

RESEARCH ARTICLE

POTENTIAL AVOCADO GROWING REGIONS IN INDIA: AN ECOLOGICAL NICHE MODELLING APPROACH

N. Sivaraj^{1*}, K. Anitha¹, B. Parameswari¹, L. Saravanan¹, Prasanna Holajjer¹, B. Bhaskar¹, G. Karunakaran² and M. Srinivas Rao³

¹ICAR-National Bureau of Plant Genetic Resources, Regional Station,
Hyderabad-500 030, Telangana, India

²Division of Fruit Crops, ICAR-Indian Institute of Horticultural Research,
Bengaluru-560089, Karnataka, India

³Deccan Exotics Farmer Producing Company Limited, Hyderabad, Telangana, India
Email: sivarajn@gmail.com

Received-01.03.2023, Revised-12.03.2023, Accepted-23.03.2023

Abstract: The present study aims to identify the suitable areas for avocado cultivation in India. The study employs ecological niche modelling techniques to identify the potential avocado growing regions based on various bioclimatic variables (19) such as maximum temperature of warmest month, precipitation of wettest month, precipitation of coldest quarter, precipitation of warmest quarter, mean temperature of warmest quarter, temperature annual range, temperature seasonality, isothermality etc. The MaxEnt algorithm was used to generate a model for avocado cultivation sites in India. The results indicate that the regions with the highest suitability for avocado cultivation are concentrated in the western, southern and northern parts of the country, with some potential areas in the northeast. The study also provides insights into the climatic and environmental factors that affect avocado growth and suggests possible strategies for avocado cultivation in India. This study can serve as a valuable guide for farmers and policymakers in identifying suitable locations for avocado cultivation and promoting the development of the avocado industry in India.

Keywords: Avocado, Bioclimatic variables, Cultivation, Germplasm

INTRODUCTION

Avocado is a highly nutritious and versatile fruit that has gained popularity in recent years due to its numerous health benefits and culinary uses. Although avocado is primarily grown in tropical and subtropical regions of the world, its cultivation is still in its infancy in India. However, with the increasing demand for avocados in the Indian market, there is a growing interest in exploring the potential of avocado cultivation in different regions of the country (Tripathi *et al.*, 2014). In this article, we will discuss the potential avocado growing regions in India, using an ecological niche modelling approach. This approach involves the use of climate and environmental data to identify areas that are suitable for avocado cultivation based on the crop's ecological requirements. By analyzing various climatic and environmental factors, we can identify regions in India where avocado cultivation is likely to be successful. Through this article, we aim to provide valuable insights to farmers, researchers, and stakeholders who are interested in exploring the

potential of avocado cultivation in India. Our findings will help to identify suitable regions for avocado cultivation, thereby contributing to the development of the avocado industry in India.

Major Avocado growing regions of world

Avocados are grown in various regions around the world, with some countries being major producers. Some of the major avocado growing regions are provided below:

Mexico: Mexico is the world's largest producer of avocados, accounting for over a third of global production. The state of Michoacán is the top producer in Mexico.

Peru: Peru is the second largest producer of avocados in the world. The country exports a significant amount of avocados to the United States and Europe.

California, USA: California is the largest producer of avocados in the United States. The state produces Hass avocados, which are known for their creamy texture and rich flavor.

Chile: Chile is a major producer and exporter of avocados, particularly to the United States and

*Corresponding Author

Europe. The country is known for producing high-quality avocados.

South Africa: South Africa is one of the largest producers of avocados in the southern hemisphere. The country produces both Hass and green-skinned varieties.

Spain: Spain is one of the largest avocado producers in Europe, with most of its production coming from the southern region of Andalusia.

Colombia: Colombia is a significant producer of avocados, particularly the Hass variety, and is known for producing high-quality fruit.

Australia: Avocado production in Australia has been increasing in recent years, with most of the production coming from the state of Queensland.

Other countries that produce avocados include Israel, Brazil, Kenya, New Zealand, and Indonesia, among others. Worldwide 5,575,358 tonnes of avocado produced per year with Mexico being the largest producer with 1,889,354 tonnes per year (<https://www.atlasbig.com>). Global exports of avocados grew to approximately 2.3 million tonnes in 2020, an increase of 8.2 percent from 2019 (FAO, 2021).

Status of Avocado cultivation in India

Avocado cultivation in India is still in its nascent stages, but it has been gaining momentum in recent years. The country's tropical climate and diverse soil types provide a suitable environment for avocado cultivation. Majority of the avocado cultivation in India is concentrated in the southern states of Tamil Nadu, Kerala, Karnataka and Maharashtra. The total area under avocado cultivation in India was 1,328 hectares in 2019-20, with a total production of 2,538 metric tons. The state of Tamil Nadu is the largest producer of avocados in the country, followed by Kerala. It is also being cultivated in Sikkim, a state in north east Indian region at altitudes ranging between 800-1600 m (Tripathi et al., 2014). The major varieties of avocados grown in India include Hass, Fuerte, Nabal, TKD-1, Linda, Puyevla, Pullock, Waldin etc. Hass is the most commonly grown variety and is preferred by consumers due to its rich flavor and creamy texture. India imports avocados primarily from Peru, Chile, and Mexico. According to data from the Agricultural and Processed Food Products Export Development Authority (APEDA), India imported 1,222 tonnes of avocados in 2020-21, with a value of \$3.23 million. The majority of avocado imports is used for the domestic market and is primarily consumed in urban areas. India also exported 36.71 tonnes of avocado to eight countries (Bhutan, Hongkong, Australia, Maldives, Thailand, Mali, Qatar and United Arab Emirates) valued at 39.20 lakhs during 2021-22 (<https://agriexchange.apeda.gov.in>).

Avocado cultivation in India is primarily done by small and marginal farmers who are looking to diversify their income sources. The demand for avocados in the country is increasing, and the fruit is

becoming popular among health-conscious consumers. However, there are some challenges associated with avocado cultivation in India, including a lack of technical knowledge among farmers, limited availability of quality planting material, and high cost of inputs such as fertilizers and pesticides. Overall, the avocado cultivation in India is still in its early stages, but it has the potential to become a significant contributor to the country's horticulture sector in the coming years.

Plant Description

Avocado is a fruit-bearing tree that belongs to the Lauraceae family. It is native to Central and South America, but it is widely cultivated in many tropical and subtropical regions of the world. The avocado tree can grow up to 20 meters in height, but it is usually pruned to a smaller size for ease of harvesting. It has a dense, evergreen canopy with glossy, dark green leaves that are elliptical in shape and 12-25 cm in length. The avocado fruit is oval or pear-shaped, and it can vary in size from 7 to 20 cm long and weigh between 100 to 1000 grams, depending on the variety. The skin of the fruit is rough and leathery, ranging in colour from green to black, and it is often covered in small bumps. The flesh of the fruit is creamy, buttery, and high in healthy fats. It is pale yellow or greenish-yellow in colour and has a rich, nutty flavour. Avocado trees are dioecious, meaning they have separate male and female flowers on different trees. The flowers are small and greenish-yellow in color, and they bloom in the spring. The fruits develop on the tree over several months and are usually harvested in the fall or winter when they are mature. Overall, the avocado is a versatile and delicious fruit that is enjoyed around the world for its unique flavour and numerous health benefits. Avocado trees thrive in warm, subtropical or tropical climates, where temperatures are above 60°F (16°C) year-round. The trees grow best in well-drained, loamy soil with a pH between 6 and 7.5.

Varieties of Avocado

There are many different varieties of avocados, belonging to Mexican (*Persea americana*, variety *drymifolia*), West Indian (*P. americana* variety *americana*) and Guatemalan (*P. americana*, variety *guatemalensis*) cultivars (>1000) (Ghosh, 2000). Some of the most common ones are provided below:

Hass: The Hass avocado is one of the most popular varieties in the world, and it accounts for the majority of the avocados sold in the United States. It has a dark, bumpy skin and a creamy, nutty flesh.

Fuerte: The Fuerte avocado is a larger variety with a smooth, thin skin. It has a buttery, rich flavor and is often used for making guacamole.

Bacon: The Bacon avocado has a smooth, green skin and a milder flavor than other varieties. It gets its name from its long, narrow shape, which resembles a strip of bacon.

Reed: The Reed avocado is a larger variety with a smooth, green skin. It has a creamy texture and a slightly sweet, nutty flavor.

Pinkerton: The Pinkerton avocado has a rough, bumpy skin and a large seed. It has a mild flavor and a creamy texture, and it is often used in salads and sandwiches.

Zutano: The Zutano avocado is a large, pear-shaped variety with a thin, smooth skin. It has a slightly bitter flavor and a firmer texture than other varieties, which makes it ideal for slicing and adding to sandwiches and salads.

Lamb Hass: The Lamb Hass avocado is a smaller version of the Hass avocado. It has a dark, bumpy skin and a creamy, nutty flavor, and it is often used in salads and as a garnish.

Gwen: The Gwen avocado is a medium-sized variety with a smooth, green skin. It has a creamy texture and a nutty, buttery flavor, and it is often used in salads and sandwiches.

MATERIALS AND METHODS

Presence points

The geographical coordinates of avocado cultivating countries were acquired through several internet sources including Genesys germplasm database (<https://www.genesys-pgr.org/a/v2XagyVJ80g>).

The occurrence points used in the present study represent 22 countries (Table 1), where avocados are currently grown.

Environmental variables

Nineteen bioclimatic predictor variables (BC) were selected for building the ecological niche models, which represent annual trends, seasonality and extreme or limiting environmental factors. Bioclimatic variables are generally selected based on species ecology (Roura-Pascual *et al.*, 2009). For the current climate (baseline) of India we used monthly data from the WorldClim (WC) database sourced from global weather stations. The variables, including annual mean temperature, mean diurnal range, maximum temperature of warmest month, minimum temperature of coldest month, annual precipitation, and precipitations of the wettest and driest months were downloaded from the World Clim dataset – (freely available at <http://www.worldclim.org>). The World Clim data provide interpolated global climate surfaces using latitude, longitude and elevation as independent variables and represents long term (1950-2000) monthly means of maximum, minimum, mean temperatures and total rainfall as generic 2.5 arc-min grids.

Model building

MaxEnt 3.3.3k software (www.cs.princeton.edu/~schapire) was used as it requires only presence records and its efficacy has been well recognized (Elith *et al.*, 2006; Phillips *et al.*, 2006; Phillips & Dudik, 2008; Peterson *et al.*,

2011). The follow settings were used during the run: 68 presence records used for training; 10053 points used to determine the Maxent distribution (background points and presence points); Environmental layers used (all continuous): bio1, bio10, bio11, bio12, bio13, bio14, bio15, bio16, bio17, bio18, bio19, bio2, bio3, bio4, bio5, bio6, bio7, bio8, and bio9; Regularization values: linear/quadratic/product: 0.141, categorical: 0.250, threshold: 1.320, hinge: 0.500; Feature types used: hinge linear quadratic; response curves: true; jackknife: true; output format: logistic; Grids\Bioclim_2.5 arc min and Random test points: 25. The outputs of ten replicates were combined to give a mean output. A logistic output for constructing the predictive models was selected as it is the easiest to comprehend, giving a value between 0 and 1 as the probability of occurrence of grass species (Phillips & Dudik, 2008). Jackknife analyses and mean area-under-curve (AUC) plots were created using MaxEnt. AUC is commonly used as a test of the overall performance of the model and it remains a handy indication of the usefulness of a model (Elith *et al.*, 2006, 2011). A value of 1.00 is an exact agreement with the model, while a value of 0.50 represents a random fit. Jackknife analysis indicates which variable has the greatest stimulus on the model and the overall success of the model. DIVA-GIS software version 7.5, freely downloadable software from www.diva-gis.org was used to generate the potential distribution map with input ASCII file obtained in MaxEnt analysis (maximum entropy method).

RESULTS AND DISCUSSION

Avocado is not native to India, but it is becoming increasingly popular in the country due to its health benefits and versatility in cooking. In recent years, avocado cultivation has been introduced in certain parts of India, such as the Nilgiris in Tamil Nadu and the Western Ghats in Karnataka. However, the production of avocados in India is still limited, and most of the avocados consumed in the country are imported from other countries, such as Peru, Chile, and New Zealand. Despite the limited production of avocados in India, they are gaining popularity among health-conscious consumers, and are often used in salads, sandwiches, smoothies, and dips. Additionally, some restaurants in major Indian cities have started to incorporate avocados into their menus.

Maximum Entropy (MaxEnt) is a niche modelling approach that has been developed linking species distribution information built only on identified presences and is a general-purpose method for making predictions or inferences from incomplete information. MaxEnt can take the environmental conditions at occurrence locations and produce a probability distribution that can then be used to

assess every other location for its likely occurrence/cultivation. The result is a map of the probability of conditions being favourable to grow avocado. It estimates target prospective cultivation sites of avocado around the world by finding the highest probability of distribution of the maximum entropy (*i.e.*, most spread out or closest to uniform with indication to a set of bioclimatic variables).

Figure 1&2 depicts the MaxEnt model for highest (0.7-1.0) and high (0.3-0.7) potential climate suitable sites for the cultivation of avocado based on the present climate scenario in India, respectively. Warmer colours (Red, Orange and Yellow) indicate the highest probability of climate suitable sites for avocado in India. The MaxEnt model indicated that parts of Kerala, Karnataka, Maharashtra, Tamil Nadu, Andhra Pradesh, Chhattisgarh, Madhya Pradesh, Goa, Odisha, Bihar, Jharkhand, Uttar Pradesh, Uttarakhand, Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Assam, Arunachal Pradesh, Gujarat, West Bengal, Sikkim, Meghalaya, Tripura, Manipur, Mizoram, Nagaland are highly suitable for cultivation of avocado varieties climatically. Interestingly, fewer parts of Rajasthan and Gujarat are also suitable for cultivation of avocado as inferred from the model. In addition to mainland states, Northern parts of Andaman and Nicobar Islands are also suitable for cultivation of avocado as drawn from ecological niche model generated. Highest probability value (Shannon index) ranging from 0.7 to 1.0 observed in all these states.

Figure 3 shows the omission rate and predicted area as a function of the cumulative threshold for current climatic scenario. 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.

Table 2 gives estimates of relative contributions of the environmental variables to the MaxEnt model for current climatic scenario. 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. The model is re-evaluated on the permuted data, and the resulting drop in training AUC is shown in the table,

normalized to percentages. The regularized training gain is 1.220, training AUC is 0.856, unregularized training gain is 1.584 for the current climate scenario of Avocado. As with the variable jackknife, variable contributions should be interpreted with caution when the predictor variables are correlated. Precipitation of driest month (Bio 14), Isothermality (Bio 3), Precipitation seasonality (Bio15) and Maximum temperature of warmest month (Bio 5) are the top four variables contributing maximum to MaxEnt model for current climate with 29.25%, 14.7%, 9.3% and 9.1 % respectively, (see Table 1).

Fig.4 shows the results of the jackknife test of variable importance. The environmental variable with highest gain when used in isolation is bio3, which therefore appears to have the most useful information by itself. The environmental variable that decreases the gain the most when it is omitted is bio15, which therefore appears to have the most information that isn't present in the other variables.

Maximum entropy (MaxEnt) is considered as the most accurate model performing extremely well in predicting occurrences in comparison to other common approaches (Elith *et al.*, 2006; Hijmans and Graham, 2006), especially with incomplete information. MaxEnt is a niche modelling method that has been developed involving species distribution information based only on known presences. MaxEnt is a niche modelling method and was selected to model potential current climate suitability for cultivation of avocados in the present study. MaxEnt has been successfully used by many researchers earlier to predict distributions such as dragon fruit (Srinivas Rao *et al.*, 2021); macrofungi (Wollan *et al.*, 2008); seaweeds (Verbruggen *et al.*, 2009); nematode (Holajjer *et al.*, 2022); sorghum (Sivaraj *et al.*, 2016); banana (Sivaraj *et al.*, 2022), forests (Carnaval and Moritz, 2008); rare plants (Williams *et al.*, 2009) and many other species (Elith *et al.*, 2006). Several articles describe its use in ecological modelling and explain the various parameters and measures involved (Philips *et al.*, 2004, 2006; Elith *et al.*, 2011). Reddy *et al.*, (2015 a, b) presents a novel approach to assess the potential areas for extending the cultivation of Roselle and Ceylon spinach, using MaxEnt with regional-level occurrence data. The identified regions in the present study could be targeted for selection of cultivation sites of avocado varieties based on climate suitability and for identifying on-farm conservation areas, and managing other related genetic resources activities.

Table 1. Presence points of Avocado from around the world.

Country	Region: Geographical coordinates
Argentina	Tucuman: 26.8083° S, 65.2176° W Mendoza: 32.8902° S, 68.8272° W

<i>Australia</i>	Perth: 31.9505° S, 115.8605° E Margaret River: 33.9550° S, 115.0735° E Carnarvon: 24.8829° S, 113.6576° E Coffs Harbour: 30.2963° S, 153.1150° E Tweed Heads: 28.1720° S, 153.5397° E Lismore: 28.8136° S, 153.2773° E Sunshine Coast: 26.6550° S, 153.0900° E Atherton Tablelands: 17.2580° S, 145.4699° E Bundaberg: 24.8708° S, 152.3514° E Mornington Peninsula: 38.3089° S, 145.0381° E Gippsland: 38.2806° S, 146.4179° E
<i>Brazil</i>	Sao Paulo: 23.5505° S, 46.6333° W Minas Gerais: 18.5122° S, 44.5550° W
<i>Chile</i>	Valparaiso: 33.0392° S, 71.6296° W Metropolitana de Santiago: 33.4489° S, 70.6693° W O'Higgins: 34.3778° S, 70.8450° W
<i>Colombia</i>	Antioquia: 6.6344° N, 75.1579° W Caldas: 5.2984° N, 75.2372° W
<i>Greece</i>	Crete: 35.2401° N, 24.8093° E
<i>India</i>	Tamil Nadu: 11.1271° N, 78.6569° E Kerala: 10.8505° N, 76.2711° E
<i>Israel</i>	Upper Galilee: 33.0464° N, 35.5329° E Sharon plain: 32.3078° N, 34.8814° E Haifa: 32.7940° N, 34.9896° E Tel Aviv: 32.0853° N, 34.7818° E Jerusalem: 31.7683° N, 35.2137° E
<i>Italy</i>	Sicily: 37.5994° N, 14.0154° E
<i>Kenya</i>	Murang'a County: 0.6608° S, 37.1744° E Meru County: 0.0477° N, 37.6451° E Kisii County: 0.6762° S, 34.7784° E
<i>Mexico</i>	Uruapan: 19.4062° N, 102.0667° W Tancitaro: 19.3153° N, 102.2273° W Ziracuaretiro: 19.5781° N, 101.9387° W Tepatlán de Morelos: 20.8107° N, 102.7645° W Ciudad Guzmán: 19.7046° N, 103.4586° W Compostela: 21.2367° N, 104.9079° W Xalisco: 21.5326° N, 104.8814° W Tlaquitenango: 18.6903° N, 99.1317° W Petatlán: 17.5209° N, 101.2672° W
<i>Morocco</i>	Souss-Massa Region: 30.5067° N, 9.6856° W Marrakesh-Safi Region: 31.6258° N, 8.0356° W
<i>Peru</i>	La Libertad: 8.3761° S, 78.0090° W Lima: 12.0464° S, 77.0428° W Junin: 11.0864° S, 75.2784° W
<i>Philippines</i>	Davao Region: 7.1907° N, 125.4553° E Calabarzon: 14.0524° N, 121.3180° E
<i>Portugal</i>	Algarve: 37.1028° N, 8.6748° W
<i>South Africa</i>	Limpopo: 23.4013° S, 30.4478° E Mpumalanga: 25.5653° S, 30.5279° E KwaZulu-Natal: 29.8587° S, 31.0218° E
<i>Spain</i>	Malaga Province: 36.7213° N, 4.4212° W Granada Province: 37.1773° N, 3.5986° W Malaga, Spain - 36.7213° N, 4.4216° W
<i>Sri Lanka</i>	Ratnapura District: 6.6931° N, 80.3993° E
<i>Tanzania</i>	Mbeya Region: 8.9095° S, 33.4719° E Arusha Region: 3.3811° S, 36.6822° E
<i>Uganda</i>	Wakiso District: 0.3610° N, 32.5428° E Kabale District: 1.2491° S, 30.0048° E

<i>USA</i>	San Diego County: 33.0381° N, 116.8728° W Ventura County: 34.3705° N, 119.1391° W Santa Barbara County: 34.4221° N, 119.7027° W Riverside County: 33.9533° N, 117.3962° W San Luis Obispo County: 35.3102° N, 120.4360° W Miami-Dade County: 25.5516° N, 80.6327° W Collier County: 26.0409° N, 81.5596° W Maui County: 20.8034° N, 156.3114° W
<i>Zimbabwe</i>	Mashonaland West Province: 17.4691° S, 30.7128° E Manicaland Province: 19.5782° S, 32.0647° E

Table 2. Estimates of relative contributions of the environmental variables to the Maxent model for Avocado.

Variable	Percent contribution	Permutation importance
Precipitation of driest month (Bio 14)	29.2	0
Isothermality (Bio 3)	14.7	19.3
Precipitation seasonality (Bio 15)	9.3	20.7
Max temperature of warmest month (Bio 5)	9.1	0
Precipitation of wettest month (Bio 13)	5.7	8
Precipitation of coldest quarter (Bio 19)	5.4	0
Precipitation of warmest quarter (Bio 18)	4.4	0
Mean temperature of warmest quarter (Bio 10)	3.3	0
Temperature annual range (Bio 7)	2.7	12.5
Mean temperature of coldest quarter (Bio 11)	2.7	5.3
Precipitation of driest quarter (Bio 17)	2.1	0.3
Mean diurnal range (Bio 2)	1.8	3.1
Annual precipitation (Bio 12)	1.7	8.1
Min temperature of coldest month (Bio 6)	1.7	5.3
Mean Temperature of westtest quarter (Bio 8)	1.6	0.6
Precipitation of wettest quarter (Bio 16)	1.5	2.2
Mean temperature of driest quarter (Bio 9)	1.3	7.6
Annual mean temperature (Bio 1)	1.2	6.9
Temperature seasonality (Bio 4)	0.7	0

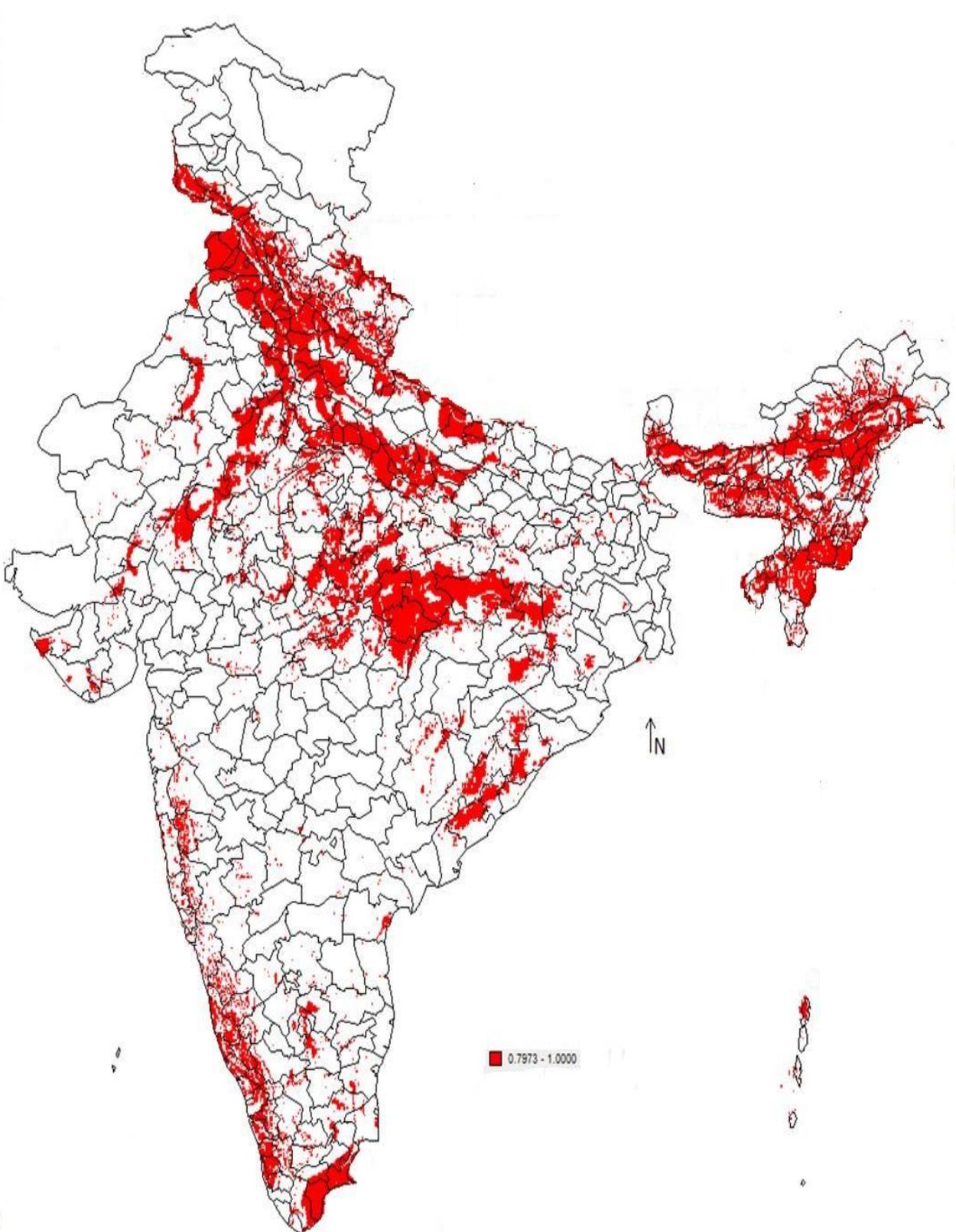


Fig. 1. Ecological niche model depicting highest probable and potential Avocado growing regions in India (0.79-1.0 Probability index)

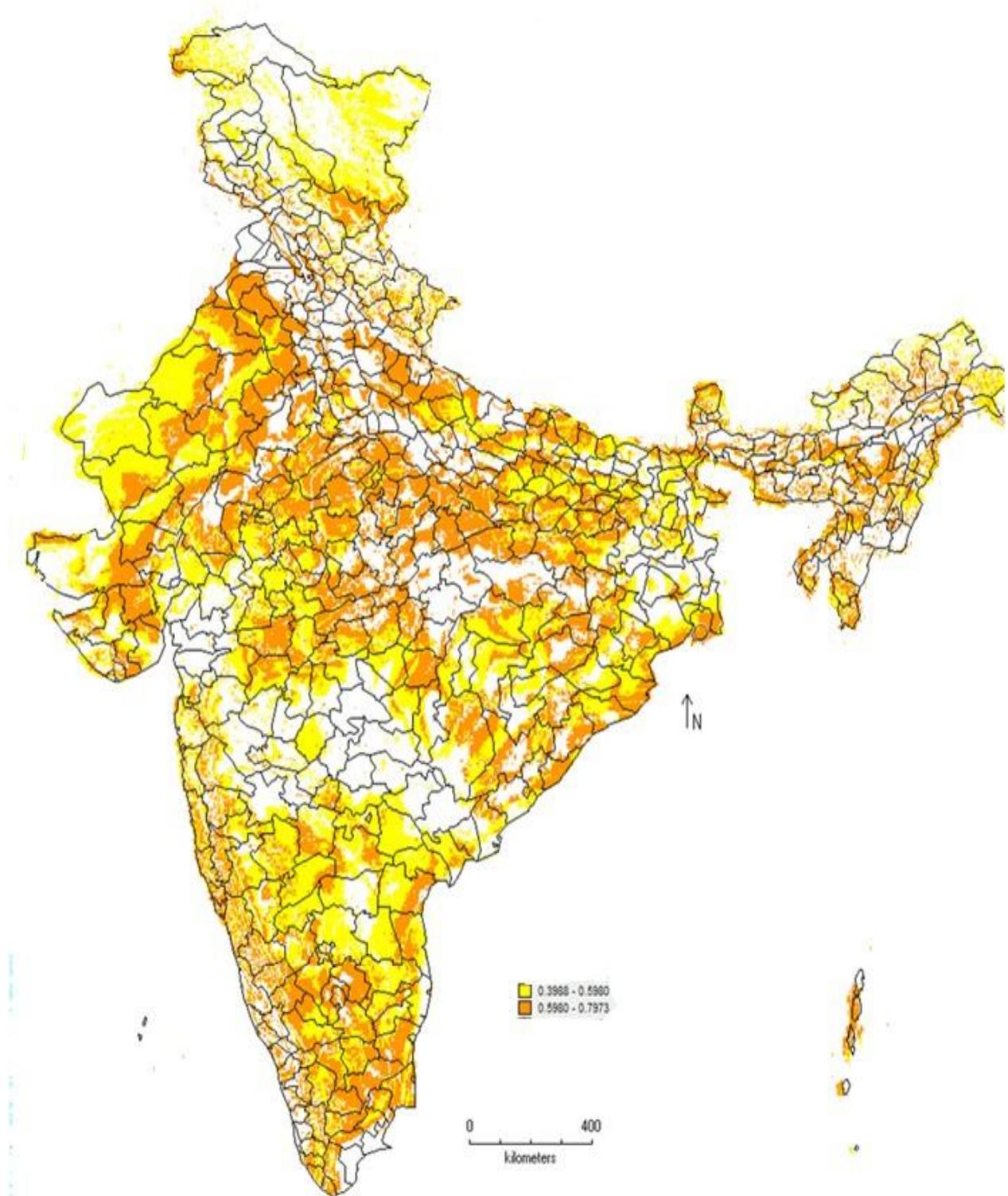


Fig. 2. Ecological niche model depicting high probable and potential Avocado growing regions in India (0.39-0.79 probability index)

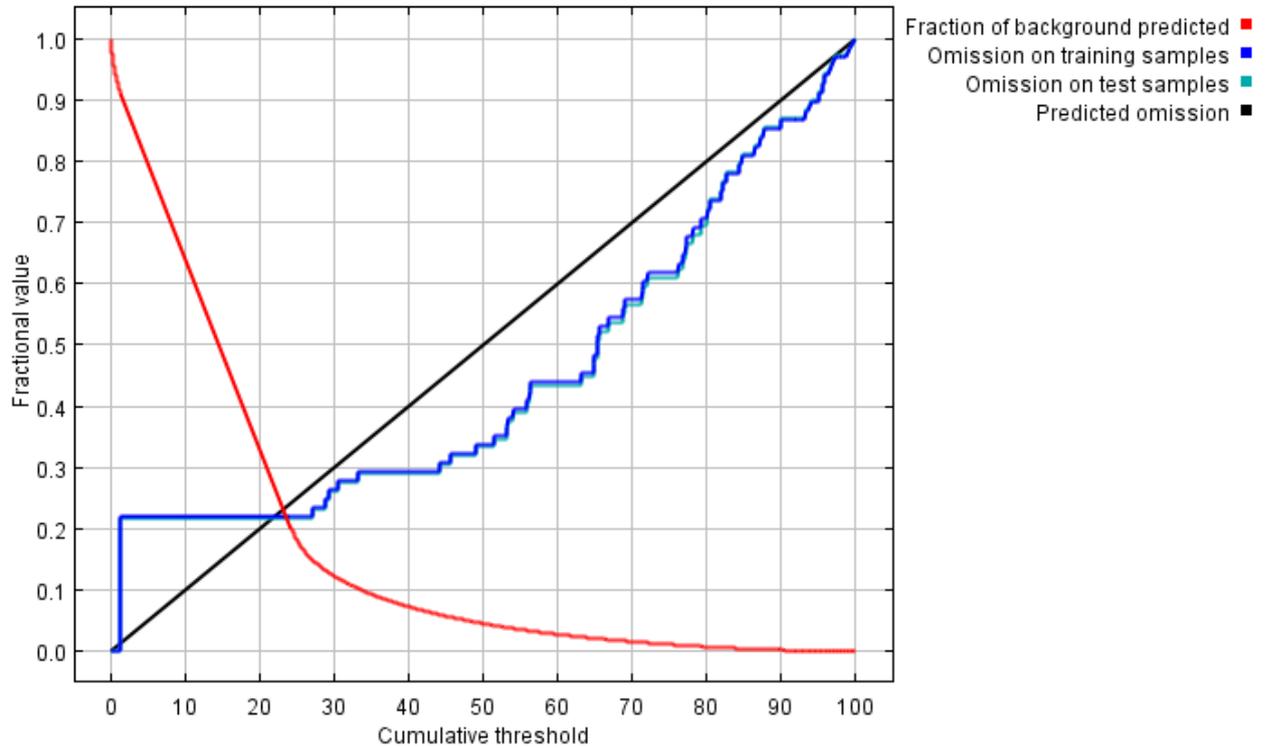


Fig. 3. Omission and predicted area for Avocado

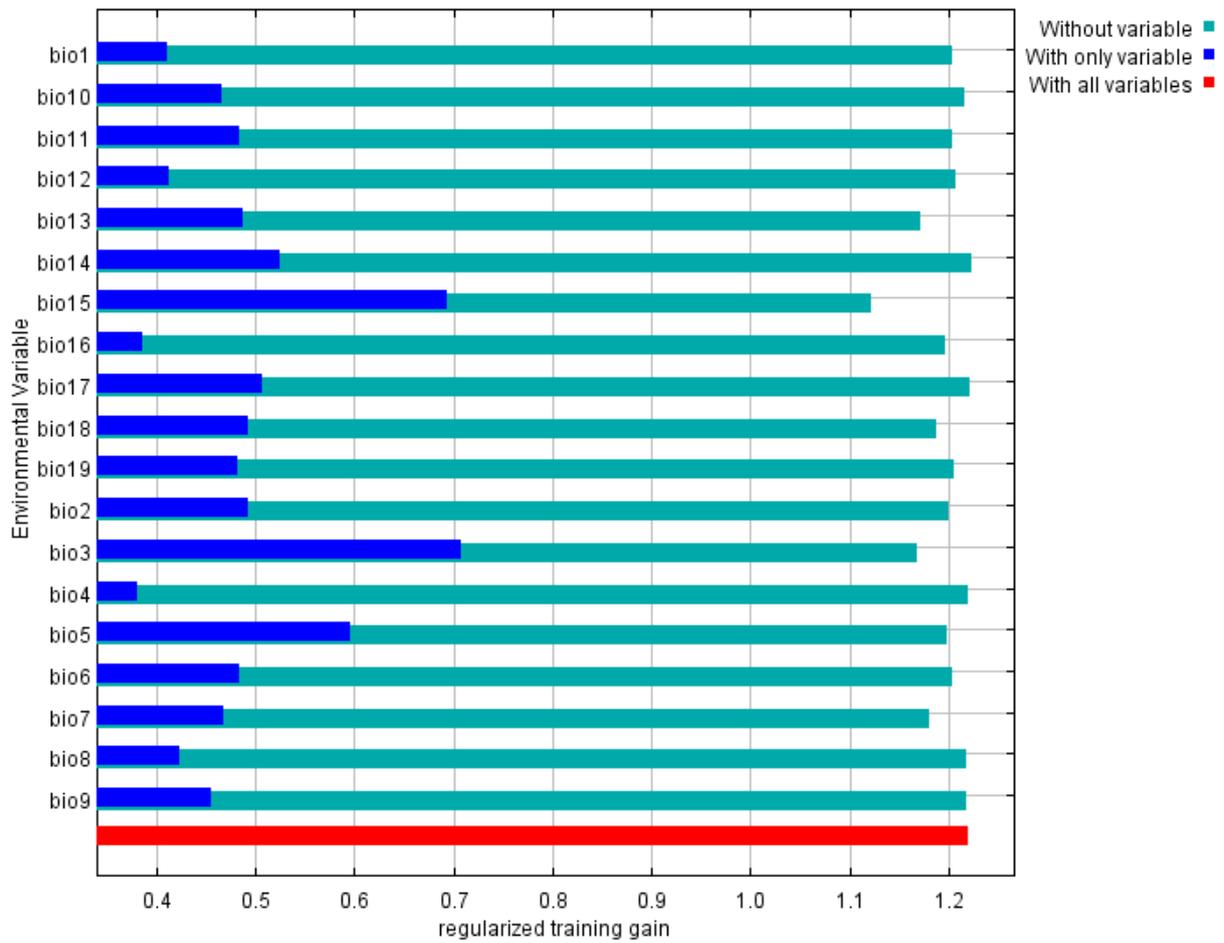


Fig. 4. Jackknife of regularized training gain for Avocado

ACKNOWLEDGEMENT

The authors are thankful to the Director, ICAR-NBPGR, New Delhi and to the Head, Division of Plant Quarantine, ICAR-NBPGR, New Delhi for support in carrying out the work.

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