, and have highly competitive biological traits (Subhashni and Lalit, 2014). Both expansion and contraction of habitat suitability of invasive species following climate change were reported (Roger et al., 2015; Ahmad et al., 2019). Therefore, more detailed studies need to be undertaken to analyze how climate change will modify the existing plant invasions (Manzoor et al., 2018).

Parthenium hysterophorus L. (Asteraceae) is an annual or perennial (short-lived) flowering plant that degrades natural ecosystems and causes a significant hypersensitive reaction in people and domesticated livestock (Adkins and Shabbir, 2014). It's native to America and is thought of as a serious weed globally (Bukombe et al., 2013). Currently, it is known to occur in several countries in Africa including Ethiopia, South Africa, Kenya, Tanzania, Somalia, Madagascar, and Mozambique (Zuberi et al., 2014). The high spread of *P. hysterophorus* in Ethiopia has become a major threat to the various suitable ecosystems including flora, fauna, and microbes (Shiferaw et al., 2018).

The threat of *P. hysterophorus* has been increasing with the rapid growth of globalization and the changing climate (Tamiru, 2017). *P. hysterophorus* weed can invade a range of crops, and a particular concern is the invasion of cereal crops such as rice, wheat, maize, teff and sorghum (Adkins and Shabbir, 2014). In such crops, it is reported to reduce yields by as much as 40% in India and by as much as 40% and above in Ethiopia, if not managed (McConnachie et al., 2011). The yield reduction in Ethiopia is a serious threat to Ethiopian food security. The species is a major problematic weed to agriculture due to its ability to invade large areas in a short space of time (Amare, 2018).

A variety of factors have been suggested to influence invasiveness. These factors govern the extent to which a species introduced outside its native range may overcome various biotic and abiotic barriers to determine its establishment in a new environment (Singh et al., 2011). Resource availability may be a key factor that determines the susceptibility of a community to invasion by exotic species (Meyer et al., 2021). The fluctuating resources hypothesis states that a plant community becomes more liable to invasion whenever there is a rise in the number of unused resources (Zhang et al., 2022). Climate and edaphic conditions are thought to be fundamental determinants of the potential distribution of invasive species (Ahmad et al., 2016). Physiological properties and reproductive and life-history characteristics are also cited frequently to clarify the invasiveness of plant species (Zuberi et al., 2014).

The importance of the factors role in explaining the success of plant invaders, their establishment, spread, and better performance within the invaded range depends on the sort of species, spatial scale, and native environmental context (Funk, 2013; Kueffer et al., 2014); Van Kleunen et al., 2015). This happens as a result of the effect of the complex interactions between plants, climate, and soil at an area scale (Kardol et al., 2014; Svenning et al., 2014), thereby influencing invasiveness. Therefore, factors that influence patterns of invasion observed in one site or continent are also difficult to extrapolate to other continents or sites because those observations are specific to a time, place, and spatial scale. Strikingly, factors that deter or promote the establishment and invasion of *P. hysterophorus* under climate change are not well known in developing countries including Ethiopia, as most studies were conducted in developed countries.

Despite its recognition to be as among the worst invasive alien species, its potential distribution under climate change scenarios in Ethiopia has yet to be investigated. It is therefore important to understand its spatial distribution across landscapes and predict its potential shifts and impacts on various ecosystems. Species distribution models (SDMs) are scientifically proven tools for assessing and predicting the impacts of climate change on the distribution of flora and fauna from occurrence (presence only or presence and absence) data (Thapa et al., 2018).

This study is therefore designed (1) to explore the potential distribution of *P. hysterophorus* under current and three future Representative Concentration Pathway scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) for the two time periods (2050 and 2070), and (2) to identify if environmental factors (precipitation and temperature) derived bioclimatic variables influenced the invasion of *P. hysterophorus*.

MATERIALS AND METHODS

Study area description

Ethiopia is located in the horn of Africa between 3° 15' N and 48º E. Ethiopia is in the tropical zone lying between the equator and the tropics of cancer. It has an area of about 1.13 million km^2. In Ethiopia, the climate varies mostly with altitude, and it goes from the hot and arid climate of the lowlands to the cool climate of the plateau (Fazzini et al., 2015). Lying just north of the equator, the country experiences little variations in temperature throughout the year (Figure 1).

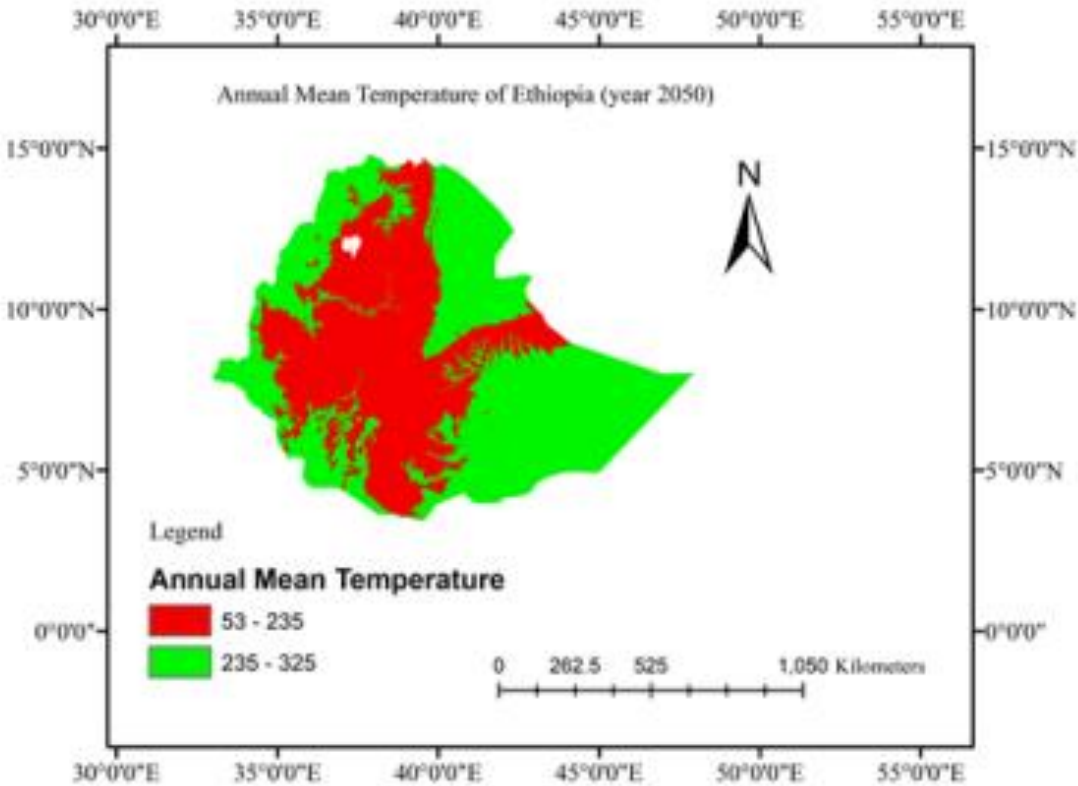

Figure 1. Location of the study area.

Ethiopia has three different traditional climate zones based on elevation (Fazzini et al., 2015). The primary climate zone is *Kolla* (tropical zone) is below 1830 meters in elevation and has an average annual temperature of about 27°C with an annual rainfall of about 510 millimetres. The Danakil Depression is about 125 meters below sea level and also the hottest region in Ethiopia where the temperature climbs up to 50°C. The second is *Woina Dega* (Subtropical zone). This includes the highlands areas of 1830 to 2440 meters in elevation have an average annual temperature of about 22°C with annual rainfall between 510 and 1530 millimetres. The third is *Dega* (cool zone) is above 2440 meters in elevation with an average annual temperature of about 16°C with annual rainfall between 1270 and 1280 millimetres. The major soil types vary in response to parent materials and landforms among other factors of soil formation. Rock types affect soil texture and mineralogy while landform affects the spatial distribution of soils due to complex erosion and depositional processes. Nitisols and Vertosols dominate basalt formation whereas leptosols exclusively dominate hill slopes irrespective of the geological formation (Abebe et al., 2023). This physiographic diversity makes the country suitable for the invasion of *P. hysterophorus*.

Parthenium hysterophorus occurrence point data collection

A total of 1,184 species occurrence records of *P. hysterophorus* were obtained from the Global Biodiversity Information Facility (GBIF) database (www.gbif.org) https://doi.org/10.15468/dl.eh3qux, (accessed on 29 August 2020). To check the ground truth, we collected 168 occurrences of the species in the study area employing a Global Positioning System (GPS). The species occurrence points were collected at 500 m successive intervals. We selected a maximum of 1 km sampling interval to reduce sampling bias using the spatial thinning method. Finally, a total of 1,162 occurrence records were used to run the models.

Environmental variables

Nineteen current bioclimatic variables were downloaded from the WorldClim database version 2 (www.worldclim.org) at a spatial resolution of 30 seconds approximately~1km^2 (Table 1). These variables were computed from minimum, maximum, and average values of monthly, quarterly, and annual ambient temperatures further as precipitation values recorded from 1970 to 2000 (Fick and Hijmans, 2017). For future projection, we used bioclimatic variables representing simulations for 3 climate change RCP scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) for the two time periods (2050 and 2070).

Table 1. The 19 bioclimatic variables downloaded from the WorldClim database.

List of variables	Code	Scaling	Units
Annual Mean Temperature	Bio1	10	Degrees Celsius
Mean Diurnal Range (Mean of monthly	Bio2	10	Degrees Celsius
Isothermality (BIO2/BIO7)	Bio3	100	Degrees Celsius
Temperature Seasonality (Standard Deviation)	Bio4	100	Degrees Celsius
Max Temperature of Warmest Month	Bio5	10	Degrees Celsius
Min Temperature of Coldest Month	Bio6	10	Degrees Celsius
Temperature Annual Range (BIO5-BIO6)	Bio7	10	Degrees Celsius
Mean Temperature of Wettest Quarter	Bio8	10	Degrees Celsius
Mean Temperature of Driest Quarter	Bio9	10	Degrees Celsius
Mean Temperature of Warmest Quarter	Bio10	10	Degrees Celsius
Mean Temperature of Coldest Quarter	Bio11	10	Degrees Celsius
Annual Precipitation	Bio12	1	Millimeters
Precipitation of Wettest Month	Bio13	1	Millimeters
Precipitation of Driest Month	Bio14	1	Millimeters
Precipitation Seasonality	Bio15	100	Fraction
Precipitation of Wettest Quarter	Bio16	1	Millimeters
Precipitation of Driest Quarter	Bio17	1	Millimeters
Precipitation of Warmest Quarter	Bio18	1	Millimeters
Precipitation of Coldest Quarter	Bio19	1	Millimeters

Sources: Fick et al, 2017

Modelling approach

Several species distribution models (SDM) are widely employed in many ecological applications (Ahmad et al., 2019). These models establish relationships between occurrences of species and biophysical and environmental factors in the study area. However, one model does not provide the most effective predictive accuracy in SDM. Therefore, an ensemble of many SDM algorithms was employed to produce better accuracy. We used five modeling algorithms analyzed under the SDM packages in R statistical software (a generalized linear model (GLM), support vector machine (SVM), a random forest algorithm (RF), boosted regression tree (BRT), and multivariate adaptive regression splines (MARS)) to construct most effective predictive accuracy.

As these bioclimatic variables are often correlated, it ends up in poor model performance and misleading interpretations (Dormann et al., 2013). Therefore, Pearson's correlation analysis was performed. Then, each pair of highly correlated variables with Pearson's parametric statistic ($r^2 < 0.8$) was selected for modelling the species distribution. After pairwise correlations among predictors variables with correlations below $|r| < 0.8$ were considered unproblematic. We removed the highly correlated pairs and also the minor variable after assessing variable importance. Finally, seven variables remained for model fitting.

Forecasting accuracy and substantiation of the models were assessed supported area under receiving operator curve (AUC), and sensitivity (true positive rate) against 1-specificity (false positive rate). AUC values range from 0 to 1. The values of AUC between 0 - 0.5 were considered poor, 0.5 - 0.8 fair, 0.8 - 0.9 good and 0.9 - 1 superb while validating the importance of variables (Ahmad et al., 2019). Only the model with a good forecasting index and AUC > 0.8 was built for the final ensemble model from the projection outputs (Gallien et al., 2012).

The Receiving Operator Curve (ROC) provides another technique for the assessment of the accuracy of ordinal score models. The development of the ROC utilizes all possible thresh for classifying the scores into confusion matrices, obtaining each matrix sensitivity and specificity; and then comparing sensitivity against the corresponding proportion of false positives (equal to 1-specificity). Evaluation of accuracy was assessed by dividing the presence points into training and test points per species. The training dataset comprised 70% of the data and therefore the test dataset comprised 30% of the species occurrence points. Finally, one ensemble projection of the current and six ensemble projections of future habitat suitability reminiscent of three RCPs (2.6, 4.5, and 8.5) for the years 2050 and 2070 were obtained.

Image classification and analysis

The changes in habitat suitability between current and future climate conditions were assessed under all RCPs by identifying climate suitability areas where suitable habitat was projected in the present and future.

The habitat suitability changes for the current and future were examined under four categories to spot areas of unsuitable, low, moderate, and high suitability using ArcGIS 10.6. We used two indicators to research the role of climate change on the distribution of *P. hysterophorus*. The primary indicator was changes in the percentage of the unsuitable area (AC) and the second indicator was the share gain or loss area for 2050 and 2070 (CH). The indicators were calculated as per Sintayehu et al. (2020) using the subsequent formula.

$$AC = \frac{Af - AC}{AC} \times 100\% \quad (1)$$

$$CH = \frac{Af - AC}{Af} \times 100\% \quad (2)$$

Where Af is the predicted suitability area in the future and, AC is the non-suitable predicted habitat under current climate conditions.

Variable's importance

The variable's grandness provides statistics on the significance of each variable in the model. It was assessed by employing the getVarimp function in R software with permutation-based on two metrics (Pearson Correlation and AUC) method. The percent contribution of each variable was calculated as 1-correlation values by keeping the other variables constant (Harisena et al., 2021).

RESULTS

Model performance

The mean of each model was presented (Table 2). The final ensemble model has a mean AUC value of 0.91. This showed the prediction accuracy of the model was high.

Table 2. The model mean performance based on AUC value in predicting the potential distribution of *Parthenium hysterophorus* in Ethiopia.

Model	GLM	SVM	RF	BRT	MARS
AUC	0.84	0.89	1	0.9	0.9

'AUC' = Area Under Receiving Operating Curve, GLM = Generalized Linear Model, SVM = Supportive Vector Machines, RF = Random Forest Algorithm, BRT = Boosted regression Tree, MARS = Multivariate adaptive regression splines.

The mean area under the receiving operating curve for the training dataset and test dependence of the ensemble model were 0.85 and 0.84 respectively (Figure 2). The mean area under the ROC of the ensemble model showed that the prediction accuracy of the model in predicting the potential distribution of the *P. hysterophorus* under changing climate change was 0.84 under current climate conditions.

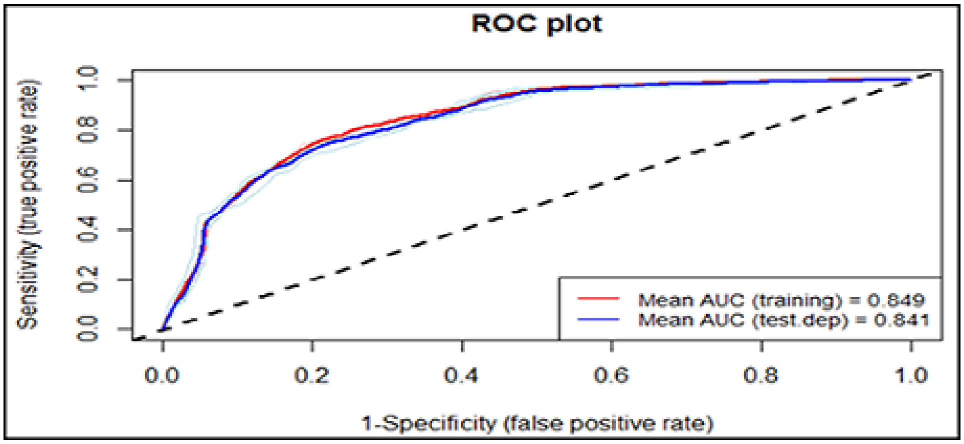

Figure 2. Average sensitivity (true positive rate) vs. 1-specificity (false positive rate) of *Parthenium hysterophorus* in Ethiopia.

Current predicted suitable area

The current habitat suitability area percentages and distribution map are shown in Table 2 and Figure 3. The ensemble model showed that 72.8% of the area of the country is not suitable for the distribution of *P. hysterophorus.* The model also depicted that 18.5%, 6.8%, and 1.9% areas were identified as low, moderate, and high suitability areas for the *P. hysterophorus* respectively.

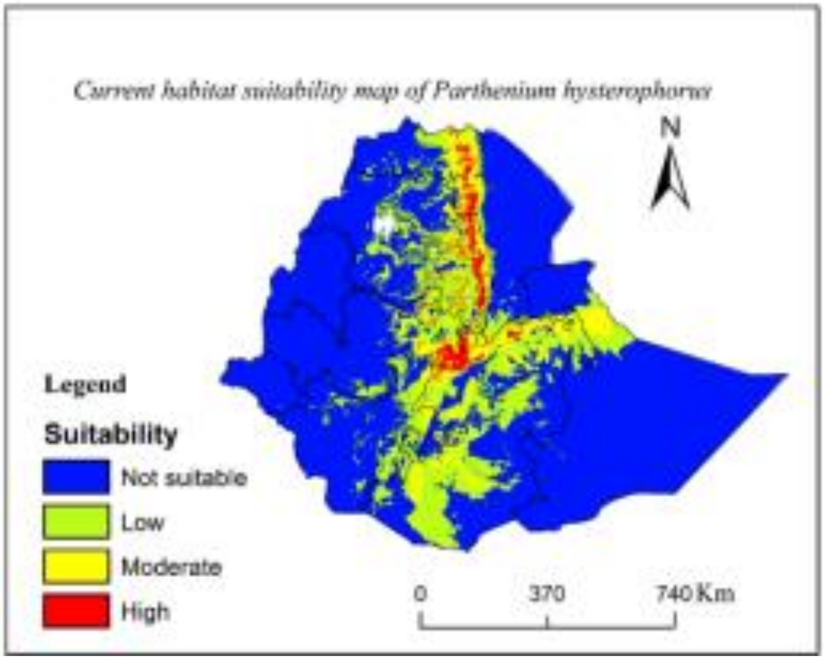

Figure 3. Current habitat suitability maps for *P. hysterophorus* in Ethiopia.

Future predicted *P. hysterophorus* habitat suitability area

Compared to the current habitat suitability, the total predicted area of high suitability by 2050 will gradually increase by 8.4%, 8.5%, and 9.6% under RCP (2.6, 4.5, and 8.5) respectively (Table 3, Figure 5). Similarly, the highly suitable area by 2070 will be expected to increase by 7.8%, 6.1%, and 16% under RCPs (2.6, 4.5, and 8.5) respectively. But compared to the future predicted high suitable area of the year 2050, the predicted high suitable area by 2070 will be expected to decrease by 0.6 % and 2.4% under RCP (2.6 and 4.5) respectively.

Table 3. Percent (%) predicted area of habitat suitability of *Parthenium hysterophorus* under changing climate scenarios for current and future periods (2050 and 2070) in Ethiopia.

Years	Scenarios	Total suitability (%)			
		Unsuitable	Low	Moderate	High
Current	_	72	19.0	6.8	2.0
2050	RCP2.6	26	44	21.7	8.4
	RCP4.5	25	44.6	21.7	8.5
	RCP8.5	32	43.4	15	9.6
2070	RCP2.6	27	44.5	20.7	7.8
	RCP4.5	27.2	45.7	21	6.1
	RCP8.5	2.0	25	57	16

Variable's importance

The evaluation of the selected variable importance (training gain) of the selected variables based on correlation metrics is shown in Figure 4. Among the selected variables, the mean diurnal range (Bio2) (53.9%) followed by precipitation of coldest quarter (Bio19) (26.1%) and annual mean temperature (Bio1) (11.4%) contributed a high percentage.

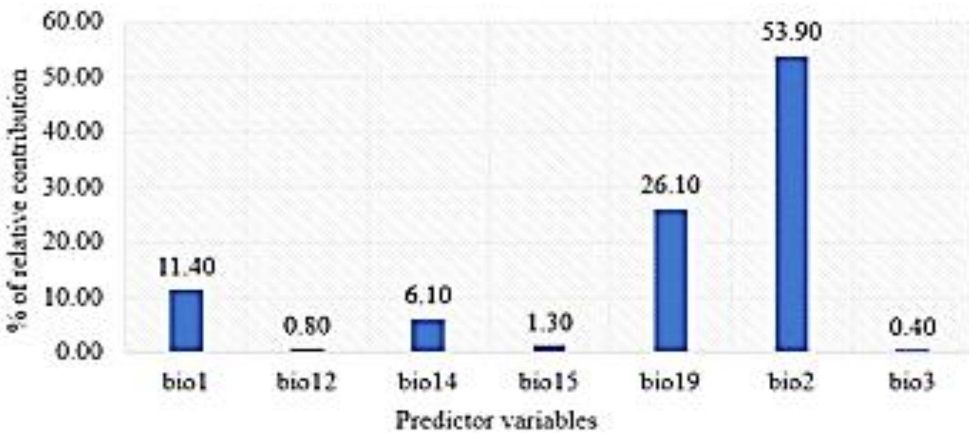

Figure 4. Mean percent contribution of each variable to the ensemble model for prediction of suitable habitat for *P. hysterophorus* in Ethiopia (bio1= annual mean temperature, bio12= annual precipitation, bio14 = precipitation of driest month, bio15 = precipitation seasonality, bio19 = precipitation of coldest quarter, bio2 = mean diurnal range, bio3 = isothermality).

Vulnerability assessment or change detection

Future habitat suitability projections map under RCP (2.6, 4.5, and 8.5) for the years 2050 and 2070 showed that compared to current habitat suitability, the future unsuitable habitat will be invaded under future climate change scenarios by *P. hysterophorus* (Figure 5). In 2050, the current unsuitable habitat will be vulnerable to invasion by -176.9%, -188%, and -125% under RCP 2.6, 4.5, and 8.5, respectively (Table 4).

Table 4. Percentage of change (gain or loss) of habitat suitability of *Parthenium hysterophorus* for current and future periods (2050 and 2070) under RCP (2.6, 4.5, and 8.5) in Ethiopia.

Decades	Scenarios	% Change compared to the current suitability			
		Unsuitable	Low	Moderate	High
Current	-	-	-	-	-
2050	RCP2.6	-176.9	56.8	68.7	76.2
	RCP4.5	-188	57.4	68.7	76.5
	RCP8.5	-125	56.2	54.7	79.2
2070	RCP2.6	-166.7	57.3	67.1	74.4
	RCP4.5	-164.7	58.4	67.6	67.2
	RCP8.5	-3,500	24	88.1	87.5

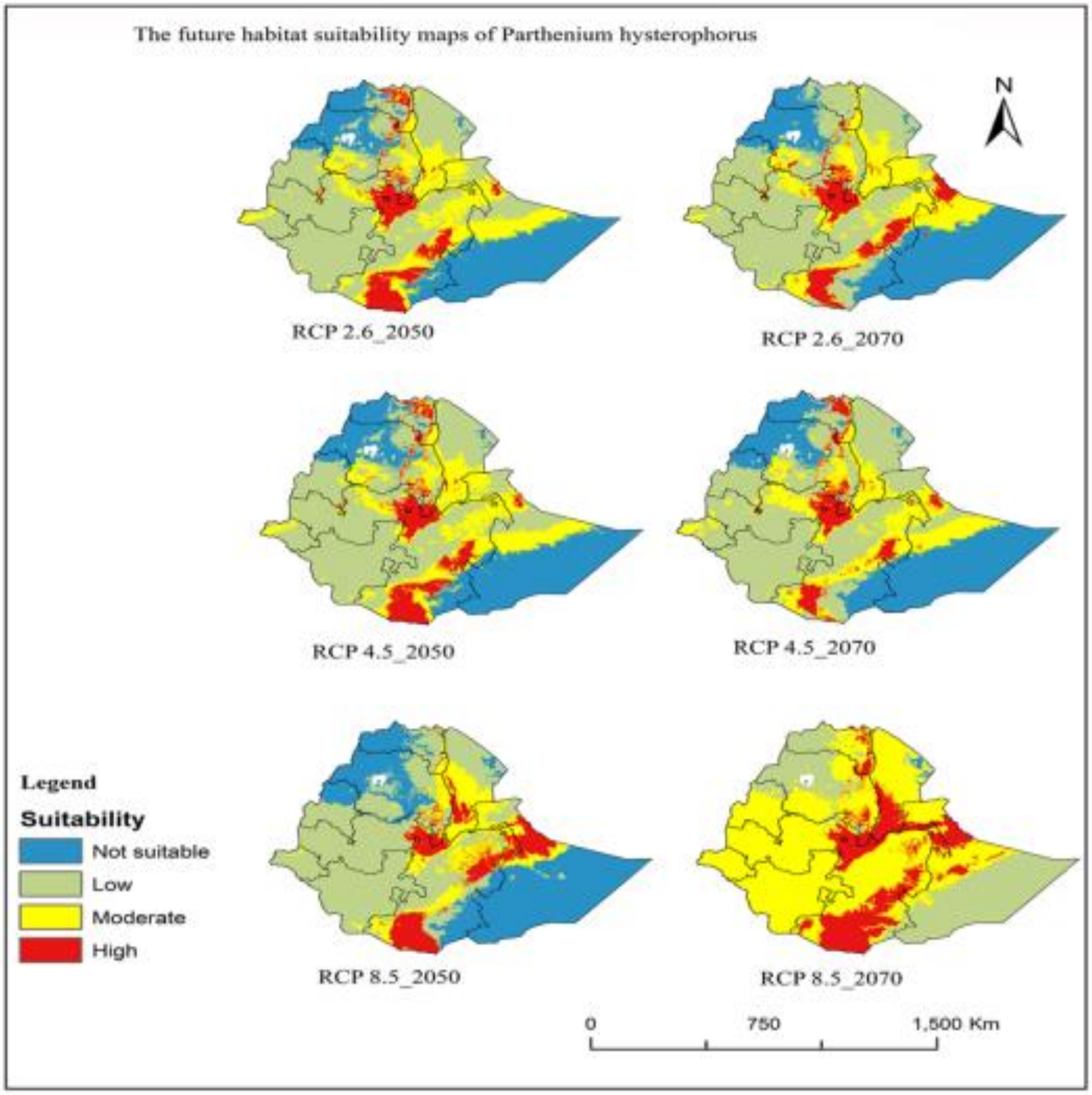

Figure 5. Future habitat suitability projections map for *Parthenium hysterophorus* under RCP (2.6, 4.5, and 8.5) for 2050 and 2070 years in Ethiopia.

DISCUSSION

The statistical models within their respective high means scores from the five algorithms were used to construct the final ensemble model by applying a weighted mean approach. The result indicated the robustness of the model in discriminating the habitat suitability of *P. hysterophorus* with greater accuracy (AUC = 0.9). The suitability maps revealed that most parts of the country's regions including the West, East, and North Shewa, west and east Hararge around Dire Dawa of Oromia Regional State, Eastern Amhara bordering the Afar region, Northern Somali, Sidama, and southeast of Tigray regions are currently under the invasion of *P. hysterophorus*. The current prediction map showed a high invasion of *P. hysterophorus* was observed along the long road running from Addis Ababa to the Northern region and the eastern parts of the country.

A narrowing of overall habitat suitability for the study species was seen under future climate change scenarios with highly suitable habitats under RCP 4.5 for the year 2070. This agreed with some recent studies that have reported a loss of range expansion of invasive plant species including *P. hysterophorus* following climate change. A study conducted to predicting the invasion potential and niche dynamics of *P. hysterophorus* in India under projected climate change reported the reduction of range expansion of the species under future climate change (Ahmed et al., 2019). However, climate change is favoring the range expansion of invasive species rather than range reduction (Finch et al., 2021). It creates favorable conditions for the spread of invasive species by altering the invasion pathways and environmental factors such as temperature and precipitation which facilitate the range expansion of the invasive species.

The ensemble model outputs revealed that the mean diurnal range (53.90%) followed by precipitation of the coldest quarter (26.10%) and annual mean temperature (11.40%) were the most predictor variables of the potential distribution of the study species. Hence, these variables are the most determinant of the distribution of *P. hysterophorus* in Ethiopia. This is in agreement with some studies that state both temperature and precipitation-derived bioclimatic variables as the main governors of the distribution of invasive species including *P. hysterophorus* (Ahmad et al., 2019; Sintayehu et al., 2020).

A reduction of habitat suitability for the *P. hysterophorus* was seen under future climate change scenarios with highly suitable habitats under RCP 2.6 and 4.5 for the year 2070 compared to 2050. Our study is in agreement with a few other studies that have reported a reduction in the distribution of invasive species both globally as well as regionally following climate change (Panda et al., 2018; Ahmad et al., 2019). Roger et al. (2015) conducted a study on naturalized alien species in Australia and concluded that the majority of the species showed a decrease in habitat suitability under climate change.

Several studies concluded that climate change encourages the distribution of invasive species by creating favorable conditions, shifts in species range, and species richness (Panda et al., 2018; Sintayehu et al., 2020). Similarly, our ensemble model showed that temperature and precipitation-derived bioclimatic variables will facilitate the distribution and spread of *P. hysterophorus* by creating favorable conditions in Ethiopia. The decrease in precipitation coupled with an increase in temperature under projected climate change may adversely affect the distribution of *P. hysterophorus*. The temperature fluctuation (the mean diurnal range) coupled with moisture availability of the driest month associated with this country may facilitate its distribution under climate change.

Parthenium hysterophorus expands along roadsides and spreads quickly due to disturbance by vehicular movement. It distributes quickly along the roadsides due to transportation. The seed is spread by animals, wind, water, vehicles, agricultural and road construction machinery and fodder as well as other human activities (Masum et al., 2013). The protected areas, which are in direct contact with the road in Ethiopia like Awash National Park, Babile Elephant Sanctuary, Nechisar National Park, and others are at high risk of invasion by the species. Agricultural lands, and protected areas found around the suitable habitat of *P. hysterophorus* including mountains and hot areas are also predicted to be at high risk of invasion under RCP.4.5 and RCP 8.5 in 2050 and 2070.

CONCLUSION AND RECOMMANDATION

Parthenium hysterophorus had already been distributed in several parts of Ethiopia causing adverse effects on biodiversity, ecosystem, agriculture, and therefore the economy. Fast and mass invasion could be a key issue of this invasive species, thanks to its rapid dispersion. If climates change, then the species may disperse into novel climate regions. It's predicted to invade most parts of the country under future temperature change scenarios. Mapping the suitability habitat is critical in identifying environmental factors for the distribution of *P. hysterophorus* and helps in developing management strategies. For decision-makers, our risk maps essentially represent a prioritization surface that guides them in allocating tactics aimed at detecting and controlling the spread of the species. The risk maps are very useful to structure an early detection survey and to describe the potential extent of the impact. Monitoring, early detection, and rapid response are the foremost effective options for *P. hysterophorus* management.

DISCLAIMER

Findings, opinions conclusions, and recommendations expressed in this material are those of the Authors and the funding agencies do not accept any liability in this regard.

ACKNOWLEDGEMENTS

The financial support granted to the first author from the Africa Centre of Excellence for Climate Smart Agriculture and Biodiversity Conservation Haramaya University in Ethiopia is gratefully acknowledged. We sincerely thank those who provided relevant information regarding *Parthenium hysterophorus* and reviewed the manuscript.

REFERENCES

Abebe, B., Ayalew, D., Regassa, A. and Taye, G. 2023. Geology and Geomorphology In: S. Beyene, A. Regassa, B. B. Mishra, and M. Haile, ed., *The Soils of Ethiopia*. Springer International Publishing. pp. 51–69.

Adkins, S., and Shabbir, A. 2014. Biology, ecology and management of the invasive parthenium weed (*Parthenium hysterophorus* L.). *Pest Management Science*, **70(7):1023–1029**.

Ahmad, R., Khuroo, A. A., Hamid, M., Charles, B. and Rashid, I. 2019. Predicting invasion potential and niche dynamics of *Parthenium hysterophorus* (Congress grass) in India under projected climate change. *Biodiversity and Conservation*, 28(8–9), 2319–2344. doi.org/10.1007/s10531-019-01775-y.

Ahmad, Z., Khan, S. M., Abd Allah, E. F., Alqarawi, A. A. and Hashem, A. 2016. Weed species composition and distribution pattern in the maize crop under the influence of edaphic factors and farming practices: A case study from Mardan, Pakistan. *Saudi Journal of Biological Sciences*, **23(6), 741–748**. doi.org/10.1016/j.sjbs.2016.07.001.

Amare, T. 2018. Allelopathic effect of aqueous extracts of Parthenium (*Parthenium hysterophorus* L.) parts on seed germination and seedling growth of maize (Zea Mays L.). *Journal of Agriculture and Crops*, **4(12):157-163**. doi.org/10.32861/jac.412.157.163.

Bellard, C., Jeschke, J. M., Leroy, B. and Mace, G. M. 2018. Insights from modeling studies on how climate change affects invasive alien species geography. *Ecology and Evolution*, **8(11):5688–5700**.

https://doi.org/10.1002/ece3.4098.

Bukombe, J., Mweya, C. N., Mwita, M., Kija, H. and Fyumagwa, R. 2013. Prediction of suitable habitat for potential invasive plant species *Parthenium hysterophorus* in Tanzania: A Short Communication. *International Journal of Ecosystem*, **4:82–89**.

Dormann, C. F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J. R. G., Gruber, B., Lafourcade, B., Leitão, P. J., Münkemüller, T., Mcclean, C., Osborne, P. E., Reineking, B., Schröder, B., Skidmore, A. K., Zurell, D. and Lautenbach, S. 2013. Collinearity: A review of methods to deal with it and a simulation study evaluating their performance. *Ecography*, **36(1), 27–46**. doi.org/10.1111/j.1600-0587.2012.07348.x

Fazzini, M., Bisci, C., and Billi, P. 2015. The climate of Ethiopia. In: P. Billi, ed., Landscapes *and landforms of Ethiopia* Edition: World geomorphological landscapes, Springer Verlag, pp. 65–87. doi.org/10.1007/978-94-017-8026-1_3.

Fick, S. E. and Hijmans, R. J. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, **37(12):4302–4315**. doi.org/10.1002/joc.5086.

Finch, D. M., Butler, J. L., Runyon, J. B., Fettig, C. J., Kilkenny, F. F., Jose, S., Frankel, S. J., Cushman, S. A., Cobb, R. C., Dukes, J. S., Hicke, J. A. and Amelon, S. K. 2021. Effects of climate change on invasive species. In: T.M Poland, T.P. Weynand, D.M. Finch, C.F. Miniat, D.C. Hayes, V.M. Lopez, ed., *Invasive Species in Forests and Rangelands of the United States*. Springer International Publishing, pp. 57–83. doi.org/10.1007/978-3-030-45367-1_4.

Funk, J. L. 2013. The physiology of invasive plants in low-resource environments. *Conservation Physiology*, **1(1):1–17**. doi.org/10.1093/conphys/cot026.

Gallien, L., Douzet, R., Pratte, S., Zimmermann, N. E. and Thuiller, W. 2012. Invasive species distribution models - how violating the equilibrium assumption can create new insights. *Global Ecology and Biogeography*, **21(11):1126–1136**. doi.org/10.1111/j.1466-8238.2012.00768.x

Grimm, N. B., Chapin, F. S., Bierwagen, B., Gonzalez, P., Groffman, P. M., Luo, Y., Melton, F., Nadelhoffer, K., Pairis, A., Raymond, P. A., Schimel, J., & Williamson, C. E. (2013). The impacts of climate change on ecosystem structure and function. *Frontiers in Ecology and the Environment*, *11*(9), 474–482. doi.org/10.1890/120282

Harisena, N. V., Groen, T. A., Toxopeus, A. G. and Naimi, B. 2021. When is variable importance estimation in species distribution modelling affected by spatial correlation? *Ecography*, **44(5):778–788**. doi.org/10.1111/ecog.05534.

Kardol, P., Dickie, I. A., St. John, M. G., Husheer, S. W., Bonner, K. I., Bellingham, P. J. and Wardle, D.

A. 2014. Soil-mediated effects of invasive ungulates on native tree seedlings. *Journal of Ecology*, **102(3): 622–631**. doi.org/10.1111/1365-2745.12234.

Kueffer, C., Daehler, C., Dietz, H., McDougall, K., Parks, C., Pauchard, A., Rew, L., Alexander, J., Arévalo, J. R., Cavieres, L., Edwards, P. J., Haider, S., Loope, L., Mack, R. N., Milbau, A., Naylor, B. J., Otto, R., Pollnac, F., Reshi, Z. A. and Walsh, N. 2014. The mountain invasion research network (MIREN): Linking local and global scales for addressing an ecological consequence of global change. *GAIA - Ecological Perspectives for Science and Society*, **23(3):263–265**. doi.org/10.14512/gaia.23.3.11.

Manzoor, S. A., Griffiths, G., Iizuka, K. and Lukac, M. 2018. Land cover and climate change may limit invasiveness of *Rhododendron ponticum* in Wales. *Frontiers in Plant Science*, **9:664**. doi.org/10.3389/fpls.2018.00664.

Masum, S. M., Hasanuzzaman, M. and Ali, M. H. 2013. Threats of *Parthenium hysterophorus* on agro-ecosystems and its management : a review. *Interantional Journal of Agriculture and Crop Sciences*, **6(11):684–697**.

Mayer, S., Callaham, M.A., Stewart, J.E., and Warren , S.D. 2021. Invasive species response to natural and anthropogenic disturbance. In: T. M. Poland, T. Patel-Weynand, D. M. Finch et al. ed., *Invasive species in forests and rangelands of the United States*. Springer, pp. 85-110.

Mcconnachie, A. J., Strathie, L. W., Mersie, W., Gebrehiwot, L., Zewdie, K., Abdurehim, A., Abrha, B., Araya, T., Asaregew, F., Assefa, F., Gebre-Tsadik, R., Nigatu, L., Tadesse, B. and Tana, T. 2011. Current and potential geographical distribution of the invasive plant *Parthenium hysterophorus* (Asteraceae) in eastern and southern Africa. *Weed Research*, **51(1):71–84**. doi.org/10.1111/j.1365-3180.2010.00820.x.

Ochieng, A. O., Nanyingi, M., Kipruto, E., Ondiba, I. M., Amimo, F. A., Oludhe, C., Olago, D. O., Nyamongo, I. K. and Estambale, B. B. A. 2016. Ecological niche modelling of Rift Valley fever virus vectors in Baringo, Kenya. *Infection Ecology and Epidemiology*, ***6*(1)**. doi.org/10.3402/IEE.V6.32322.

Panda, R. M., Behera, M. D. and Roy, P. S. 2018. Assessing distributions of two invasive species of contrasting habits in future climate. *Journal of Environmental Management*, **213:478–488**. doi.org/10.1016/j.jenvman.2017.12.053.

Roger, E., Duursma, D. E., Downey, P. O., Gallagher, R. V., Hughes, L., Steel, J., Johnson, S. B. and Leishman, M. R. 2015a. A tool to assess potential for alien plant establishment and expansion under climate change. *Journal of Environmental Management*, **159:121–127.** doi.org/10.1016/j.jenvman.2015.05.039.

Shiferaw, W., Demissew, S. and Bekele, T. 2018. Invasive alien plant species in Ethiopia: ecological impacts on biodiversity a review paper. *International Journal of Molecular Biolo*gy, **3(4):171-178**. doi.org/10.15406/ijmboa.2018.03.00072.

Simberloff, D. 2011. How common are invasion-induced ecosystem impacts? Biological Invasions. *Biological Invasions*, **13:1255–1268**. doi.org/10.1007/s10530-011-9956-3

Singh, R. P., Singh, R. K. and Singh, M. K. 2011. Impact of Climate and Carbon Dioxide Change on Weeds and their Management-A Review. *Indian Journal of Weed Science*, **43:1–11**.

Sintayehu, D. W., Dalle, G. and Bobasa, A. F. 2020. Impacts of climate change on current and future invasion of Prosopis juliflora in Ethiopia: environmental and socio-economic implications. *Heliyon*, **6(8)**, e04596. doi.org/10.1016/j.heliyon.2020.e04596.

Subhashni, T. and Lalit, K. 2014. Impacts of climate change on invasive *Lantana camara* L. distribution in South Africa. *African Journal of Environmental Science and Technology*, **8(6):391–400**. doi.org/10.5897/ajest2014.1705.

Svenning, J. C., Gravel, D., Holt, R. D., Schurr, F. M., Thuiller, W., Münkemüller, T., Schiffers, K. H., Dullinger, S., Edwards, T. C., Hickler, T., Higgins, S. I., Nabel, J. E. M. S., Pagel, J. and Normand, S. 2014. The influence of interspecific interactions on species range expansion rates. *Ecography*, **37(12):1198–1209**. doi.org/10.1111/j.1600-0587.2013.00574.x.

Tamiru, G. 2017. Invasive alien weed species distribution, impacts on agriculture, challenge and reaction in Ethiopia: A Review. *Journal of Biology, Agriculture and Healthcare*, **7(7):136-146**.

Thapa, S., Chitale, V., Rijal, S. J., Bisht, N., and Shrestha, B. B. 2018. Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. *PLoS ONE*, ***13*(4)**. doi.org/10.1371/journal.pone.0195752.

van Kleunen, M., Dawson, W., Essl, F., Pergl, J., Winter, M., Weber, E., Kreft, H., Weigelt, P., Kartesz, J., Nishino, M., Antonova, L. A., Barcelona, J. F., Cabezas, F. J., Cárdenas, D., Cárdenas-Toro, J., Castaño, N., Chacón, E., Chatelain, C., Ebel, A. L. and Pyšek, P. 2015. Global exchange and accumulation of non-native plants. *Nature*, **525(7567):100–103**. doi.org/10.1038/nature14910.

Zhang, Z., Liu, Y., Hardrath, A., Jin, H. and van Kleunen, M. 2022. Increases in multiple resources promote competitive ability of naturalized non-native plants. *Communications Biology*, ***5*(1):1–6**. doi.org/10.1038/s42003-022-04113-1.

Zuberi, M. I., Gosaye, T. and Hossain, S. 2014. Potential threat of alien invasive species : *Parthenium hysterophorus* L . to subsistence agriculture in Ethiopia. *Sarhad Journal of Agriculture*, **30(1):9**.