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RESEARCH ARTICLE

Identifying the potential global distribution and conservation areas for *Terminalia chebula*, an important medicinal tree species under changing climate scenario

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Abstract

Terminalia chebula Retz. (Combretaceae), commonly-known as chebulic myrobalan is one of the important Non-Timber Forest Product (NTFP) species which is harvested for its fruits and galls. The species known as the "King of medicines" is used widely in Ayurveda, Sidda, Unani, and traditional Chinese medicines for curing a wide variety of diseases in Asia and Africa. *Terminalia chebula* is an important ingredient of Triphala (Ayurvedic medicine) along with *Terminalia bellirica* and *Phyllanthus emblica*. The fruits of the tree also yields a dye which is used as an organic dye in the textile industries. In recent years, there is an increasing demand for herbal remedies and organic dyes, resulting in extensive extraction of fruits and galls from *T. chebula*. In this study, the major objective was to identify sites for the conservation of *T. chebula* and to identify important environmental variables determining its distribution. Based on the existing species distribution records (primary and secondary), along with a suite of climatic variables, the present and future distribution of the species were predicted. The study identified ecological niches that are suitable for the cultivation of the species; the species occurs in India, Pakistan, Sri Lanka, Cambodia, Myanmar, Vietnam, China, Laos, Thailand, Bhutan, Taiwan, Nepal and Bangladesh under the current climatic scenario. Within India, our results suggest that the central and south India are highly suitable in the current scenario. The mean annual temperature, temperature seasonality and isothermality seem to be the most important variables determining the distribution of the species which is directly influenced by climate change. Overall, the study indicated that under the future climate change scenarios the distribution of *T. chebula* is likely to decrease. The results indicate that *T. chebula* is highly vulnerable to climate change. Considering the economic importance of the species, it is important to understand how the species distribution will alter in the wake of climate change to develop effective conservation strategies. The study also provides important environment variables that determine the species distribution which could aid in identifying areas where the species could be cultivated.

Keywords Conservation · Conservation sites · Ecological niche models · Maximum entropy

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Introduction

Climate change is one of the major factors influencing the distribution of plant species. The Intergovernmental Panel on Climate Change (IPCC) in its fifth annual report (2014) has indicated that the mean annual temperature of the earth's surface increased by 0.85 °C over the past 130 years (1880–2012). However, the mean temperature increased by 0.72 °C between the years (1951–2012) and the mean global surface temperature is predicted to increase by an additional 0.3–4.8 °C by the end of the twenty-first century (IPCC 2013). Climate change has resulted in an increased temperature and irregular rainfall patterns, both droughts, and floods, which has led to uncontrolled insect infestations

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and dominance of invasive species, increased fire vulnerability, and severely impacting biodiversity, as well as the livelihood of the people (Ravindranath et al. 2006; Mukhopadhyay 2009, Shresta 2019). With an average rise in temperatures of about 2–3 °C globally, there is an increased risk of upto 20–30 percent of species extinction (Warren et al., 2010; Stocker et al. 2014). Several studies have shown that climate change can cause significant change to ecological processes including change in the distributional range of species (Priti et al. 2016; Subba et al., 2018; Rana et al. 2021) as well as impacting the phenology of tree species (Piao et al. 2019). Assessing and predicting the potential change in the distributional range of species is crucial for developing optimum conservation and management plans.

In recent years, ecological niche modelling (ENM, also known as species distributional modelling, SDM) have been widely used to infer the environmental variables required for the survival of a species. The ENMs use biophysical methods and environmental variables taken from the known distribution areas of the species to predict their ecological niche as well as their potential future distribution (Elith et al. 2009; Shivaprakash et al. 2013). The ENM is widely used for assessing the distribution of species (Sen et al. 2016a; Kumar et al. 2020), for assigning conservation areas (Joshi et al. 2017; Sumangala et al. 2017), for predicting invasion risk (Sen et al. 2016b) and in assessing impacts of climate change on species distributions (Priti et al. 2016; Subba et al., 2018; Rana et al. 2021).

Terminalia chebula Retz. (Combretaceae) is an important plant used in traditional medicine not only in India and China but also in South Asia and in Africa. The plant is widely used for curing multiple ailments such as digestive disorders, urinary diseases, diabetes, skin diseases, heart diseases, irregular fevers, constipation, ulcers, vomiting, colic pain, and haemorrhoids (Muhammad et al. 2012; Nigam et al. 2020). The plant is considered as the "King of medicine" due to the presence of a large number of phytochemicals that are used for treating a variety of disorders (Gupta 2012). The plant is extensively used in Indian traditional medicine such as Ayurvedic, Sidda, Unani. *Terminalia chebula* is an important ingredient of Ayurvedic medicine "Triphala" for curing many diseases. The fruits of *T. chebula* have been used as a household remedy since time immemorial (Bag et al., 2013). This species has a profound impact on human health in the Asian tropics. In Southeast Asia, *T. chebula* fruits are widely used in traditional medicine, dyeing, and are also traded (Nigam et al. 2020). The dried galls of *T. chebula* are considered to have anti-aging properties, are astringent, purgative, and boost immunity and are widely used in Thai Lanna, Tibetan, and Chinese medicine. They are sold at markets across Southeast Asia (Manosroi et al. 2010). *Terminalia chebula* occurs in mixed deciduous forests and irregularly in teak forests in Malaysia (Chattopadhyay and Bhattacharyya 2007). In Myanmar, *T. chebula* sparsely occurs in degraded and timber harvested forests (Oo and Lee 2007). In Sri Lanka, *T. chebula* occurs in mixed deciduous forests and scrubs (APFSOS II). Besides deciduous forests in Cambodia, Laos, Southern Laos and northeastern Thailand, *T. chebula* is grown in between paddy fields (Natuhara et al. 2012). In South-eastern China, *T. chebula* is present in open deciduous and bamboo forests, along forest margins, and cultivated near villages. It is distributed across India from Arunachal Pradesh to Punjab and from Tamil Nadu to Jammu & Kashmir. With the increasing demand for herbal remedies and organic dyes, there is extensive extraction of fruits and galls from the *T. chebula* from the various forests across India.

In this study using distribution data, we have mapped the geographical distribution of the species, predicted the possible sites of occurrence of *T. chebula* in India using Ecological Niche Modelling (ENM). The major objective of the study was to identify sites for the conservation of this economically important medicinal tree species. We also intended to identify the environmental factors that are critical for the distribution of the species both in the present as well as in future climate change scenarios. Based on these, we intend to determine ecological niches that are suitable for the cultivation of the species both in India as well as in other South Asian countries.

Materials and methods

Species occurrence records

Global occurrence data for *T. chebula* were collected by primary and secondary sources (See Table 1). Primary data sources were collected by field survey's using GPS, where the actual location of the species was recorded. Totally 49 primary data points were collected from the field. The secondary data were collected from multiple resources which include free and open access viz., 167 points from Global biodiversity information system (GBIF), 386 points from the India Bioresource Information network (www.ibin.gov.in), 50 points from the Indian Biodiversity Portal. Further, the distribution records were also obtained from floras (273 points), from the Herbarium records collected from Central National Herbarium (CAL, 91 points), Botanical Survey of India (BSI), Calcutta, Northern Regional Centre, Dehradun (NRC, 10 points), Western Regional Centre, Pune (WRC, 15 points) and Southern Regional Centre, Coimbatore (SRC, 51 points). In all, up to 1092 records were collected.

The secondary resources often tend to have spatial sampling biases (Aiello-Lammens et al. 2015; Sumangala et al. 2017; Ahmad et al. 2019; Hamid et al. 2019). Addressing the effects of sampling bias remains an important issue. For

Table 1 Distribution of *Terminalia chebula* in other Southeast Asian countries

Sl	Countries	Distribution	References
1	Bangladesh	Rare in Moulvibazar, Chittagong and Mymensingh districts of Bangladesh	Kabir et al. (2014); Akbar (2020)
2	Bhutan	Goshing, Ngangla and Phangkhar Gewogs of Kheng region in Bhutan. Deciduous forests	Purna and Tenzi (2012); Phurpa et al (2017)
3	Cambodia	Virachey National Park, Veun Sai-Siem Pang National Park, Siem, Pang Khang Lech Wildlife Sanctuary in Cambodia Deciduous forests and cultivated	Philip (1999); Loveridge et al. (2017)
4	China	Native in West Yunnan, cultivated in Fujian, Guangdong, Guangxi	Flora of China
5	Indonesia	Riau Province, Sumatra, Indonesia Cultivated	Catalogue of Life; Mahyar et al. (1991)
6	Laos	Nakai-Nam Theun National Park, Laos.Dry deciduous forests and degraded savannas in northern Thailand and Laos	Philip (1999)
7	Malaysia	Sarawak	Rathinamoorthy and Thilagavathi (2014); Nicholson 1965
8	Myanmar	Bago, Kachin, Mandalay and Yangon of Myanmar Deciduous forests	Rathinamoorthy and Thilagavathi (2014)
9	Nepal	Rasuwa and Jhapa District, Nepal. Deciduous forests	Annotated checklist of Flowering Plants of Nepal; Saru et al 2020; Yadav et al 2010; Raut et al 2018
10	Pakistan	North West Frontier Province, Pakistan and also cultivated	Arshad et al. (2010); Flora of Pakistan
11	Sri Lanka	Gal Oya National Park of Badulla and Wilpattu National Park of Anuradhapura and Puttalam districts Dry and open forests. Occur Naturally in Intermediate zones and cultivated in agro-climatic zones	Forest Department Government of Sri Lanka (2009); Sanjeewa et al 2013; Green (1990); Wilpattu National Park
12	Taiwan	Nantou Tsien, Chushan Town and Kaoshiung Hsien of Taiwan, also cultivated	Taiwan Plant names; Database of Native Plants of Taiwan
13	Thailand	Chae-Son district, Lampang, Thailand Dry deciduous forests and degraded savannas	Philip (1999); Wilart (2020)
14	Vietnam	Buon Ma Thuot, Dak Lak Province, Vietnam Dry deciduous forests and degraded savannas	Philip (1999); Nguyen (2016) Tropicos.org

many datasets of occurrence records (especially from museums and herbaria), geographic sampling bias is pervasive (Hijmans et al. 2000; Reddy and Dávalos 2003; Graham et al. 2004; Kadmon et al. 2004; Hijmans 2012). Ideally, spatial thinning of occurrence records is inevitable to substantially reduce the effects of sampling bias whilst simultaneously retaining the greatest amount of useful information. The spatial thinning can be done manually; however, this is prohibitively time consuming for large datasets. Therefore, we used the randomization approach, i.e., the 'thin' function in the spThin R package to obtain an occurrence dataset with the maximum number of records for thinning distance of 10 km. The output of this exercise was used to develop a robust species distribution model for the target species.

Climatic variables

Species Distribution Modelling (SDM) require a suite of the climatic representative dataset that influence distribution of species. Hence, ecologically meaningful variables i.e., bioclimatic variables i.e., Bioclim1—19 V1.4 (Hijmans et al. 2005) were downloaded from WorldClim (Table 1, https://www.worldbioclim.org) and were used for modelling the distribution of the species. Bioclimatic data used for modelling had a spatial resolution of 1 km^2 (30 arc seconds). The environmental variables often have a high correlation. Hence, we tested for collinearity by examining pairwise correlations between the variables. Among the pair of variables, those variables having Pearson's correlation coefficient $r > 0.7$ were excluded from the analysis (Dormann et al. 2013; Sarma et al., 2018). The final set of variables used for modelling *T. chebula* are Bio1, Bio2, Bio3, Bio4, Bio12, Bio14, Bio15, Bio18 and Bio19 (Appendix S1).

Species distribution modelling

We used the maximum entropy implemented in Maxent which simulates the potential geographical distribution of a species using its current distribution as well as by employing various environmental data (Phillips et al. 2006, 2017). Maxent is the most favoured model as it is simple and quick to run, provides stable operation results, and allows prediction results to be tested (Ortega-Huerta et al. 2008). Maxent, requires the presence only data and background data for modelling the ecological niches. The performance of the model is robust and relatively better than other modelling algorithms (Elith et al. 2006; Rahimian et al. 2019; Ghareghan et al. 2020) and is hardly influenced by small sample sizes (Pearson et al. 2007). We used maxent and ran the model for Current, and different Representative Concentration Pathway (RCP) such as RCP 2.6, RCP 4.5, RCP 6.0 & RCP 8.5 for 2070. The year 2070 was taken for the analysis as the annual temperature increase in 2070 has been predicted to be over 7.5 °C across most of Asia (Xu et al. 2020). The various RCP's used in the study describe different plausible climate futures, all of which are likely possible depending on the extent of greenhouse gas emissions. IPCC has adopted these four different climate change scenarios under the various Representative Concentration Pathways (RCPs).

Model development and selection

Ranges of models were developed for mapping the climatic niche of *T. chebula.* Further, to assess the model complexity, we additionally fit the MaxEnt models using the existing default settings, which enabled the implementation of more complex feature classes such as (L-linear, Q-quadratic, H-Hinge) depending on the occurrence records. We used LQH (=linear, quadratic, hinge), LQ (=linear, quadratic), LQH, LQ and H (=hinge) and regularization multipliers 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. We used randomly generated 10,000 points and default settings to calibrate the models. The outputs i.e., predictions and lambdas file were downloaded (Radosavljevic and Anderson 2014) and used for model selection in ENM Tools. Maxent also produces continuously varying, non-negative suitability scores for each cell in a specified geographic region. The ENM Tools uses this suitability scores and occurrence points and estimates the likelihood of observing the occurrence records under a selected model. Once observed, a suite of parameters captured in lambdas file counting any parameter with weightage having non-zero will be estimated and produces an output with criterion-based model selection using Akaike Information Criterion (AIC), Akaike Information Criterion corrected for small sample sizes (AICc) and Bayesian information Criteria (BIC) (Warren et al. 2010). The AIC, AiCc and BIC are quality metrics that are generally used to ensure the accuracy of the modelling outcome. These metrics help at selecting the "best model" which is a key step in ensuring the modelling outcome. To accomplish this we used a script with a relative path to the files (predictions and lambdas). Previous studies indicate that AICc outperforms BIC in selecting models on simulated data and hence we selected the models having low AIC value (Warren et al. 2010). The model selected for final distribution modelling features LQHP with Regularization Multiplier 1.5 (Appendix S2). The final model was calibrated using the following settings: number of iterations were set to 5000, and 10,000 random background points, replicated type as "sub-sample", 10 replicates, output type as 'cloglog' and other features were default. We used 70 percent of the occurrence points for model calibration and 30 percent for model testing with independent validation as per Bohl et al. (2019). The variable importance was measured using the Jack-knife test to determine the dominant climatic factors (Raman et al. 2020), and all other default settings based on Elith et al. (2010).

Model evaluation

The model was evaluated by Area under Receiver Operating Curve (ROC) popularly known as AUC (Swets 1988). The AUC values vary from 0 to 1 where the value <0.5 signifies that the model is worse than random, 0.5–0.7 signifies poor performance, 0.7–0.9 signifies moderate performance and >0.9 signifies high performance (Kumar et al., 2020). The final model obtained showed high performance value indicating that the performance was good. The final predicted Model of habitat suitability were divided into four levels: unsuitable regions (0.00–0.25), poorly suitable regions (0.25–0.50), moderately suitable regions (0.50–0.75), and highly suitable regions (>0.75).

Results

A total of 1092 was obtained from various sources. After spatial thinning, a total of 1002 occurrence records were retained which showed uniform distribution across the sampling landscape. The distribution of the species using both primary and secondary data within India shows that the species is widely distributed with higher densities in the Western and Eastern Ghats (Fig. 1). These points were used in building a model for current and future distribution (Fig. 2). After correlation analyses and jack-knife tests (Fig. 3), nine environmental variables were used to construct the models. The variables that contributed significantly to a model for the current distribution for Asia are Bio1 (Annual Mean Temperature) having a contribution of 35.1%, Bio4 (Temperature Seasonality) with 24.6% and Bio3 (Isothermality) with 10.9% contribution (Table 2). The result of the jackknife test of variable importance shows that the environmental variable with the highest gain, when used in isolation, is Bio4 (Temperature seasonality), which appears to have the most useful information by itself.

Model evaluations and current distributions

The predicted distribution model had mean AUC of 0.884 ± 0.006, which indicate that the performance of the model was good (Fig. 4). As per the predictions, *T. chebula* occurs in India, Pakistan, Sri Lanka, Cambodia, Myanmar, Vietnam, China, Laos, Thailand, Bhutan, Taiwan, Nepal

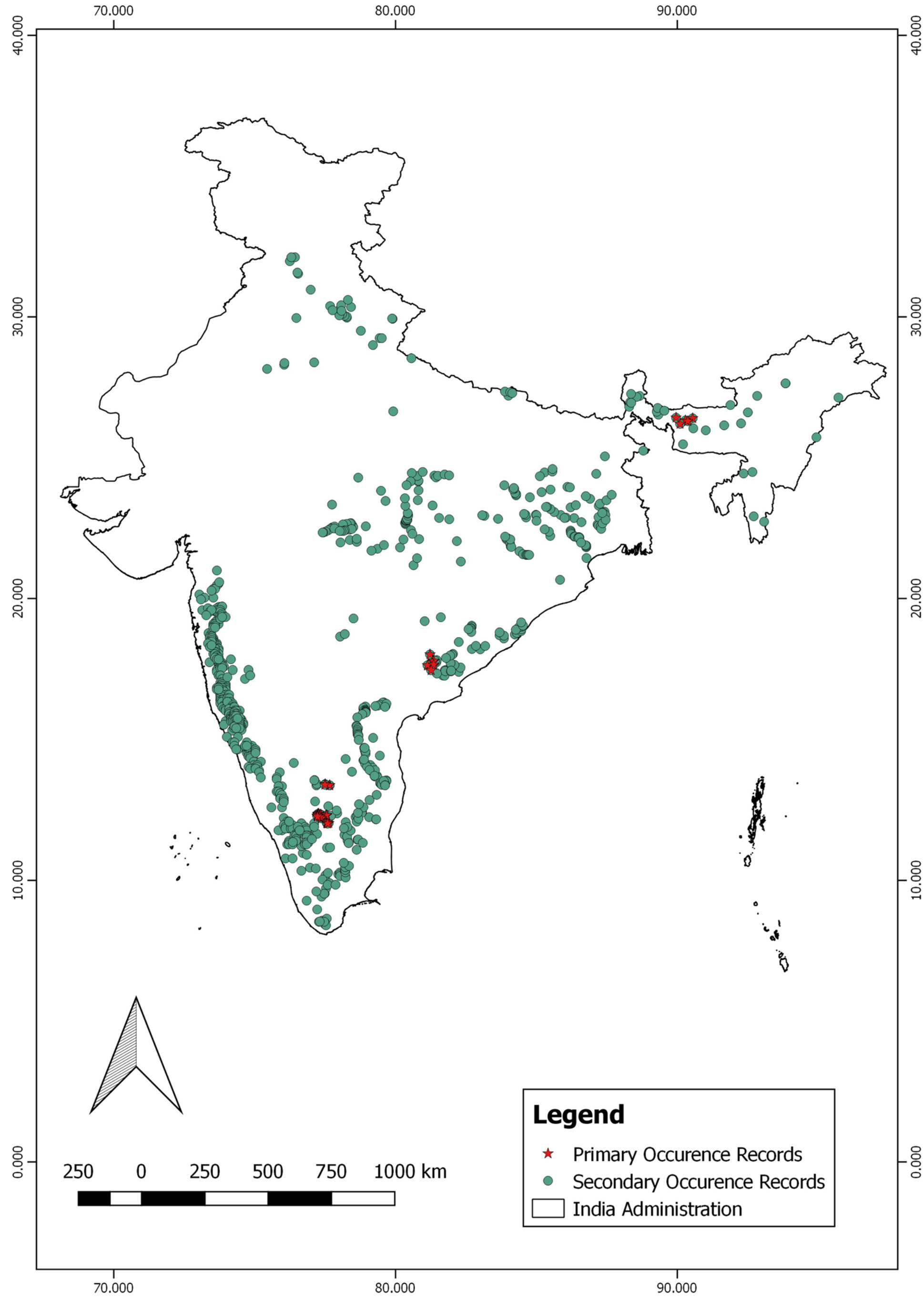

Fig. 1 Distribution of *Terminalia chebula* in India

and Bangladesh under the current climatic scenario. Under the current climatic scenario, the MaxEnt predicted India, Bangladesh, Sri Lanka, Bhutan, Myanmar (Burma), Laos, Thailand, Cambodia, Vietnam and Pakistan as favourable for the sustenance of the *T. chebula.* In India, the Deccan plateau, central India, Western Ghats, are extremely favourable whilst the North, and Eastern parts are highly favourable. The other parts of the country are moderately favourable for the species. The model predicts, Bhutan with moderate to highly favourable climatic conditions. The Bangladesh, Myanmar, Thailand, Cambodia, Vietnam, Laos, is largely moderately favourable and intermittent with highly favourable conditions. The South Pakistan shows mixture of moderate and high favourable zones. The northern part of the Sri Lanka showed intermittent high, medium and excellent habitats.

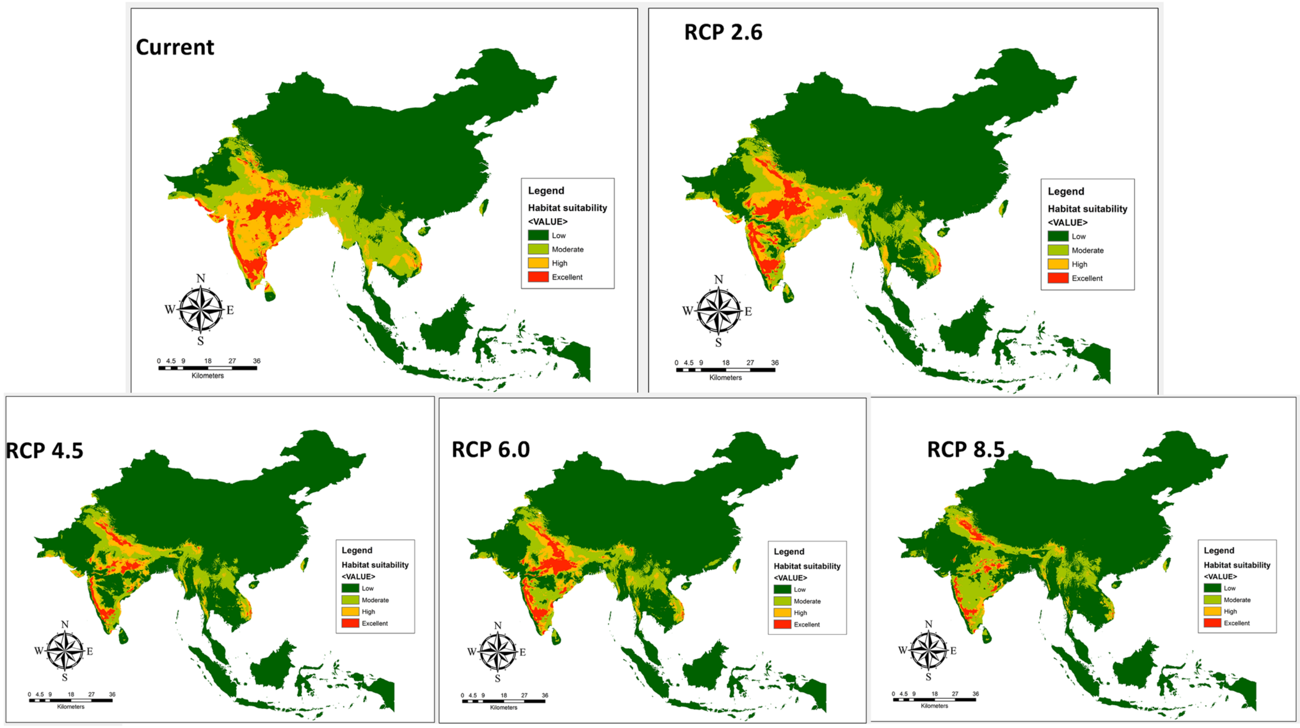

Fig. 2 Distribution of *Terminalia chebula* under different projected climate change scenarios

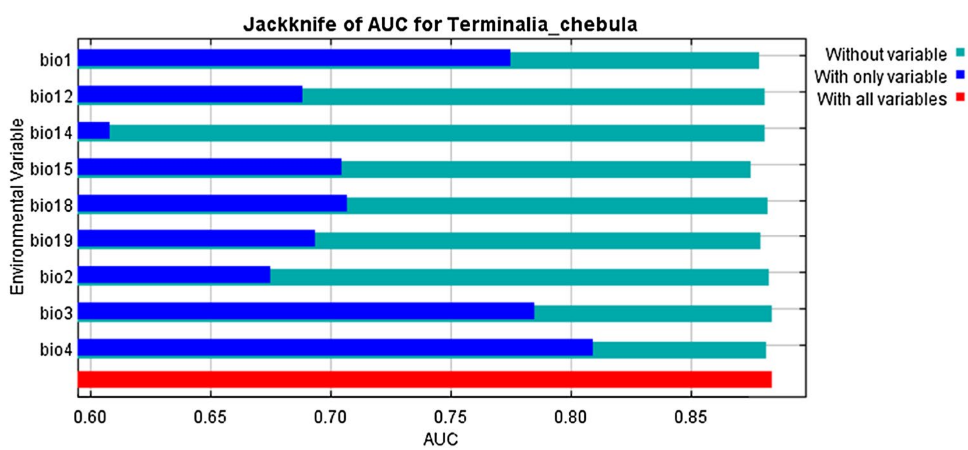

Fig. 3 Results of Jackknife test, using AUC on test data

Future projections

The distribution of *T. chebula,* across future projections, showed significant decline under all RCPs (Fig. 5, Table 3). The RCP 2.6—2070, RCP 4.5—2070, RCP 6.0—2070 and RCP 8.5—2070 projections reveal a significant decline in the suitable habitats in India, Pakistan, Sri Lanka, Cambodia, Myanmar, Vietnam, China, Laos, Thailand, Bhutan, Taiwan, Nepal and Bangladesh. The MaxEnt model for RCP 2.6—2070 shows significant loss in the climatically suitable habitats in the central and western parts of the India. The Bangladesh, Bhutan, Laos, Sri Lanka, Thailand, Cambodia and Vietnam face significant decline i.e., moderate to low habitats. Under the RCP 4.5—2070, the Deccan plateau and Central Parts of the India shows significant loss of the habitat when compared to current climatic scenario and the RCP 2.6. The Bangladesh, Bhutan, Sri Lanka, Myanmar, Thailand, Laos, Cambodia and Vietnam face further significant loss when compared to Current and RCP 2.6—2070 scenarios. The climatically suitable habitat under RCP 6.0—2070 in the Deccan plateau, central parts of India and Sri Lanka experiences significant loss when compared to current scenario and RCP 2.6—2070 however, these regions experience

Table 2 Contribution of environmental variables

Variable	Description	Percent contribution
bio1	Annual mean temperature	35.1
bio4	Temperature seasonality	24.6
bio3	Isothermality	10.9
bio15	Precipitation seasonality	8.8
bio18	Precipitation of warmest quarter	5.8
bio12	Annual precipitation	5.4
bio19	Precipitation of coldest quarter	4
bio2	Mean diurnal range	3.7
bio14	Precipitation of driest month	1.8

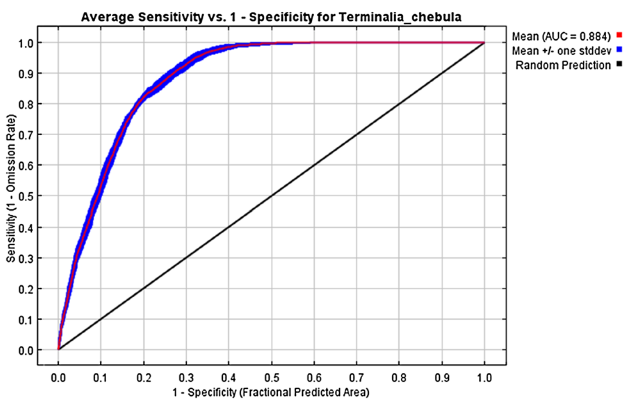

Fig. 4 Receiver operating characteristic (ROC) curve for the same data, again averaged over the replicate runs

increase in the moderately suitable habitat when compared to RCP 4.5—2070.

The other countries Vietnam, Sri Lanka, Bhutan, Bangladesh, Pakistan, Laos, and Cambodia too face significant loss in the moderate, highly suitable and excellent habitats when compare to Current, RCP 2.6, RCP 4.5 and RCP 6.0. In general, the studied species *T. chebula* is highly vulnerable to climate change in all the projected climate change scenarios.

Discussion

A number of factors such as climate change, habitat disturbance, overharvesting, invasive species and pollution are viewed as major threat to global biodiversity in general and the medicinal plant species in particular (Hirch 2010). Climate change results in increased temperatures, disrupting precipitation patterns and in increasing extreme climate events. These factors are known to affect growth and reproduction, alter phenological patterns of trees as well as influence the distribution of species at a regional scale (Priti et al. 2016). The current measures used for the conservation of medicinal plant species such as the establishment of medicinal plant conservation areas (MPCA's) within the protected areas network are based on the current distribution of species. But these areas would face increasing challenges as the effects of climate change increase (Sen et al. 2016a; Joshi et al. 2017). In the light of climate change altering species distributions and impacting native plant populations, using niche modelling approach to map the potential distribution of species can aid in the development of effective restoration and conservation management plans (Adhikari et al. 2018).

The *T. chebula* has become endangered locally in several regions of India (Jagdish 2014) and the status of this tree remains largely unknown. We used Maxent and optimized factors known to influence the prediction results of the model. The performance of the ENM is significantly influenced by the number of records as well as the variables selected. It is suggested that at least 100 point records should be used in the Maxent model to ensure optimum results (Saatchi et al. 2011). The outcome of the model is also influenced by the input variables and the accuracy of the datapoints. In this study, we used a large data set (up to 1002

Fig. 5 Area change analysis using MaxEnt in Asia

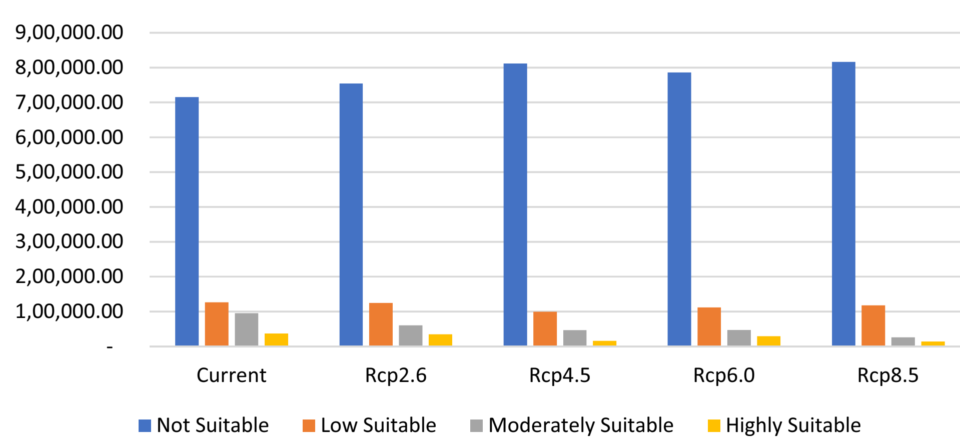

Table 3 Change in the area range under different climatic scenario (in Square kilometre)

Range	Description	Current	RCP2.6	RCP4.5	RCP6.0	RCP8.5
0.0–0.25	Not Suitable	7,15,207.00	7,54,495.00	8,11,714.00	7,85,952.00	8,16,547.00
0.25–0.5	Low Suitable	1,26,171.00	1,24,440.00	99,399.00	1,11,487.00	1,17,325.00
0.5–0.75	Moderately Suitable	95,253.00	60,164.00	46,600.00	47,117.00	25,835.00
0.75–1.0	Highly Suitable	36,856.00	34,388.00	15,774.00	28,931.00	13,780.00

records after filtering) to reduce any errors and also ensured that the data points reflect the actual distribution of the species. We used the nine bioclimatic variables that contributed significantly for modelling and mapping. Among the nine variables, the Annual Mean Temperature, Isothermality and Temperature Seasonality are the three variables that largely determine the distribution of *T. chebula.*

Our data adequately covered the entire distributional range of the species across India, China, Pakistan, Sri Lanka, Nepal and other south Asian countries. The predictive accuracy of the distributional models are estimated using the AUC (Lobo et al. 2008). The high AUC values in the present study for training and testing (0.884) indicate that the niche model has a good ability to differentiate between presence and absence areas for the species. AUC value (> 0.8) exhibits that the model performance has been satisfactory and that the prediction of the species distribution has been accomplished with higher discrimination of the input data (Lobo et al. 2008). The Receiver Operating Characteristic (ROC) curve summarizes the model performance over all conditions. The niche model successfully predicted the distribution of the species in the Indian sub-continent. The species has its core distribution in Southern and Central India, where the model predicts very high suitability. These areas could be ear-marked for conservation of the species and population of the species in this region could be enriched.

The overall distribution of *T. chebula* under different RCP scenarios shows a drastic decline indicating that it is highly vulnerable to climate change. The mean annual temperature, temperature seasonality and isothermality seem to be the most important variables determining the distribution of the species which is directly influenced by climate change. Lower degree of prediction in the future (Fig. 5, Table 3) also hints at the possibility of a niche shift for the species in future, which needs to be studied further. The study also found that there is a significant loss of suitable habitat in all the countries in which *T. chebula* is distributed.

The impacts of climate change depends on species vulnerability to change, which is expected to be far greater in the tropics (Deutsch et al. 2008). Tropical regions with less than 1 °C of warming, are projected to experience extreme conditions much earlier than rest of the world (Beaumont et al. 2011). Climate change is known to impact phenology including leafing, flowering, and fruiting in seasonally dry tropical areas; however the magnitude and direction of phenological changes are likely to vary among species (Sheldon 2019). Thus, though the study shows that the suitable areas of *T. chebula* would vastly decrease in the dry tropical areas; the impact of climate change on the phenology of the species cannot be predicted. Most species in the tropics show variable capacity to adjust physiologically to temperature changes. Shifts in phenology could lead to tropic mismatches between pollinators and dispersal agents and could have cascading effect on the species (Sheldon 2019).

Terminalia chebula is one of the tropical forest species in high trade that has been listed as a priority species that needs management intervention (Goraya and Ved 2017). Considering that the suitable area for this species would vastly decrease, various countries in which this tree is distributed should further strengthen the governance to provide adequate protection to *T. chebula*. Within India, both the RCP 4.5 as well as RCP 8.5 predict decrease in the overall distribution especially in Southern India (Fig. 2). However, in the northern regions, more areas are likely to become suitable areas especially in the state of Uttar Pradesh. In most of Asia, it is predicted that climate change would have drastic impact with temperatures set to increase by 7.5 °C (Xu et al. 2020). This increase in temperatures especially in Central India could lead to shift in suitable habitats towards northern and more cooler latitudes. The results predicted here need to be assessed in the background that a number of other variables have not been taken into account. For example, we have not considered the possible change in the land-use categories. Any regions that are predicted to be highly suitable here may not be actually available for the species if the land is utilised for other purposes. However, our study has identified areas both with India as well as across South Asia, regions that are likely to become highly suitable or excellent habitats in the future. These regions could be overlaid with other layers of information such as threat status, vegetation type and levels of protection. Based on that, suitable areas can be considered for the conservation of the species.

The study also provides geographical perspective of the distribution of species across wide landscapes and habitats both in the present as well as under different scenarios in future. Based on this information, decision could be taken for conservation of the species as well as for collection of germplasm of the species. Considering the economic and medicinal potential of the species, it is inevitable that large-scale cultivation of the species need to be taken up and establishing the arboreta with diverse germplasm gains importance.

It is necessary to intensify the efforts to conserve (*in-situ* and *ex-situ* conservation) and cultivate the *T. chebula* to prevent it from further depletion. We also recommend *in-situ* conservation by enriching their densities in nature reserves as well as *ex-situ* conservation through medicinal plant gardens, in botanical gardens and arboreta especially in Southern and Central India, where the model predicts as the excellent niche for the species. These steps would also reduce the supply constraints as well as meet the industrial and the domestic demand.

The species also requires a stringent assessment of population size and the threatened status. The tropical region within the country where the species is distributed also offers diverse niches for the species and provides an opportunity to assess the role of biotic factors that determine its distribution (Dash et al. 2020). Efforts should also be made among local farmers in various countries for their commercial cultivation. The study provides a useful means for identifying species hotspots for prioritizing conservation. The ecological niche maps generated in this study could be overlaid with other factors such as demographic data, threat status etc. so that a comprehensive map for the conservation of the species could be arrived at. Similarly, different measures such as conservation status, risk factors, economic values, expert opinion and measure of species preference by the communities can be used as weights to evaluate the worth of a given habitat for conservation and sustainable management.

Conclusions

In this study, we used present-day occurrence data to predict the potentially suitable distribution area of *T. chebula* in Asia based on an optimized Maxent model under different climate change scenarios.

Our study indicated that the most suitable habitat for *T. chebula* is found to be in the Central and South India (largely across Western Ghats). While there is not much change in the distribution of the species in RCP 2.6 scenario, the RCP 4.5 scenario indicated that there would be decline in the suitable habitats in Central India and more suitable areas in northern India especially in the state of Uttar Pradesh. Similarly, the RCP 8.5 scenario also indicated overall decrease in the habitat suitability of the species. The results also indicated that the predicted potential suitable distribution area of *T. chebula* of the present day matched the actual occurrence. Overall, the future climate change scenarios indicated that the distribution of *T. chebula* is likely to decrease. Future steps need to include data on demography, its threat status to develop a detail conservation action plan. Based on the niche maps, conservation, as well as cultivation of the species, can be taken up.

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Author contributions KBR, SS, GR & KK led the manuscript writing with inputs from all the authors. KBR, gathered data, BC developed methodology for modelling, KBR and BC performed analysis. GR revised the manuscripts with inputs from all the authors. All the authors gave final approval for publication.

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