



Research article

Ecological niche modelling for climate suitability of spineless fodder cactus pear (*Opuntia ficus-indica* (L.) Mill.) in semiarid and arid regions of India

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Received: 12th December, 2025

Accepted: 30th April, 2026

Abstract

Spineless cactus pear [*Opuntia ficus-indica* (L.) Mill.] is a promising non-conventional fodder crop in India. Ecological niche modeling studies using the maximum entropy approach have been used to assess the suitable cactus growing regions in India. The dataset for cactus pear presence locations was obtained from various centers. WorldClim dataset representing current and future climate was downloaded from <http://www.worldclim.org>. The cactus presence locations dataset and the WorldClim dataset were used with Maximum entropy (MaxEnt) modeling to generate the climate suitability map to show potential growing sites in India. The generated maps indicated that potential regions for cactus cultivation exist in several states of India, viz., Andhra Pradesh, Bihar, Delhi, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Odisha, and Uttar Pradesh. The outcome of the study would help in managing cactus pear genetic resources in the country to meet the challenges of climate change and fodder production.

Keywords: DIVA-GIS, Ecological Niche, Fodder, Modeling, *Opuntia ficus-indica*, Spineless cactus pear

Introduction

Agriculture in semiarid and arid regions of India is mostly rainfed, diverse, complex, under-invested, risky, and vulnerable. In addition, extreme weather conditions, like droughts, short-term rain, and sometimes extreme events like flooding in fields, add to the uncertainties and seasonal migrations (Todmal, 2019). The annual rainfall is around one-fifth to one-half of the potential evapotranspiration ($0.2 < P/E_p \leq 0.5$ where P is Precipitation and E_p is Evapotranspiration) (Scholes, 2020). The region can supply only one-fifth or half of the water demand of the plants and support plant growth for about 60 to 180 days (Scholes, 2020). Due to the intrinsic characteristic of global atmospheric circulation, the region has a large variability in the annual variability of precipitation (Scholes, 2020). The high evaporation potential and linear relationship between net crop production and rainfall during the growing season indicate a severe water

limitation in warm semiarid regions (Sala *et al.*, 1988). The scarcity of water in the semiarid region, with poor soil and low productivity, further aggravates the problem of food and fodder security (Golla, 2021; Palsaniya *et al.*, 2023).

The livestock pressure is high and there is a deficit of fodder and water as well for them (Prabhu *et al.*, 2025). The practice of open grazing is common in the non-cropped season (April- June) and uneconomic cattle roam as stray cattle in this area (Kumar *et al.*, 2021). For solving this typical socio-economic issue, technological options and efforts of governments/social organizations are providing meaningful solutions. In this endeavor, ICAR-Indian Grassland and Fodder Research Institute (IGFRI), with its outreach activities and on-farm demonstrations, is taking the technologies to the doorstep of farmers and its expansion in larger areas. It has collaborated with local cattle shelter houses (Gaushalas). The research findings of

the International Center for Agricultural Research in the Dry Areas and the ICAR Indian Grassland and Fodder Research Institute (ICARDA-IGFRI) cactus project have been very useful to solve the fodder crisis in such rain scanty/partially drought-prone areas. Cactus is being promoted as a non-conventional fodder resource for the lean period (dry summers/drought period). This is being promoted at community lands, degraded lands of individual farmers, field/farm boundaries, cow shelters, commercial goat farmers, and Krishi Vigyan Kendras (KVKs- Farm Science Centers).

Opuntia genus belongs to the *Cactaceae* family and is native to Central America. Over 360 species of *Opuntia* are grown in the warmer parts of the world. Low water requirement, high regeneration capacity, wider adaptation to soil types, and harsh climates make cactus a suitable candidate to incorporate into rainfed forage-based systems under such conditions. Spineless cactus pear *Opuntia ficus-indica* (L.) Mill is the most economically important species. It can be used as a vegetable as well as a valuable forage resource in arid and semiarid lands during periods of drought and shortage of herbaceous fodder plants. Spineless cactus pear is a succulent and drought-resilient xerophytic plant with multiple benefits to both man and animals, especially under stress conditions. It produces edible leaves (also known as cladodes) and a fruit with high nutritional value, as it is rich in minerals, protein, dietary fiber, and phytochemicals. The major advantage of spineless cactus pear for animal feed is that it is often one of the few sources of green forage in the dry season; it is capable of providing a vitamin A precursor, which leads to increase milk production. Its cladodes and fruits have a number of applications, viz. in food, cosmetics, construction, dye, medicinal industries, and as ornamental plants. *Opuntia* has become an important crop for exotic fruit, vegetable, and forage production in Mexico, the USA, Chile, Argentina, Israel, Italy, and South Africa, where it has adapted to dry areas with droughty conditions, scarce rainfall, and poor, erosion-prone soils. Spineless cactus pear has a special carbon dioxide fixation pathway, known as crassulacean acid metabolism (CAM), and can have a four-to five-fold greater efficiency in converting water to dry matter than even C4 plants such as maize. It has a higher water-carrying capacity than any other drought-tolerant fodder in extremely arid and semiarid areas and remains green and succulent during drought, thus capable of supplying much-needed energy and water for livestock during drought periods. Moreover, it has a very rich nutritional profile. Under the uncertain situations of rains both in normal and marginal lands, non-conventional forages like spineless cactus pear provide a viable option by providing high biomass to the livestock of poor farmers. Therefore, keeping the above facts in view, the International Center for Agricultural Research in the Dry Areas (ICARDA)

and Indian Grassland and Fodder Research Institute (ICAR-IGFRI) collaborative project was initiated to find out the potential of spineless cactus pear species as an alternate source of feed and fodder in dry areas of semiarid central India. The project envisaged building a strong foundation through the utilization of conventional and non-conventional fodder resources for crop diversification and development in semiarid regions of India for better livestock productivity with supported and improved livelihood activities in prevailing mixed farming situations. It is proven that the MaxEnt model can better predict the distribution of species than other algorithms in the case of a small sample size and can test the prediction results. It has been simple and widely used in invasive and conservation biology and in evaluating global climate change on the potential distribution of species in short computing time, and with stable computing results. 'Maximum Entropy' (MaxEnt) is considered the appropriate model that performed well across several metrics measured for multiple models in predicting occurrences in relation to other common approaches, especially with incomplete information (Hijmans and Graham, 2006). Hence, the climate suitability of the species has been assessed through the ecological niche modeling approach in the present study.

Materials and Methods

Occurrence records: Fifteen exotic germplasm materials of spineless cactus (*Yellow Roccapalumba*, *Trunzara Red Bronte*, *Yellow San Cono*, *Algerian*, *Yellow Santa Margherita Belice*, *Zastron*, *Red Roccapalumba*, *White Roccapalumba*, *Red San Cono*, *White San Cono*, *Seedless Roccapalumba*, *Morado*, *Roly Poly*, and *Blue Motto*) were multiplied and supplied to farmers who successfully established them in semiarid and arid regions of India (Fig. 1). The cladodes were distributed to Chhattisgarh (3 farmers), Delhi (3), Karnataka (5), Madhya Pradesh (588), Maharashtra (126), Odisha (625), Rajasthan (42), and Uttar Pradesh (291). The survival rate and growth of distributed cladodes were assessed during the field visits, and through telephonic conversation and agricultural officers and farmers. These locations served as occurrence records for building the model (geographical coordinates of these locations were recorded using the Garmin 12 Global Positioning System).

Bioclimatic variables: Climate dataset grids from the WorldClim (WC) database sourced (<http://www.worldclim.org> – version 2.1) (Fick and Hijmans, 2017) from global weather stations were downloaded and further used in this study. The WorldClim data provides interpolated global climate surfaces using independent variables (latitude, longitude, and elevation) and represents long-term (1970-2000 - current & future climate [downscaled and matched to the WorldClim estimates of

current climate 2xCO₂ Climate conditions CCM₃ model 2.5 min downloaded from www.diva-gis.org. A limitation of the present study is the use of the CCM3 climate model, which represents an earlier generation of global climate projections. Future studies should incorporate CMIP5 or CMIP6-based datasets to improve the accuracy of climate suitability predictions, monthly means of maximum, minimum, mean temperatures and total precipitation as generic 2.5 arc-min grids. Environmental layers used (all continuous) for this study: bio1 (annual mean temperature); bio2 (mean diurnal range); bio3 (isothermality); bio4 (temperature seasonality); bio5 (max. temperature of warmest month); bio6 (min. temperature of coldest month); bio7 (temperature annual range); bio8 (mean temperature of wettest quarter); bio9 (mean temperature of driest quarter); bio10 (mean temperature of warmest quarter); bio11 (mean temperature of coldest quarter); bio12 (annual precipitation); bio13 (precipitation of wettest month); bio14 (precipitation of driest month); bio15 (precipitation seasonality); bio16 (precipitation of wettest quarter); bio17 (precipitation of driest quarter); bio18 (precipitation of warmest quarter); bio19 (precipitation of coldest quarter). This study utilized the geo-referenced occurrence locations and climatic grid data for the spineless cacti presence points and analyzed information about environmental conditions at the current locations of the cactus to assess the probability of suitable conditions existing for the cultivation of this important prospective non-conventional fodder crop in semiarid and arid regions of India.

Building up of ecological niche model: With the occurrence records from the Indian states and the bioclimatic variables, an ecological niche model was generated for current and future climatic conditions. In the present study, ‘Maximum Entropy (MaxEnt) approach’ (<http://www.cs.princeton.edu/~schapire/MaxEnt>) has been used to assess the potential regions for cultivation of spineless cactus in India (Reddy et al., 2015). It uses presence points together with the characterization of available environments in the accessible areas to identify suitable climatic variables favored by the cactus pear. The background environment affects the model results and therefore, the percent contribution and permutation importance of climatic variables were assessed. Initially, the model has been calibrated to surrounding niche regions in the study area (Chhattisgarh, Delhi, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Rajasthan, and Uttar Pradesh) and projected to the whole of India (8°4′ to 37°6′ North latitude and 68°7′ to 97°25′ East longitude). DIVA-GIS version 7.5 downloaded from www.diva-gis.org was used to generate the final map (ecological niche models) based on the output generated from (.asci file of the operation of MaxEnt software. Model performance was evaluated using a variety of metrics. It measures

the ability of the model to estimate the true suitability of habitat. All metrics range from 1, where the truth is estimated correctly, to 0, where the projected model shows no similarity to the actual model. Metrics may be broadly useful for comparing models, but they are generally not applicable to model selection using real data, as they can only be calculated when the true niche and suitability of habitat are known. The maximum training AUC method used in the present study selects the model that produces the maximum value for the area under the receiver operating characteristic curve (AUC) calculated using the data used in model construction. The MaxEnt algorithm was used to model species distribution based on presence-only data. The model estimates probability distributions constrained by environmental variables while maximizing entropy. Model settings included: 105 presence records; 10,105 background points; Feature types: linear, quadratic, hinge, and product; Regularization parameters: default with minor adjustments; Maximum iterations: 500; Output format: logistic. The model was calibrated using occurrence data from selected states and projected across India. Environmental layers used (all continuous): bio1 bio10 bio11 bio12 bio13 bio14 bio15 bio16 bio17 bio18 bio19 bio2 bio3 bio4 bio5 bio6 bio7 bio8 bio9.

Regularization values: linear/ quadratic/ product: 0.050, categorical: 0.250, threshold: 1.000, hinge: 0.500. Feature types used: hinge, product, linear, quadratic response curves: true output format: logistic; the environmental layers: Climate Grids\Bioclim_2.5 arc min; Regularized training gain is 4.174, training AUC is 0.995, unregularized training gain is 4.346. Iterations: 500 (8 seconds). To reduce multicollinearity, a Pearson correlation analysis was conducted among the 19 bioclimatic variables, and highly correlated variables ($r > 0.7$) were excluded. The model was further validated using a 75:25 training–testing split, and both training and test AUC values were reported.

Results and Discussion

The MaxEnt model estimates an unknown probability distribution that “satisfies any constraints on the unknown distribution that we are aware of, and that subject to those constraints, the distribution should have maximum entropy” (Phillips et al., 2004). In information theory, entropy is randomness or unpredictability, meaning that the portion that is not explained by the probability distribution has no remaining information with respect to the distribution of the prior data. ‘Ecological Niche Models’ generated for the current and future climatic grids are provided in Figs 2 and 3, respectively. Niche models revealed that potential climate-suitable sites for cultivating spineless cactus pear are available in the states of Andhra Pradesh, Bihar, Delhi,

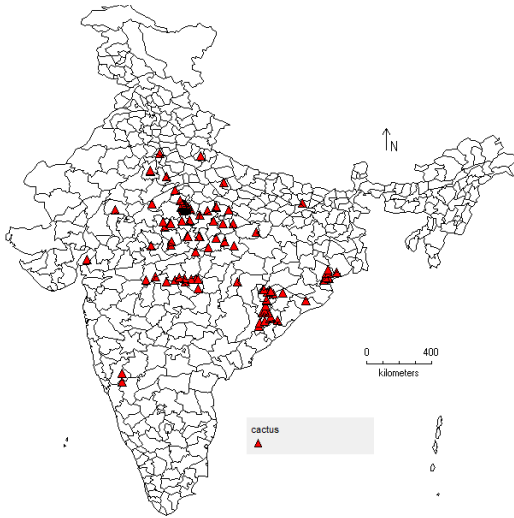


Fig 1. DIVA-GIS map showing the presence points of spineless cactus pear in India

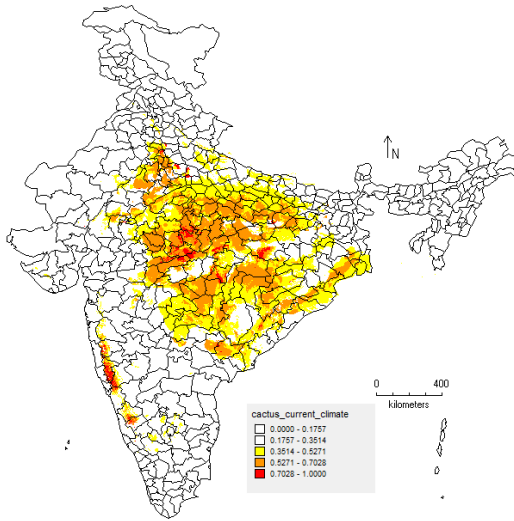


Fig 2. Ecological niche model generated for the spineless cactus pear (*Opuntia ficus-indica*) –[Current climate]

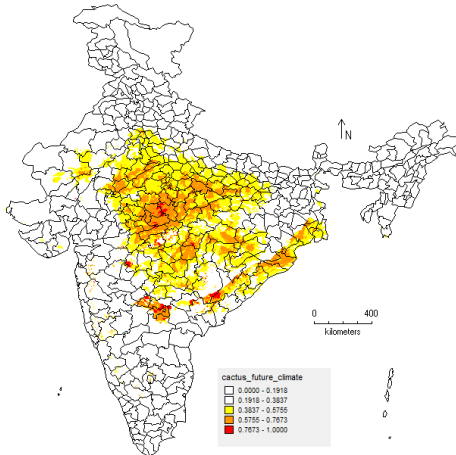


Fig 3. Ecological niche model generated for spineless cactus pear (*Opuntia ficus-indica*) –[Future climate]

Haryana, Karnataka, Madhya Pradesh, Maharashtra, Odisha, and Uttar Pradesh (Fig 2-3). Interestingly, the model identified climatically suitable regions in states such as Andhra Pradesh and Bihar, where germplasm had not been initially distributed. This reflects the MaxEnt model's ability to extrapolate suitability based on environmental similarity. These regions likely share comparable climatic conditions with established sites, particularly in terms of temperature regimes and precipitation seasonality. Such predictions are valuable for guiding future introduction and expansion strategies of *O. ficus-indica* in India. Climate change-induced biotic and abiotic stresses are threatening the future of food and fodder crop production in the country and pose a major challenge. Spineless cactus pear would be the candidate crop for expanding sustainable fodder crop production in the degraded lands of semiarid and arid regions of India with suitable climate mitigation strategies for adaptation (Kumar *et al.*, 2021; Kumar *et al.*, 2023). Thus, cactus production could be increased by bringing suitable areas in the above-mentioned states under cultivation. The suitable sites identified by the present models will help to increase fodder productivity and to meet the challenges of providing high biomass to livestock. As the cactus is an exotic introduction into India, it is essential to find out the areas of suitability for its cultivation. This *Opuntia* sp. is capable of growing under drought conditions in arid and semiarid regions and remains green during extreme weather conditions, thus able to supply energy and water for livestock during the dry season (Misra *et al.*, 2018; Das *et al.*, 2025). The suitability of the study site is an important factor to determine the productivity of the crop and suitability maps depict the remarkable area having the greatest success for growing a particular crop (Parthasarathy *et al.*, 2007). Several site suitability models have been used extensively to evaluate the potential impact of future climate change on shifts in the production and growing regions of various crops (Rosenzweig *et al.*, 1995; Tubiello *et al.*, 2000, 2002; Sivaraj *et al.*, 2016). Fig 4 displays the omission rate and predicted area as a function of the cumulative threshold. The omission rate is calculated on the training presence records and (if test data are used) on the test records. The omission rate should be close to the predicted omission because of the definition of the cumulative threshold. Figures 5 (A, B, C, D) are the response curves showing how each environmental variable affects the MaxEnt prediction for the current climate model influenced by environmental variables (bio15, bio11, bio17 and bio3). The curves show how the predicted probability of presence changes as each environmental variable is varied, keeping all other environmental variables at their average sample value. The response curves show the marginal effect of changing exactly one variable, whereas the model may take advantage of sets of variables changing together.

Table 1. Estimates of relative contributions of the environmental variables to the MaxEnt models for spineless cactus pear (*Opuntia ficus-indica*)

Variable	Percent contribution	
	Current climate	Future climate
Annual mean temperature (bio1)	3.2	2.6
Mean diurnal range (bio 2)	1.4	1.2
Isothermality (bio 3)	8.2	2.9
Temperature seasonality (bio 4)	0.3	0.1
Maximum temperature of warmest month (bio 5)	0.2	2
Minimum temperature of coldest month (bio6)	6.6	0.1
Temperature annual range (bio7)	0.7	1
Mean temperature of wettest quarter (bio8)	7	0.8
Mean temperature of driest quarter (bio 9)	0.3	0.3
Mean temperature of warmest quarter (bio10)	29.6	3
Mean temperature of coldest quarter (bio11)	8.9	22.1
Annual precipitation (bio12)	0.2	0.1
Precipitation of wettest month (bio13)	0.2	0.1
Precipitation of driest month (bio14)	11.7	0.1
Precipitation seasonality (bio15)	10.2	52.7
Precipitation of wettest quarter (bio16)	0.1	0.1
Precipitation of driest quarter (bio17)	9	10.4
Precipitation of warmest quarter (bio18)	0	0.1
Precipitation of coldest quarter (bio19)	2.2	0.4

In contrast to the above marginal response curves, Fig. 5 (E, F, G, H) each of the following curves represents a different model, namely, a MaxEnt model created using only the corresponding variable. These plots reflect the dependence of predicted suitability on both the selected variable and dependencies induced by correlations between the selected variable and other variables. Similarly, Figures 6 (A, B, C, D) represent the response curves for high-influence bioclimatic variables (bio15, bio11, bio17 and bio10) for the future climate prediction model. Figures 6 (E, F, G, H) present the dependence of predicted suitability for the future climatic model of spineless cactus pear.

Table 1 gives estimates of the relative contributions of the environmental variables to the MaxEnt models of current and future climatic conditions. Bioclimatic variables, *viz.*, Mean temperature of warmest quarter (bio10), precipitation of the driest month (bio14), Precipitation seasonality (bio15), and Isothermality (bio3), contributed the maximum to the current climate model with percentage values of 29.6, 11.7, 10.2, and 8.2, respectively. Interestingly, the niche model for future climate is governed by the bioclimatic variables, precipitation seasonality (bio15), mean temperature of the coldest quarter (bio 11), precipitation of the driest quarter (bio17), and isothermality (bio 3) with percentage values of 52.7, 22.1, 10.4 and 2.9, respectively. To determine the first estimate, in each iteration of the training algorithm, the increase in regularized gain is added to the contribution of the corresponding variable or subtracted from it if the change to the absolute value of lambda is negative. For the second estimate, for each environmental variable, in turn, the values of that variable on training

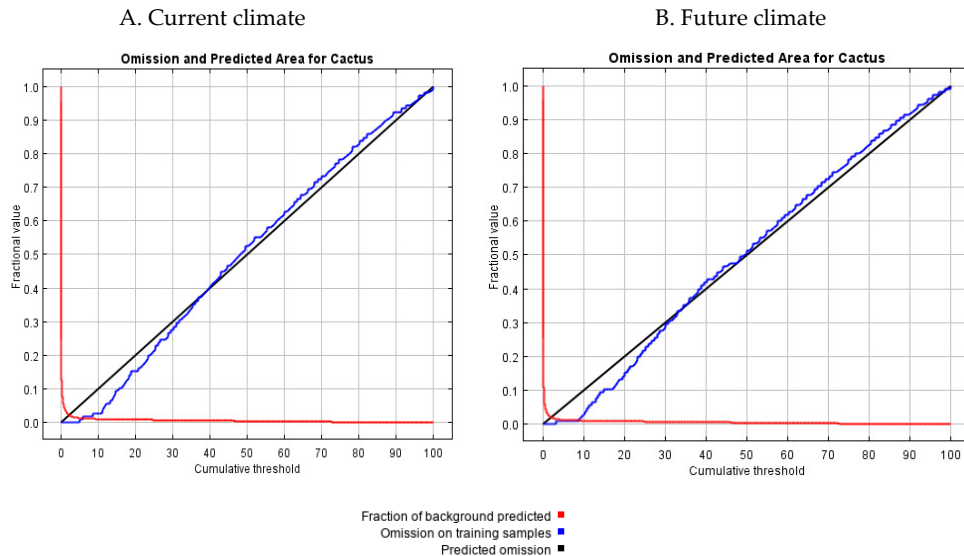


Fig 4. Omission and predicted areas depicted for cactus pear in MaxEnt model (A. Current climate and B. Future climate)

Ecological niche modeling for spineless fodder cactus

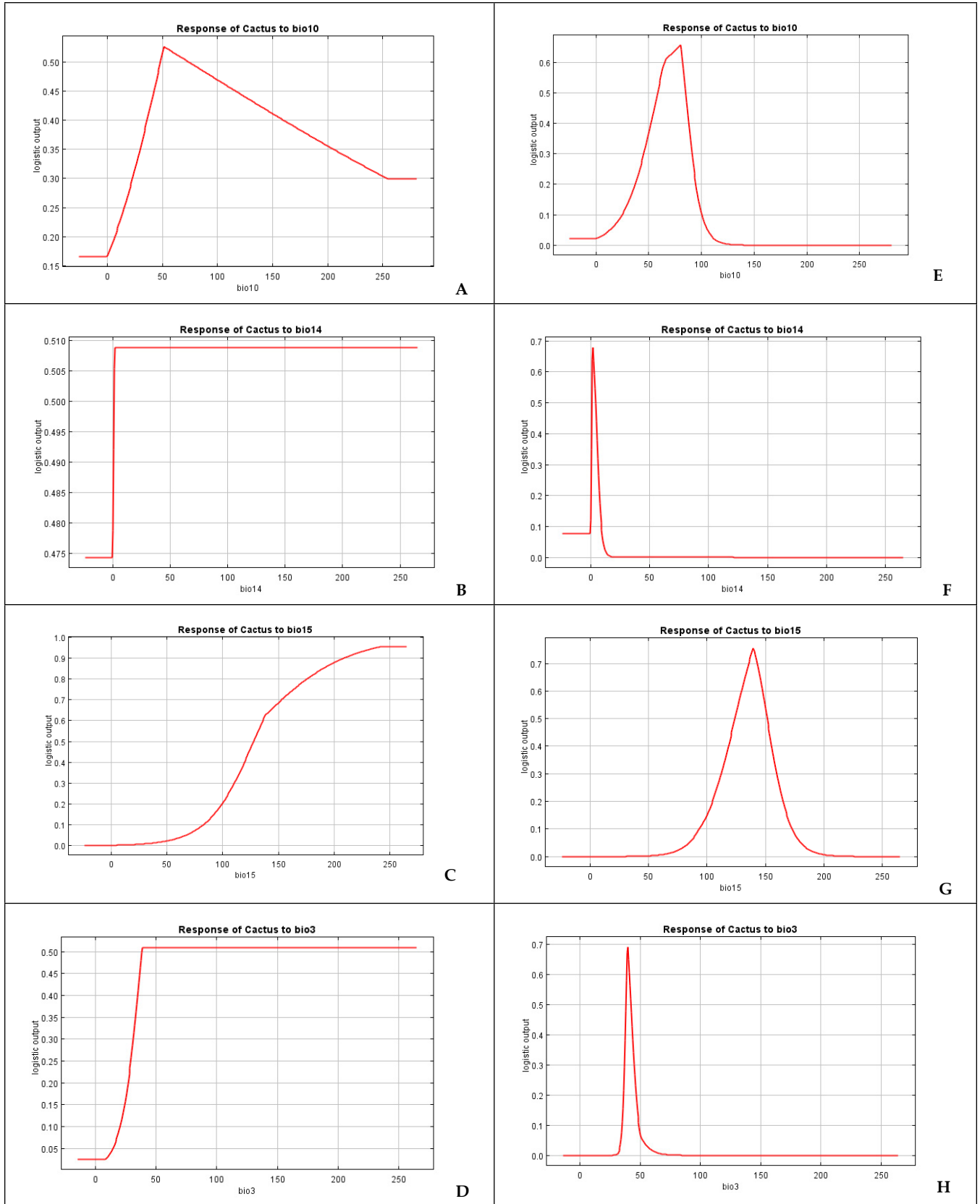


Fig 5. Response curves for bioclimatic variables having high influence on the cactus pear MaxEnt Model for current climate (A,B,C,D) and dependencies induced by correlations (E,F,G,H)

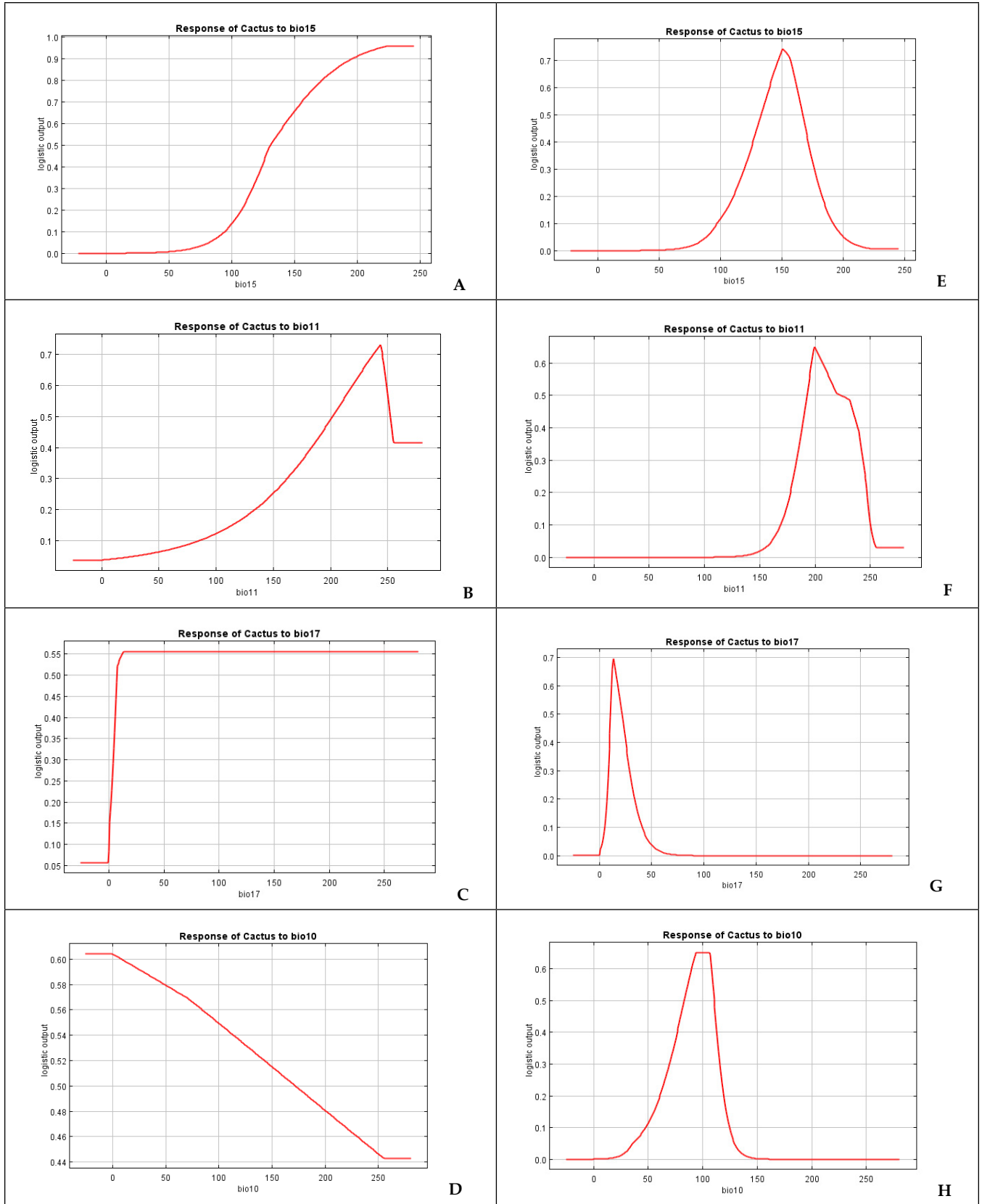


Fig 6. Response curves for bioclimatic variables having high influence on the cactus pear MaxEnt Model for future climate (A,B,C,D) and dependencies induced by correlations (E,F,G,H)

presence and background data are randomly permuted. The substantially higher contribution of precipitation seasonality (bio15) in the future climate model (52.7%) compared to the current scenario (10.2%) suggests an increased influence of rainfall variability on species distribution. This shift is likely driven by projected changes in monsoon dynamics, including greater intra-seasonal variability, erratic rainfall distribution, and increased frequency of extreme precipitation events. Such changes disproportionately affect species like *Opuntia ficus-indica*, which are adapted to water-limited environments while remaining sensitive to the temporal distribution of rainfall.

The sharp decline in the contribution of precipitation during the driest month (bio14) in future projections suggests a reduced influence of extreme dry-month conditions on species distribution. This may reflect either a projected increase in minimum rainfall levels or a shift in ecological constraints, where seasonal rainfall variability becomes more critical than absolute minima. Given the inherent drought tolerance of *O. ficus-indica*, the species appears less constrained by single-month extremes under future climate scenarios.

Spineless cactus pear is a relatively recent introduction into Indian agricultural systems. Systematic promotion began around 2013 through collaborative initiatives between ICAR and the International Center for Agricultural Research in the Dry Areas (ICARDA). Since then, the crop has gradually expanded through pilot demonstrations, watershed programs, and farmer participatory trials.

The growth trajectory has been: Introduction phase (2013–2016) - research trials and limited demonstrations; Expansion phase (2017–2020) - on-farm demonstrations across multiple states; Scaling phase (2021–present)-through government programs and international collaborations. However, the total cultivated area remains limited and fragmented, largely confined to demonstration plots, research farms, and early adopter farmers rather than widespread commercial cultivation.

Conclusion

Spineless cactus pear is a unique subtropical fodder crop that can be cultivated using poor resources on degraded lands in arid and semiarid regions of India. While ecological niche modeling provides a scientific basis for identifying climatically suitable regions, the actual expansion of spineless cactus pear in India will depend on the integrating biophysical suitability with socio-economic, institutional, and policy factors. A holistic approach combining climate modeling with adoption dynamics is essential for realistic planning and scaling of this climate-resilient fodder crop. The present study will help in managing cactus genetic resources in the country by formulating suitable sustainable crop cultivation strategies. The results of the study will be

highly useful in micro-level planning of cultivation of this non-conventional forage cactus on degraded lands, which in turn will help the farmers to increase their livelihood security in the changed climatic regime.

Acknowledgment

This study was conducted within the framework of the collaborative research program between the Indian Council of Agricultural Research (ICAR) and the International Center for Agricultural Research in the Dry Areas (ICARDA). Special thank goes to the ICAR-Indian Grassland and Fodder Research Institute (IGFRI) for implementing the study and to the Livestock, Climate and System Resilience (LCSR) of the OneCGIAR for their support. The opinions expressed in this work belong to the authors and do not necessarily reflect those of ICAR, ICARDA, or the OneCGIAR.

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