

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

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Article

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

Posted Date: October 24th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-2164260/v1>

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Abstract

Spineless cactus pear [*Opuntia ficus-indica* (L.) Mill.] is a promising subtropical non-conventional fodder crop in India. Ecological niche modelling studies using the maximum entropy approach has been used to assess the suitable cactus growing regions in India. The dataset for cactus pear presence locations was obtained from various centres. WorldClim dataset representing current and future climate was downloaded from [http:// www.worldclim.org](http://www.worldclim.org). The cactus presence locations dataset and WorldClim dataset were used with Maximum entropy (MaxEnt) modelling to generate the climate suitability map to show potential growing sites in India. The generated maps indicated that potential regions for the cultivation of cactus 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.

Introduction

Agriculture in semi-arid 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 the flooding in fields add to the uncertainties and seasonal migrations¹. The annual rainfall is around one-fifth to one-half of the potential evapotranspiration ($0.2 < P/E_p \leq 0.5$)². 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 days². Due to the intrinsic characteristic of global atmospheric circulation, the region has a large variability in the annual variability of precipitation². The high evaporation potential and linear relationship between net crop production and rainfall during the growing season indicates a severe water limitation in warm semi-arid regions^{3,4}. The scarcity of water in the semi-arid region, with poor soil and low productivity further aggravates the problem of food and fodder security⁵.

The livestock pressure is high and there is a deficit of fodder and water as well for them. The practice of open grazing is common in the non-cropped season (April- June) and uneconomic cattle roam as stray cattle in this area⁶. 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 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 ICAR Indian Grassland and Fodder Research Institute ICARDA-IGFRI cactus project has been very much 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)⁷. 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 Centres).

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 fruits with high nutritional value as it is rich in minerals, protein, dietary fibers, 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 vitamin A precursor 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 semi-arid 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, *International Center for Agricultural Research in the Dry Areas* and *Indian Grassland and Fodder Research Institute* (ICARDA-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 semi-arid central India. The project envisages building a strong foundation through the utilization of conventional and non-conventional fodder resources for crop diversification and development in semi-arid regions of India for better livestock productivity with supported and improved livelihood activities in prevailing mixed farming situations. Hence, the climate suitability of the species has been assessed through the ecological niche modelling approach in the present study.

Materials And Methods

As a part of ICARDA-IGFRI collaborative programme, IGFRI received 15 spineless cactus pear accessions (five cladodes each) from Italy in April, 2013. These accessions were *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*. Cladodes (vegetative part) were received from ICARDA, India office, New Delhi, after being

subjected to quarantine at the ICAR-National Bureau of Plant Genetic Resources, New Delhi. Our study complies with local and national regulations while handling the plant samples. These cladodes were planted in a mother nursery at IGRI research farm and multiplied in five multiplication blocks and simultaneously evaluated for survival, growth, yield potential, and nutritional parameters. These multiplied accessions were supplied to farmers in semi-arid and arid regions of India (Fig. 1) and successfully established by them. These locations served as presence points for building the model (geographical coordinates of these locations were recorded using Garmin 12 global positioning system). In the present study, the Maximum Entropy (MaxEnt) approach ([http:// www.cs.princeton.edu/~schapire/ MaxEnt](http://www.cs.princeton.edu/~schapire/MaxEnt)) has been used to assess the potential regions for the cultivation of spineless cactus in India. Climate dataset grids from the WorldClim (WC) database sourced (<http://www.worldclim.org>) from global weather stations are 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 (1950-2000-current & future) 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 the warmest month); bio6 (Min. temperature of the coldest month); bio7 (Temperature annual range); bio8 (Mean temperature of the wettest quarter); bio9 (Mean temperature of the driest quarter); bio10 (Mean temperature of the warmest quarter); bio11 (Mean temperature of the coldest quarter); bio12 (Annual precipitation); bio13 (Precipitation of the wettest month); bio14 (Precipitation of the driest month); bio15 (Precipitation seasonality); bio16 (Precipitation of the wettest quarter); bio17 (Precipitation of the driest quarter); bio18 (Precipitation of the warmest quarter); bio19 (Precipitation of the 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 cactus to assess the probability of suitable conditions existing for the cultivation of this important prospective non-conventional fodder crop in semi-arid and arid regions of India. 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) the operation of MaxEnt software⁸.

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”⁹. 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.

In the present study, the Ecological Niche Models generated for the current and future climatic grids using the Maximum entropy approach are provided in Fig. 2 and 3 respectively. Niche models reveal that potential climate-suitable sites for the cultivation of spineless cactus pear are available in the states of

Andhra Pradesh, Bihar, Delhi, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Odisha, and Uttar Pradesh. Climate change-induced stresses both biotic and abiotic 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 the expansion of sustainable fodder crop production in the degraded lands of semi-arid and arid regions of India with suitable climate mitigation strategies for adaptation. 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 so as to increase fodder productivity and to meet the challenges of providing high biomass to livestock of poor farmers in India. As this 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 semi-arid regions and remains green during extreme weather conditions. Thus, able to supply energy and water for livestock during the dry season. 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 crop¹⁰. Several site suitability models have been extensively used to evaluate the potential impact of future climate change on shifts in the production and growing regions of various crops^{10,11,12,13,14,15}. Fig. 4 displays the omission rate and predicted area as a function of the cumulative threshold. The omission rate is calculated both 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.

Fig. 5 (A, B, C, D) are the response curves which show that 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. 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 both on the selected variable and on dependencies induced by correlations between the selected variable and other variables. Similarly, Fig. 6 (A, B, C, D) represent the response curves for high-influence bioclimatic variables (Bio15, Bio11, Bio17 and Bio10) for future climate prediction model. Fig. 6 (E, F, G, H) presents 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 presence and background data are randomly permuted.

Conclusions

Spineless cactus pear is a unique subtropical fodder crop that can be cultivated with poor resources of degraded lands in arid and semi-arid regions of India. The present study would help in managing cactus genetic resources in the country by formulating suitable sustainable crop cultivation strategies. The results of the study would be highly useful in micro-level planning of cultivation of this non-conventional forage cactus in degraded lands which in turn will help the farmers to increase their livelihood security in the changed climatic regime.

Declarations

Acknowledgements

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.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to the policy restriction of the funding agency but are available from the corresponding author upon reasonable request after getting the concern from the funding agency.

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Table 1

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

Figures

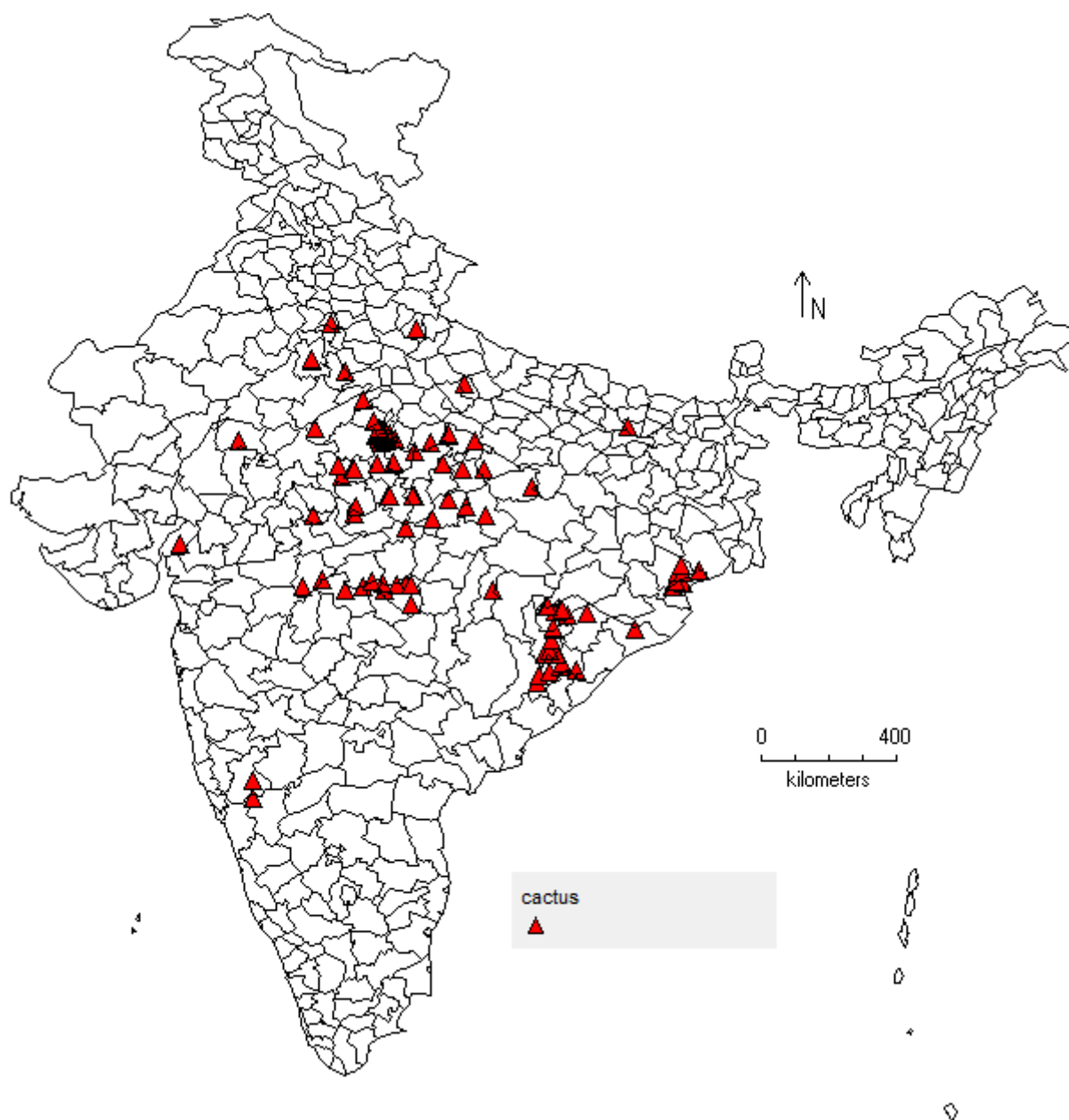


Figure 1

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

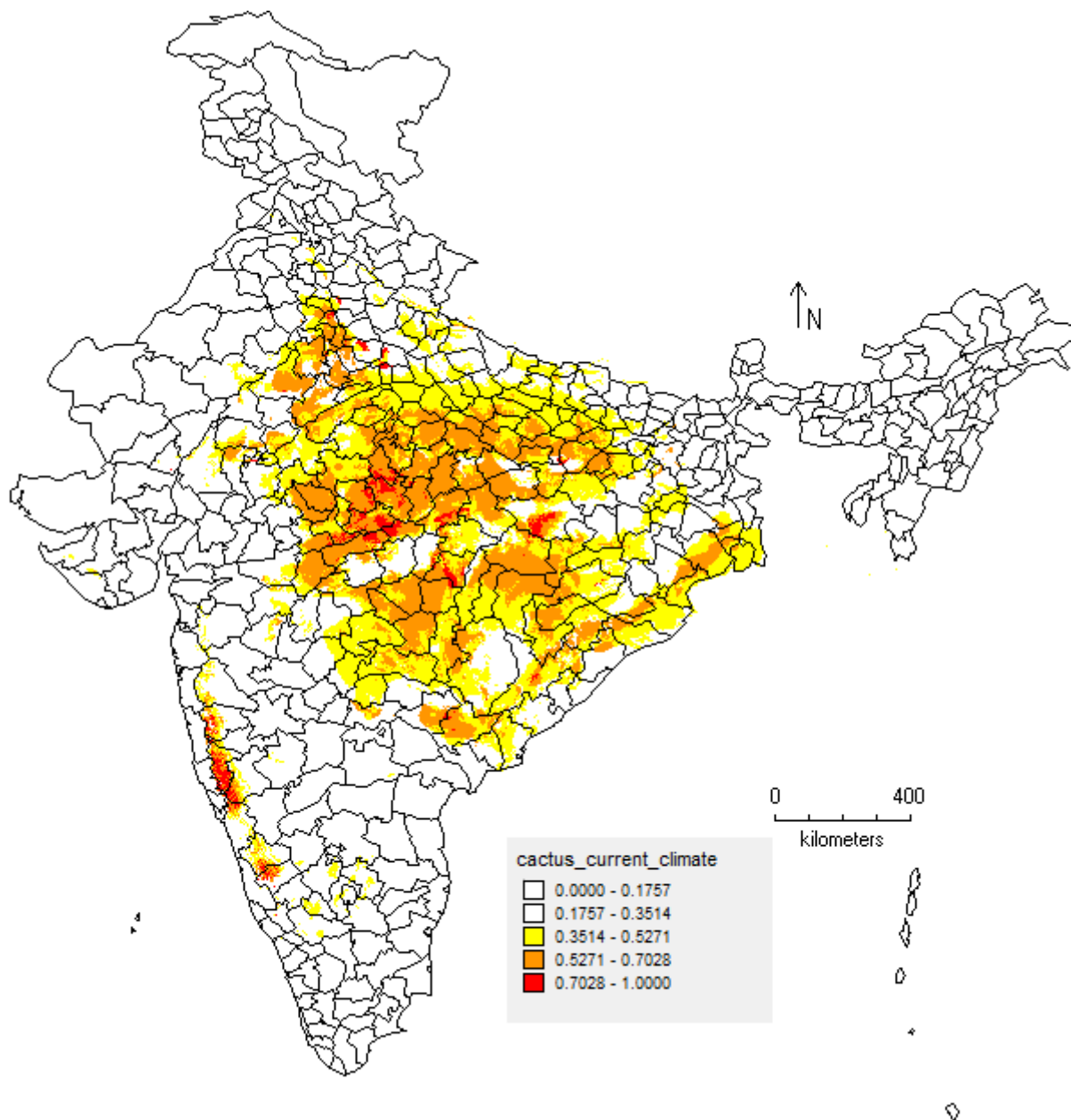


Figure 2

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

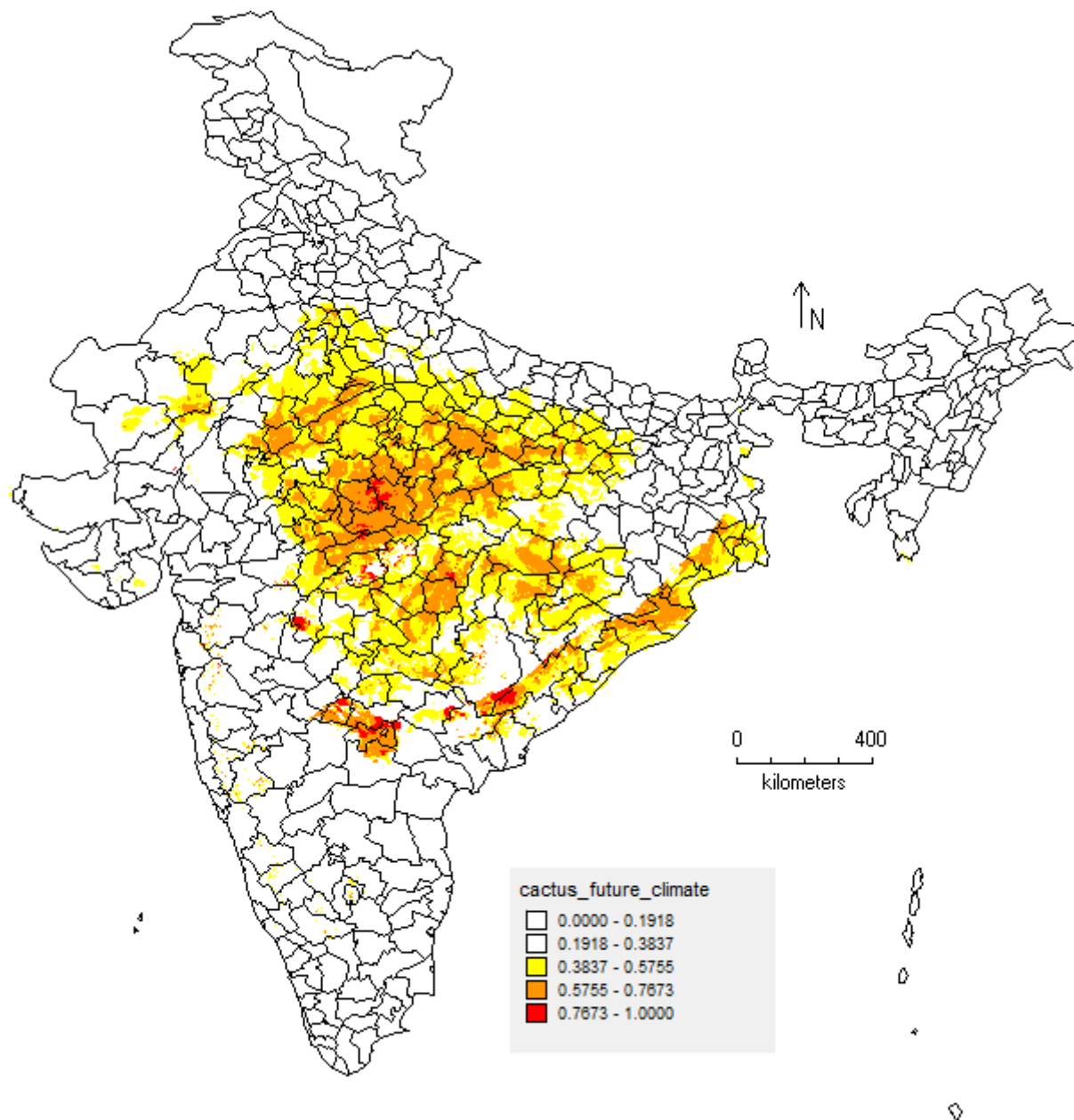


Figure 3

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

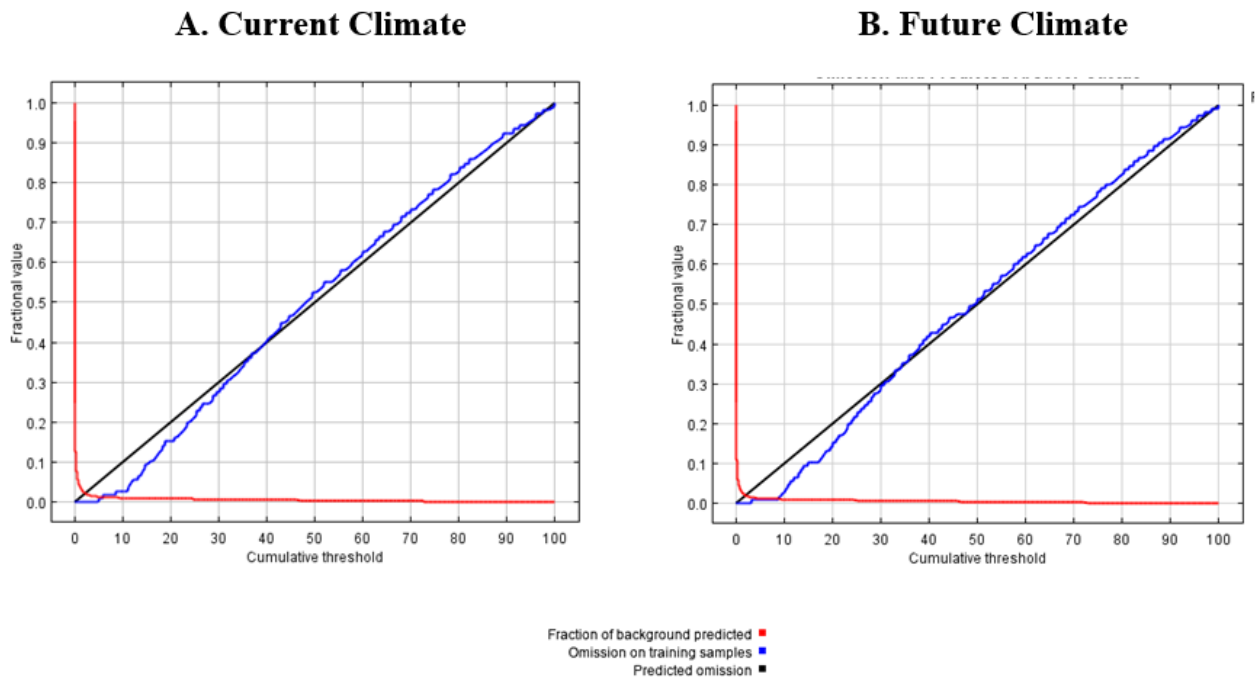


Figure 4

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

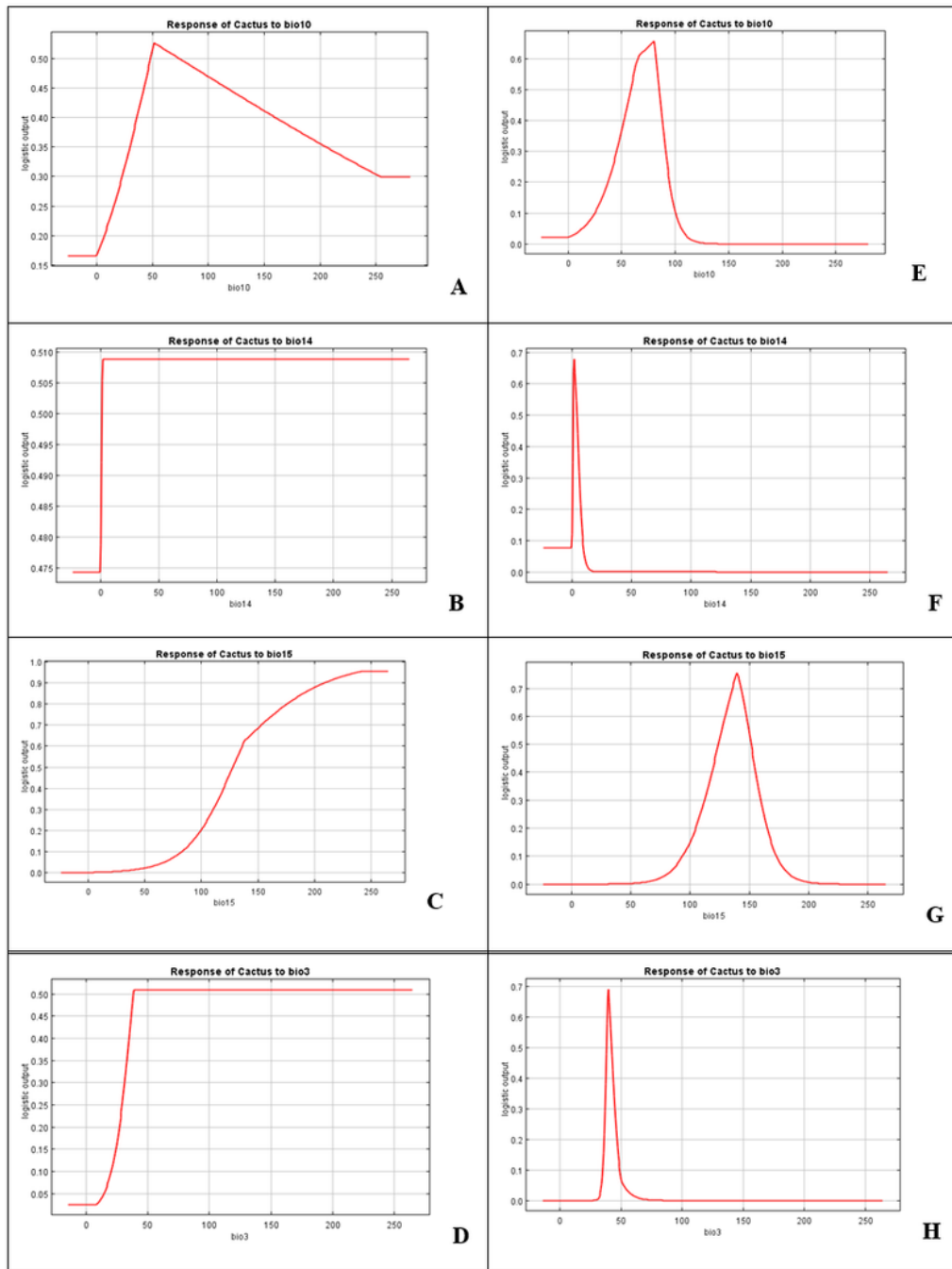


Figure 5

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).

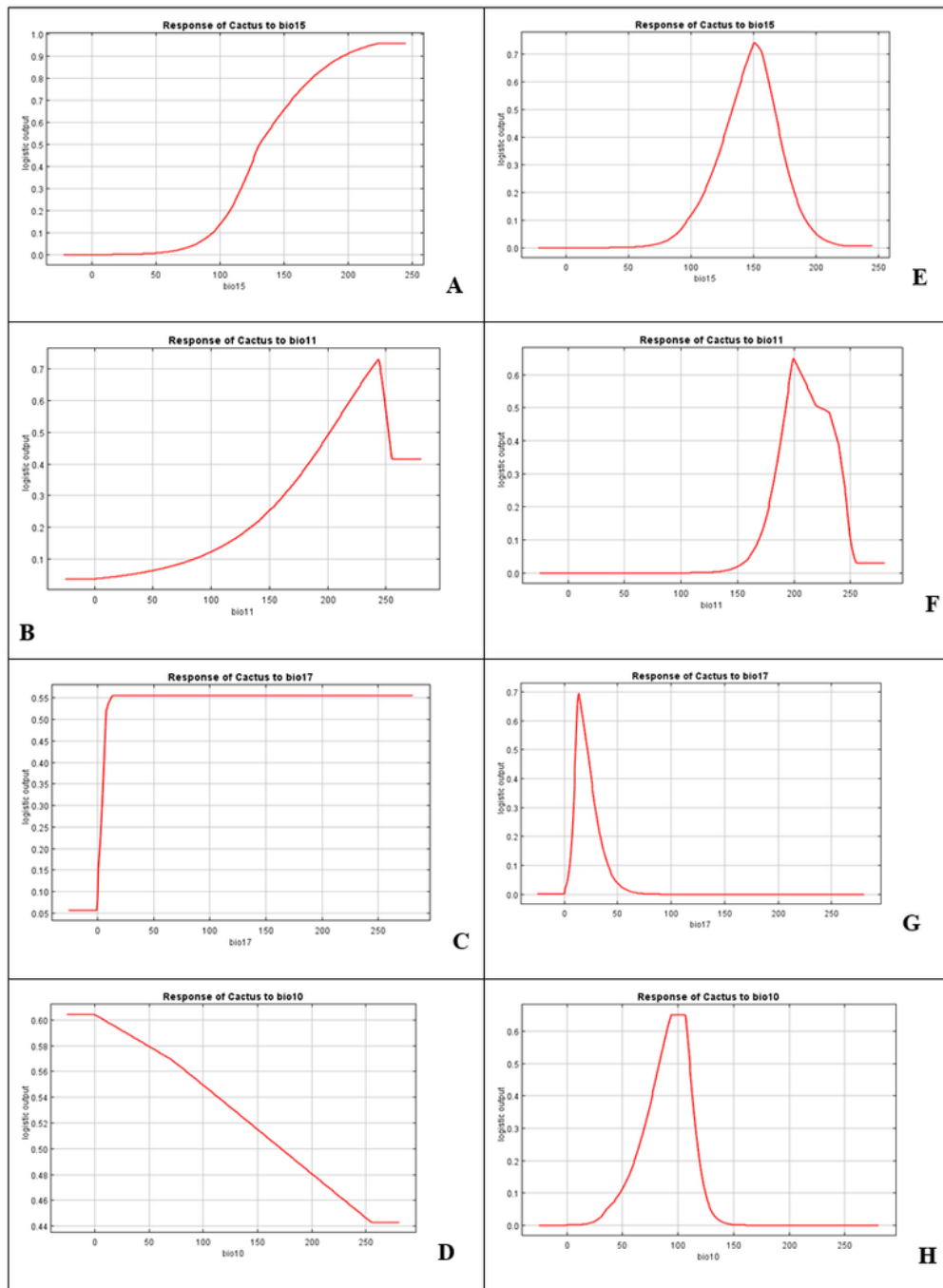


Figure 6

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).