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RESEARCH ARTICLE

Ecological niche modelling for predicting the habitat suitability of endangered tree species *Taxus contorta* Griff. in Himachal Pradesh (Western Himalayas, India)

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Abstract

The West Himalayan Yew (*Taxus contorta* Griff.) is an extremely important tree species as its bark and leaves are the source of the anti-cancer medicine Taxol® used in chemotherapy for the treatment of a number of different cancers. Unfortunately, the species is endangered because of unsustainable harvesting and over grazing coupled with a very low natural regeneration potential. The Maxent modelling algorithm was used to model the ecological niche and predict the habitat suitability of this species in the Western Himalayas of Himachal Pradesh. The purpose of the modelling was basically to restore the species in its native habitat. The model output had a reasonable area under the receiver operating characteristic curve (AUC) value of 0.905. The *jackknife* test showed that the land cover and the annual mean temperature were the most important environmental predictors that individually affected the information gain. The results suggested that the Great Himalayan National Park Conservation Area had the highest area (134.14 km^2) under the very highly suitable category. Being an International Union for Conservation of Nature (IUCN) category II protected area, it would be an ideal place to preserve and reintroduce the species. Among Wildlife Sanctuaries, the Kais Wildlife Sanctuary had the highest proportion of its area (92.46%) under very highly suitable category for *T. contorta*. Additionally, Churdhar and Tirthan Wildlife Sanctuaries are predicted to have more than 60% of their geographic areas as very highly suitable for the species. Overall, only 6% of the geographic area of Himachal Pradesh was predicted to be very highly suitable.

Keywords Bioclimatic layers · Conservation · Endangered species management · Geographic Information System (GIS) · Reintroduction and Maxent · World Database on Protected Areas (WDPA)

Introduction

The analysis of species-environment relationships is a very important research tool in ecology, biogeography, evolutionary, and conservation biology (Guisan and Zimmermann 2000; Guisan and Thuiller 2005). Ecological Niche Modelling (ENM) helps formulate maps of the potential distribution of species based on empirical correlations between species occurrences and environmental conditions of the habitat (Guisan et al. 2007; Franklin 2010). These maps could be interpreted as the suitability of each pixel to support the occurrence of the species (Guisan and Thuiller 2005; Zurell et al. 2020). An understanding of which habitats would be most suitable for a particular species is extremely beneficial for population supplementation and restoration projects especially for that of threatened species (Wilson et al. 2011).

Maxent is a software very popular among ecologists for ENM, with thousands of articles published since 2006 (Phillips et al. 2006; Kumar and Stohlgren 2009; Merow et al. 2013). Maxent is a general-purpose method for maximizing information entropy (Jaynes 1957). When used in ENM, Maxent acts as a maximum entropy based machine learning algorithm that estimates the smoothest probability distribution for the occurrence of a species that matches the

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environmental constraints (Phillips et al. 2006; Elith et al. 2011). Maxent predicts on the basis of species occurrence data and predictor variables such as topography, climate, soil etc. (Phillips et al. 2006; Elith et al. 2011). It specializes in the usage of presence-only data and that is one advantage of Maxent over other statistical modelling techniques that require both presence and absence data (Phillips et al. 2006), because absence data is difficult to obtain and has uncertainties (Anderson et al. 2003). Further, both continuous and categorical environmental data could be used and the built-in *jackknife* test evaluates the performance of the environmental variables, which makes Maxent highly useful for ENM (Phillips and Dudík 2008).

Taxus contorta Griff. commonly known as west Himalayan yew is listed as an endangered species by IUCN (Thomas 2011). The bark and leaves of *Taxus* spp are a source of taxine, a precursor to the drug Paclitaxel, sold under the brand name Taxol®, one of the best anticancer agents used in the treatment of different kinds of cancer (Lanker et al. 2010). This tree has a wide variety of ethnomedicinal uses, its wood is used in making furniture and it is also used as fuel (Beckstrom-Sternberg et al. 1993; Gaur 1999; Purohit et al. 2001; Joshi 2009; Lanker et al. 2010). Pharmaceutical companies pay villagers to bring them the bark and leaves of *Taxus* for manufacturing Paclitaxel (Poudel et al. 2013). A large proportion of the populations have already been severely harvested in the Indian Himalayan Region (IHR) because of short-term economic gain. As a result of all these multifarious uses, this species has been over-exploited to such levels that about 90% of its population in the IHR has been lost (Thomas 2011). Another problem of this species is its intrinsic poor natural regeneration ability (Rikhari et al. 1998; Pant and Samant 2008). Pant and Samant (2008) predicted that *Taxus* may soon be eradicated from Khokhan Wildlife Sanctuary, Himachal Pradesh if indiscriminate harvesting continues. During the past decades unsustainable use of this species, accompanied with its regeneration problems has neared it towards eventual extinction, which if happens would be a terrible loss to humankind given the medicinal importance of this species (Nimasow et al. 2015). Any measure taken to preserve this tree species would not only help the local communities that use it for traditional medicine, but also for the global human community, at a time when cancer has become a leading cause of death worldwide and its instances have been rising of late (Torre et al. 2015). Protection of existing habitats and well planned reintroduction of *T. contorta* in suitable habitats is highly imperative. In this regard, the present study was aimed at identifying potential sites for conservation and reintroduction of *T. contorta* through ecological niche modelling. Attempts were made to identify areas suitable for mass planting of this tree species throughout the Western Himalayas by ecological engineering.

Ecosystem restoration projects are required globally and in March 2019 the United Nations General Assembly declared 2021–2030 as the decade on ecosystem restoration (https://www.decadeonrestoration.org/about-un-decade). Apart from the ecological significance, ecosystem restoration can also improve the health of human populations, integrate national and ethnic cultures and ultimately lead to holistic social well being (Aronson et al. 2020). Lopping, bark peeling, logging, and grazing severely damage the growth and natural regeneration of *T. contorta* (Purohit et al. 2001; Perrin et al. 2006; Lanker et al. 2010). This study aimed at identifying areas which are least impacted by anthropogenic disturbances such as logging, lopping, firewood extraction and especially grazing such that planting of seedlings or propagules can be taken up. In that regard protected areas would be the best place for the reintroduction of this species. Various factors like poor regeneration, slow growth, loss of suitable habitat, and anthropogenic pressures do not allow *T. contorta* to occupy all of its suitable habitat and that is in fact leading to the decline in the populations of *T. contorta* (Samant 1999). ENM helps to identify the potential area that would satisfy the ecological requirements of the species and this knowledge is essential for reintroduction. Ecological niche modelling has already proven to be an effective tool for carrying out conservation efforts (Hill et al. 2017; Hernández-Quiroz et al. 2018; Zhang et al. 2019) and in developing habitat suitability maps (Zhang et al. 2012) and hence would be immensely beneficial to recover threatened species. Keeping in view the above pressing issues, the present research had the following objectives:

1. Characterize the ecological niche of *T. contorta,* and identify the environmental variables that are most important for this species,
2. Generate a habitat suitability map for *T. contorta* in Himachal Pradesh, and
3. Identify areas within the protected areas in Himachal Pradesh where *T. contorta* could be planted.

Materials and methods

Study area

Himachal Pradesh (30°22′40″N–33°12′40″N and 75°45′55″E–79°04′20″E) is a mountainous state of India situated in the Western Himalayas covering an area of 55,673 km^2 (India Planning Commission 2005; Himachal Pradesh GOI 2021). Elevations range from 350 to 6975 m asl and hence supports diverse habitats and vegetation (Himachal Pradesh GOI 2021; Samant et al. 2007; Upgupta et al. 2015). The annual rainfall averages 1800 mm and the temperatures range from sub-zero to around 35 °C.

The forest cover as of 2017 constitutes 27.72% of the geographic area of the state (Forest Survey of India 2019). All the 12 districts in the state are located in the mountainous regions (Fig. 1). Five national parks, 28 wildlife sanctuaries and three conservation reserves constitute the protected area network covering 15.10% of the geographic area of the state (Forest Survey of India 2019). Himachal Pradesh has been reported to harbour populations of *T. contorta* in the wild (Fig. 2).

Data sources

Occurrence data of *T. contorta* were collected from both primary and secondary sources (Table 1). Ecological field survey was done in Kullu and Shimla districts of Himachal Pradesh from April-November, 2019 and the occurrence points of *T. contorta* were marked with a Garmin eTrex 10 Global Positioning System (GPS) receiver with ± 5 m accuracy. Various location points for the different districts were collected from published literature, herbarium records, Gymnosperm Database (https://www.conifers.org/ta/Taxus_contorta.php) and Global Biodiversity Information Facility database (GBIF) (https://www.gbif.org/en/). The occurrence data totalling 533 were manually observed on QGIS version 3.4 (QGIS Development Team 2019) with an underlying Google satellite layer (Google 2015) through the QuickMapServices plugin (NextGIS 2019) and the locations that were illogical were removed. Only those points within the state of Himachal Pradesh were considered. To remove sampling bias (Kramer-Schadt et al. 2013) the occurrence data totalling to 519 points after filtering were subsequently spatially thinned using the SpThin package (Aiello-Lammens et al. 2015) on R Studio version 1.2.5042 (RStudio Team 2020) running a base R version 3.6.3 (R Core Team 2019). The thinning was run once with the thin distance set at 5 km and another time with that set to 10 km. Spatial thinning using the 5 km distance reduced the data points to 33 observations, while setting it to 10 km reduced the observations to 15. Models were run using both datasets.

For predicting the habitat suitability of *T. contorta* 23 variables were initially gathered, out of which the nineteen Bioclimatic layers (Hijmans et al. 2005) Bio1 to Bio19 of WorldClim version 2 (average monthly climate data for minimum, mean, and maximum temperature

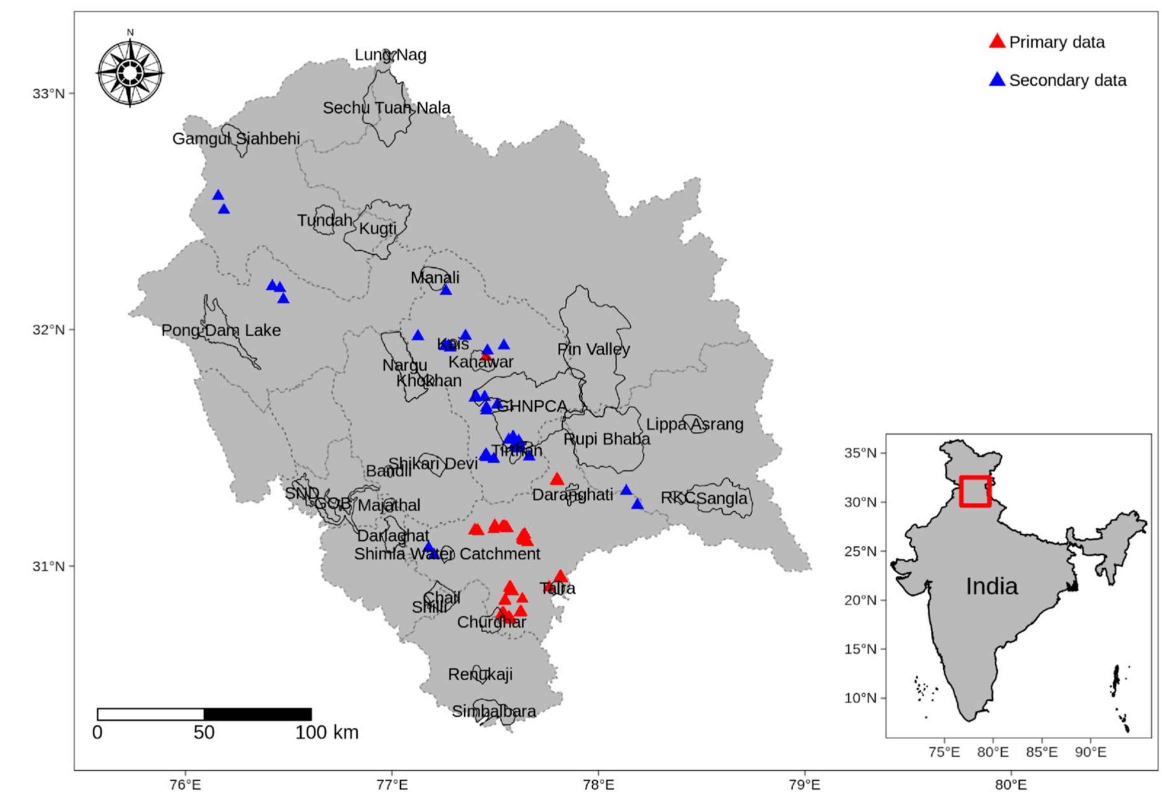

Fig. 1 Map of Himachal Pradesh showing the districts and its location in India (inset). Shown in red and blue are the primary and secondary data points respectively, collected for the modelling procedure. Internal boundaries with dotted lines represent the districts while the ones with thick continuous lines represent protected areas along with their names. *GHNPCA* Great Himalayan National Park Conservation Area, *GOB* Gobindsagar, *RKC* Raksham Chitkul, *SND* Shri Nainadevi

Fig. 2 **a** Foliage and aril with seed of *T. contorta* in a natural forest in Shimla district, and **b** Propagules of *T. contorta* raised by stem cutting based macro-propagation for reintroduction at G.B. Pant National Institute of Himalayan Environment and Sustainable Development, Himachal unit, Kullu. **c** *T. contorta* in its natural habitat in Shimla district. Pic credits: (**a**) Dr. S. Ghoshal, (**b**) Dr. K. S. Kanwal, and (**c**) Mr. Saurav Chauhan

Table 1 Occurrence data of *Taxus contorta* used in the modelling procedure

District	Primary data	Secondary data	Sources
Shimla	490	4	GBIF, Gymnosperm database
Kullu	3	31	Bodh (2017), GBIF, Gymnosperm database, Lal (2007), Rana (2007), Sharma (2008), Sharma (2013), Thakur (2012)
Kangra		3	GBIF, Gymnosperm database
Chamba		2	GBIF, Gymnosperm database

and precipitation for 1970–2000) were downloaded from WorldClim (http://worldclim.org/version2) with a spatial resolution of 30 arc-seconds (ca. 1 km^2). The Bioclimatic layers were converted from BIL to the Maxent compatible ASCII format using QGIS. The Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) with a spatial resolution of 90 m was downloaded from Earth Explorer website (https://earthexplorer.usgs.gov). As *T. contorta* have been reported to be predominantly distributed in northern aspects (Schickhoff 1996; Thomas 2011), slope and aspect data were extracted from the SRTM DEM using QGIS and were included as environmental predictor variables. Global 300 m land cover data GlobCover 2009 (Arino et al. 2012) was downloaded from http://due.esrin.esa.int.

All the variable layers were clipped to the shapefile of Himachal Pradesh, downloaded from the Database of Global Administrative Areas (GADM) (https://gadm.org/download_country_v3.html).The elevation, slope, aspect, and the land cover data were resampled to the spatial resolution of the Bioclimatic layers (30 arc-seconds) using the bilinear interpolation method for all the layers except for land cover for which the nearest neighbour interpolation method was used. All the above environmental predictor variables were examined for multicollinearity by the Pearson Correlation Coefficient (r) and the variables having cross-correlation value beyond ± 0.75 were excluded from analysis. Eleven remaining variables were used in the model (Table 2).

The protected areas shapefiles for India were downloaded from the World Database on Protected Areas (WDPA) (WDPA 2020). The protected area polygons lying within the state boundary of Himachal Pradesh were clipped for analysis.

Niche modelling

Maxent software (version 3.4.1) was downloaded from http://www.cs.princeton.edu/~schapire/Maxent/. Selected variables and occurrence data were processed in Maxent software by using 10 replicates using the subsampling method and 5000 iterations were used. Random Test percentage was set to 30% based on the formula 1/(1 + (*P*-1)^0.5, where *P* implies the number of predictor variables used (Huberty 1994). The maximum number of background points was set to 10,000. Linear and quadratic features were used (Phillips et al. 2004) and all the other values were kept as default. The generated models were evaluated based on AUC value (Area Under ROC (Receiver Operating Characteristics) Curve). AUC, a threshold-independent parameter that is used widely to evaluate model performance by a single value, ranges between 0 and 1. The AUC value is based on the ROC curve, which is the plot of the proportion of observed presences predicted correctly (sensitivity) against the proportion of observed absences predicted incorrectly (1-specificity). Sensitivity and specificity are used as they account for all the true and false presences and absences and subtracting specificity from 1 makes both the metrics vary in the same direction (Pearce and Ferrier 2000). A model that predicts very accurately will form an ROC curve that is close to the left axis and the top, while on the other hand a model that predicts no better than random would closely follow the 1:1 line (Pearson 2007). The quality of the model was evaluated and graded following the categorization based on AUC values by Swets (1988). Values less than 0.5

Table 2 Environmental predictor variables and their relative contribution in the model

Code	Environment Variables	Unit	Percent contribution
Bio1	**Annual mean temperature**	**°C**	**19.9**
Bio2	**Mean diurnal range (mean of monthly (max temp-min temp)**	**°C**	**0.1**
Bio3	**Isothermality (Bio2/Bio7) (*100)**	**Dimensionless**	**0.0**
Bio4	**Temperature seasonality (standard deviation *100)**	**Percent**	**26.7**
Bio5	Max temperature of warmest month	°C	
Bio6	Min temperature of coldest month	°C	
Bio7	Temperature annual range (Bio5-Bio6)	°C	
Bio8	**Mean temperature of wettest quarter**	**°C**	**0.2**
Bio9	Mean temperature of driest quarter	°C	
Bio10	Mean temperature of warmest quarter	°C	
Bio11	Mean temperature of coldest quarter	°C	
Bio12	Annual precipitation	mm	
Bio13	Precipitation of wettest month	mm	
Bio14	**Precipitation of Driest Month**	**mm**	**20.4**
Bio15	Precipitation seasonality (coefficient of variation)	Dimensionless	
Bio16	Precipitation of wettest quarter	mm	
Bio17	**Precipitation of driest quarter**	**mm**	**0.8**
Bio18	Precipitation of warmest quarter	mm	
Bio19	Precipitation of coldest quarter	mm	
Land cover	**Land cover**	**Categorical**	**31.5**
Elevation	**Elevation**	**m asl**	**0.3**
Slope	**Slope gradient**	**Degree**	**0.0**
Aspect	**Slope aspect**	**Degree**	**0.3**

Note: Bold letters show the environmental variables used in the model

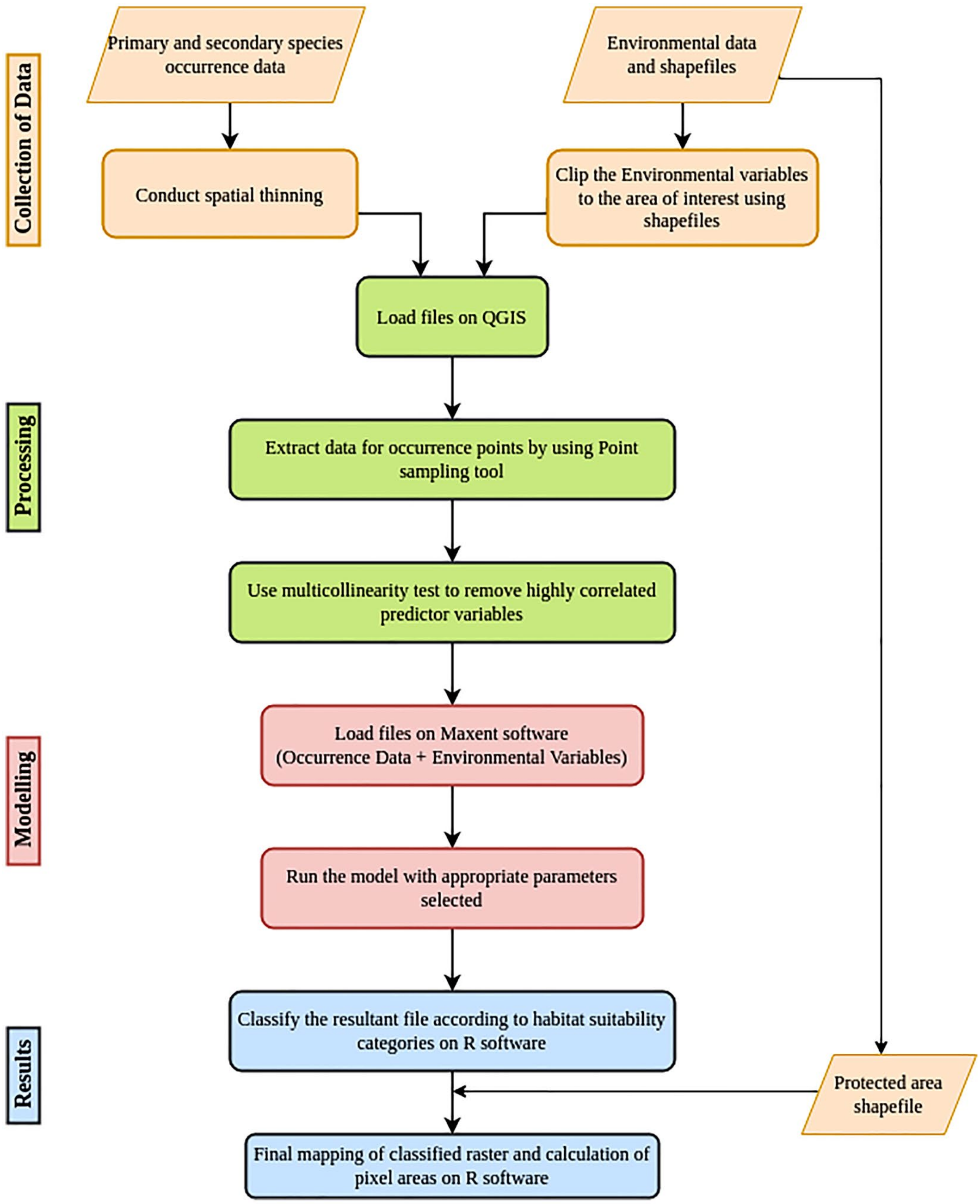

Fig. 3 Flowchart of the ecological niche modelling methodology

imply that the model performed worse than random chance, which is when the value equals 0.5. Beyond that the AUC values were graded as failed (0.5–0.6), poor (0.6–0.7), fair (0.7–0.8), good (0.8–0.9), and excellent (0.9–1). The relative importance of the variables were evaluated by the *jackknife* procedure. The cloglog output was selected. The Maxent output so generated directly predicts the species habitat suitability in a range from 0 to 1. Further, potential areas of distribution were categorized into five classes namely very low (0.0-0.10), low (0.10-0.30), medium (0.30-0.50), high (0.50-0.70), and very-high (0.70-1.0) based on the logistic threshold of 10 percentile training presence (Adhikari et al. 2012; Barik et al. 2012; Paul et al. 2019). The pixels showing the very high category of habitat suitability and falling inside the protected area polygons were extracted for each protected area and the counts were summed up and converted to km^2 to generate the total area, based on the spatial resolution of the pixels. Maxent models predict the habitat suitability and not the actual distribution and hence the predicted output is not a species distribution model in the

Table 3 Model performance under different sample sizes due to different spatial thinning distances used

Spatial thinning distance (km^2)	Resulting sample size	AUC
10	15	0.905
5	33	0.867

strict sense of the term and hence ecological niche modelling or habitat suitability modelling are appropriate terms to describe the current research (Guisan and Zimmermann 2000; Peterson and Soberón 2012). A flowchart of the methodology in brief is shown in Fig. 3.

Maps and projections

The maps were prepared on R-studio (RStudio Team 2020) using the tmap package (Tennekes 2018). The study area map was projected to Oblique Lambert azimuthal equal-area projection (Fig. 1), while the habitat suitability maps were projected to Lambert Conformal Conic projection.

Results and discussion

Model performance and contribution of variables

The AUC is widely used to estimate the predictive accuracy of the distributional models derived from species presence–absence data. The two datasets differing in number of occurrence points (15 and 33) showed different AUC values (Table 3). The one with 15 data points had the higher AUC indicating the effect of increased bias with increased sample size and that may have lead to over-fitting when using the larger dataset. A sample size of 15 falls within the range of the lower limits for sample size discussed in van Proosdij et al. (2016). The model with the higher AUC value was considered for preparing the habitat suitability map (Fig. 4). Figure 5 shows the results of the *jackknife* test. Figure 6 displays the test omission rate and predicted area as a function of the cumulative threshold, averaged over the replicate runs. Considering the definition of the cumulative threshold, the omission rate should be close to the predicted omission. For the current model the test omission rate was found to be acceptably close to the predicted omission. Figure 7 shows the ROC curve averaged over the replicate runs. ROC curve summarizes model performance overall conditions a model could operate using all information provided by the predictive model (Swets 1988). The ROC curve was reasonably close to the left axis and the top and far from the 1:1 line (Fig. 7) and hence is acceptable.

Maxent predicted the habitat suitability for *T. contorta* with an excellent level of accuracy as per Swets

Table 4 Area covered by the different habitat suitability classes of *Taxus contorta* in Himachal Pradesh

Habitat suitability	Area (km^2)	Proportion of total state area (%)
Very low	35,347.31	63
Low	7973.47	14
Moderate	4746.02	9
High	4506.17	8
Very High	3208.49	6

(1988) having the average test AUC of 0.905 (Fig. 7). AUC value (of more than 0.8) exhibits the satisfactory performance of the model in predicting species distribution with higher discrimination of input data (Lobo et al. 2008). Among the environmental layers, land cover had the highest contribution (31.5%) followed by Bio4: temperature seasonality (26.7%) and Bio14: precipitation of the driest month (21.4%) (Table 2). Forested habitats are extremely important for *T. contorta* as its seedlings require shade in the initial stages (Giertych 2000). The climatic factors are important at larger spatial extents, while at the local level land cover is generally the limiting factor for species distributions (Pearson et al. 2004; Cord et al. 2014). Hence, the importance of land cover was expected. According to the response curves (Fig. 8), GlobCover land cover categories 40 and 100 showed the highest importance in predicting the presence of *T. contorta* followed by 70. These categories are 40: Closed to open (> 15%) broadleaved evergreen and/or semi-deciduous forest (> 5 m), 100: Closed to open (> 15%) mixed broadleaved and needle leaved forest (> 5 m), and 70: Closed (> 40%) needle leaved evergreen forest (> 5 m) (Arino et al. 2012). Examples of the above three categories where *T. contorta* have been found to occur are *Quercus semecarpifolia* Sm. dominated forest community, *Q. floribunda* Lindl. ex A.Camus—*T. contorta* mixed forest community, and *Abies pindrow* (Royle ex D.Don) Royle and *Picea smithiana* (Wall.) Boiss. dominated forest communities respectively (personal observation). So these communities would be appropriate for reintroduction of *T. contorta* in the western Himalayas. Interestingly, Yang et al. (2013) had also observed that land cover was the most important variable for predicting the ecological niche of *Justicia adhatoda,* another Himalayan medicinal plant. The response curves (Fig. 8) predict that areas having annual mean temperature values (Bio1) between 7.5 and 10 °C, and precipitation of the driest month greater than 25 mm should be highly suitable areas for potential distribution of *T. contorta.* According to the *jackknife* test of the regularized training gain, Bio1: annual mean temperature seemed to be the most important variable by itself as it had the highest gain when used in isolation. Conversely, the environmental predictor that

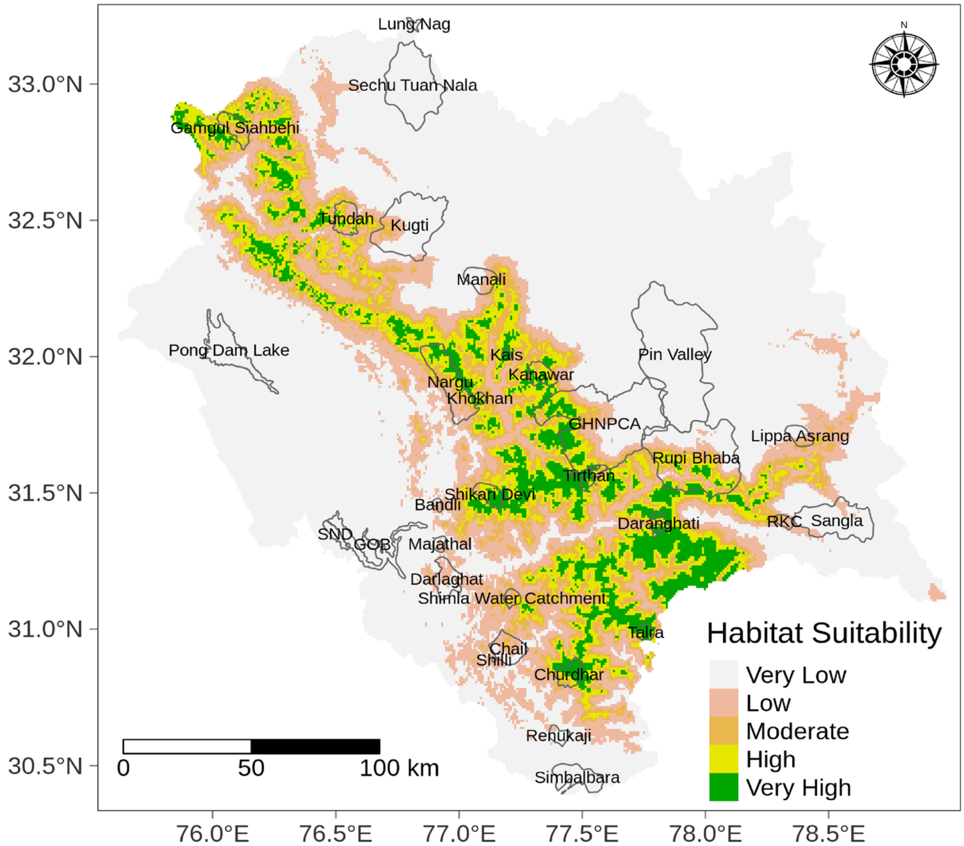

Fig. 4 Habitat suitability map of *Taxus contorta* in Himachal Pradesh. Internal boundaries represent protected areas along with their names. *GHNPCA* Great Himalayan National Park Conservation Area, *GOB* Gobindsagar, *RKC* Raksham Chitkul, *SND* Shri Nainadevi

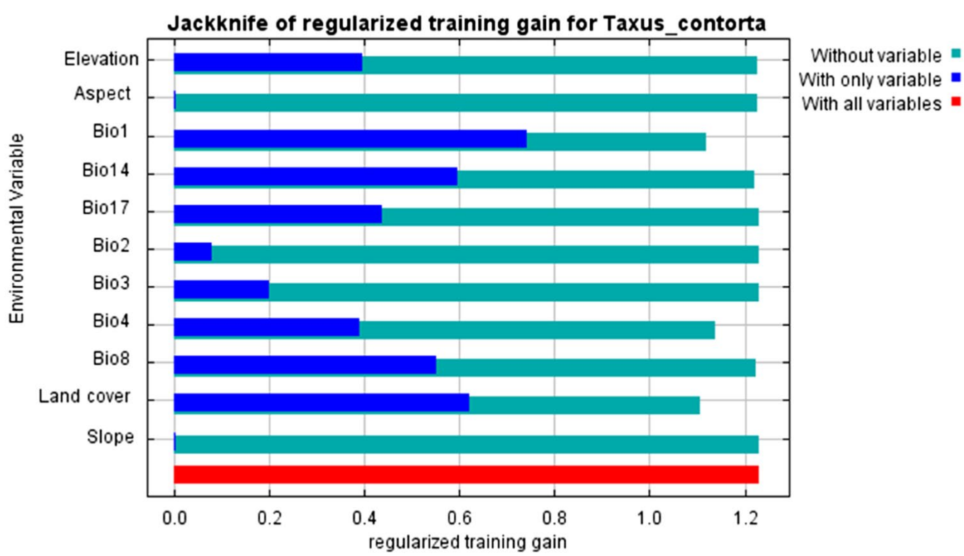

Fig. 5 Jackknife test of regularized training gain for evaluating the relative importance of environmental variables for modelling habitat suitability of *Taxus contorta* in Himachal Pradesh

decreased the gain the most when it was omitted was land cover, which therefore seems to have the most information that is absent in the other variables (Fig. 5). Slope and aspect showed zero and near zero contribution to the model respectively (Table 2) as was also observed by Glen (1999). This could be explained by the fact that slope and aspect are local variables and as the model was working on pixels of coarser resolution, these variables could not contribute to the model performance. Even though elevation did not contribute much in the model, but when used by itself, it predicted the presence of *T. contorta* between 2200 and 3000 m asl, peaking around 2600 m asl (Fig. 8), which is consistent with the average elevation in which the species have been reported (Thomas 2011). The influence of elevation would always be important and its low contribution in the model could

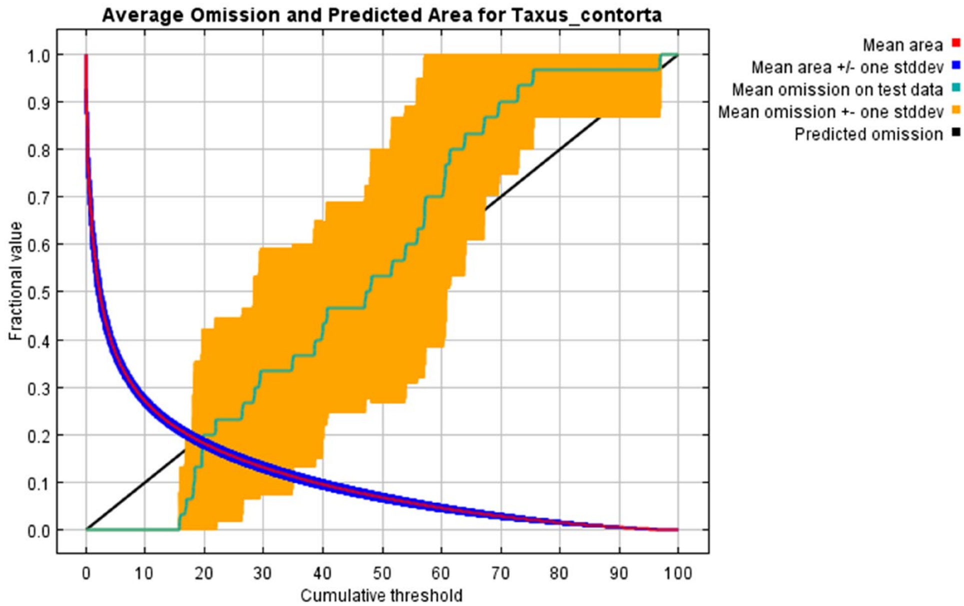

Fig. 6 The test omission rate and predicted area as a function of the cumulative threshold, averaged over the 10 replicate runs of the Maxent output for *Taxus contorta* in Himachal Pradesh

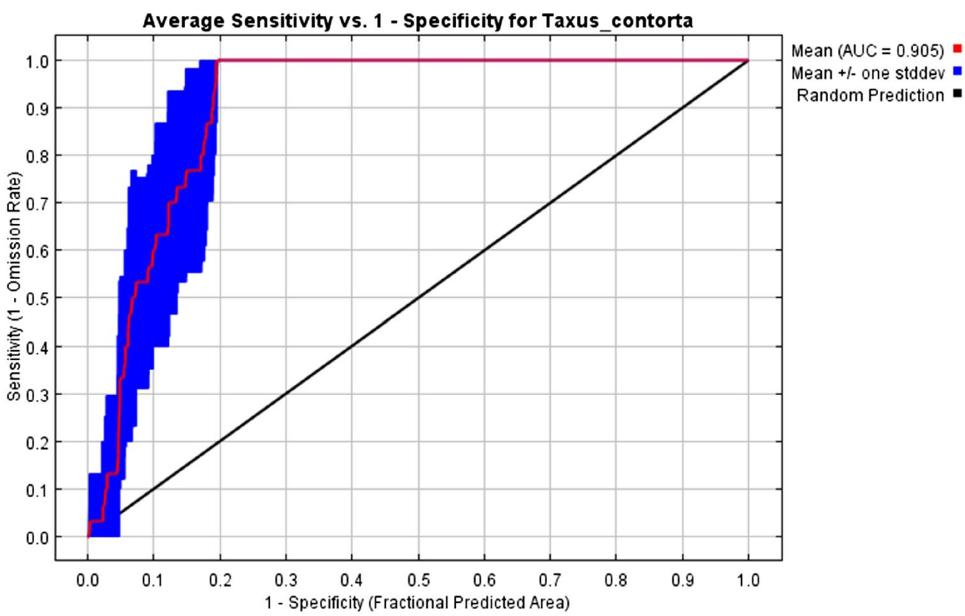

Fig. 7 The receiver operating characteristic (ROC) curve showing Average Sensitivity vs 1-Specificity averaged over the 10 replicate runs of the Maxent output for *Taxus contorta* in Himachal Pradesh

be explained by it being correlated with the other climatic variables.

Protected areas suitable for reintroduction of *Taxus contorta*

Only 6% of the total geographic area of the state could be very highly suitable (habitat suitability > 0.70) while another 8% could be highly suitable for *T. contorta* (Table 4). The ecological niche may be over-predicted in some areas by Maxent (Pearson 2007), in which case the proportion of highly suitable sites is likely to actually go further down. Because *T. contorta* is very sensitive to anthropogenic disturbances and specificity of habitat (Giertych 2000; Perrin et al. 2006; Pant and Samant 2008; Lanker et al. 2010), it would be crucial to plant the tree seedlings or saplings only in the very highly suitable sites so as to reduce the uncertainties in its establishment. The habitat suitability model overlaid with the vector layers of the protected area shapefiles downloaded from WDPA, clearly shows which protected areas fall under the predicted very highly suitable category (Fig. 4). The largest area (132.68 km^2) of predicted suitable habitat has been found to be in the Great Himalayan National Park Conservation Area (GHNPCA) (Table 5), which is a National Park and also a World Heritage site, declared in 2014 by the United Nations Educational

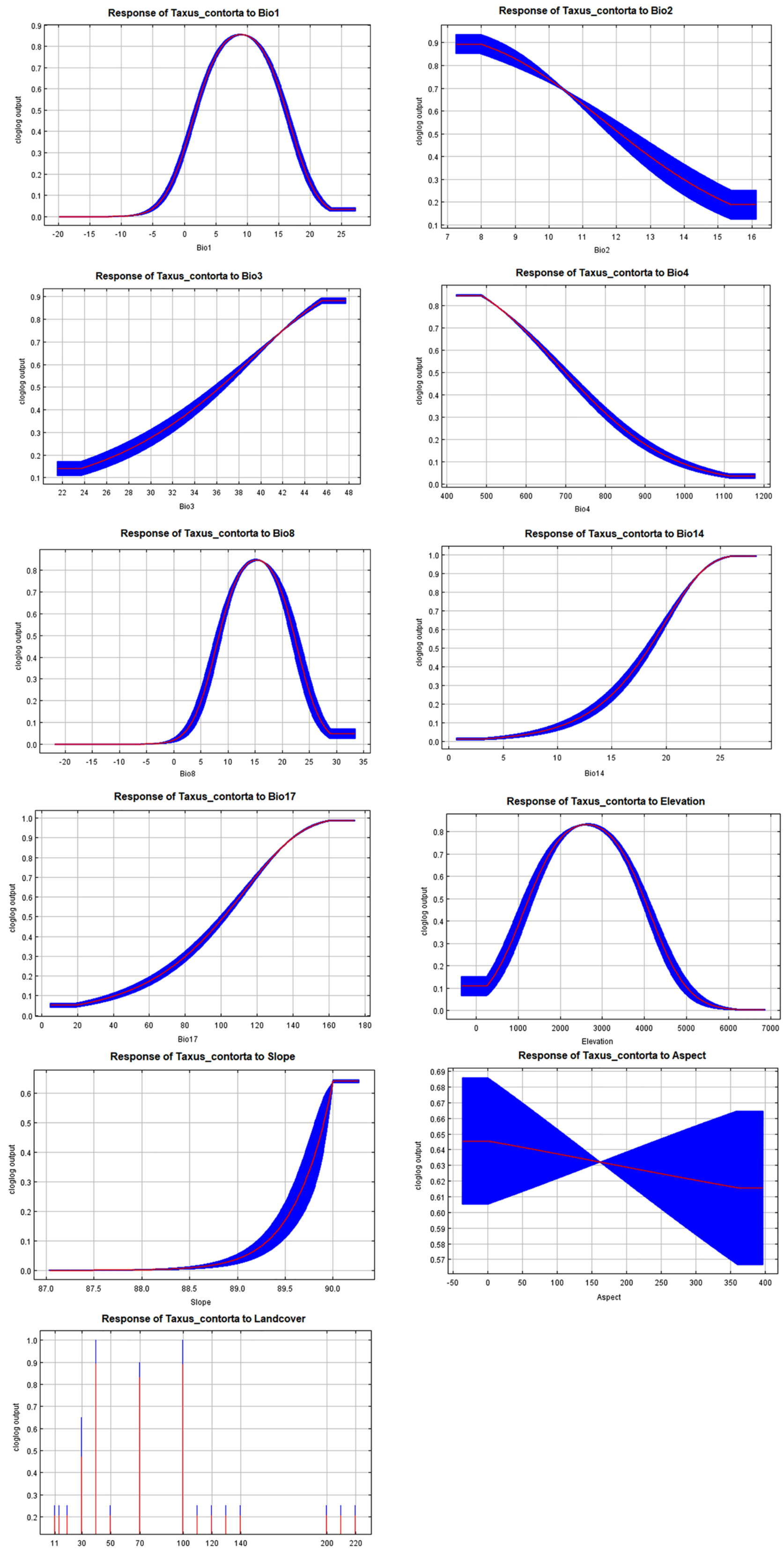

Fig. 8 Response curves obtained when running the Maxent model with only the corresponding variable. The curves show the mean response of the 10 replicate Maxent runs (red) and and the mean ± one standard deviation (blue, two shades for categorical variables e.g., landcover)

Table 5 Protected areas of Himachal Pradesh which are very highly suitable for *Taxus contorta*

Protected area	District	Suitable area (km^2)	Proportion of protected area suitable (%)
Great Himalayan National Park Conservation Area[II*]	Kullu	134.14	11.65
Rupi Bhaba Wildlife Sanctuary[IV]	Kinnaur	70.72	9.58
Nargu Wildlife Sanctuary[IV]	Mandi	55.41	17.42
Churdhar Wildlife Sanctuary[IV]	Sirmour and Shimla	43.74	66.27
Tirthan Wildlife Sanctuary[IV]	Kullu	43.01	70.37
Shikari Devi Wildlife Sanctuary[IV]	Mandi	40.10	55.69
Talra Wildlife Sanctuary[IV]	Shimla	24.79	53.89
Daranghati Wildlife Sanctuary[IV]	Shimla	24.79	14.08
Kanawar Wildlife Sanctuary[IV]	Kullu	24.06	19.76
Kais wildlife Sanctuary[IV]	Kullu	13.12	92.46
Tundah Wildlife Sanctuary[IV]	Chamba	8.75	13.63
Gamgul Siahbehi Wildlife Sanctuary[IV]	Chamba	8.02	6.47
Khokhan Wildlife Sanctuay[IV]	Kullu	4.37	19.40

Superscripts indicate the IUCN category of protected areas

* → Includes a World Heritage Site

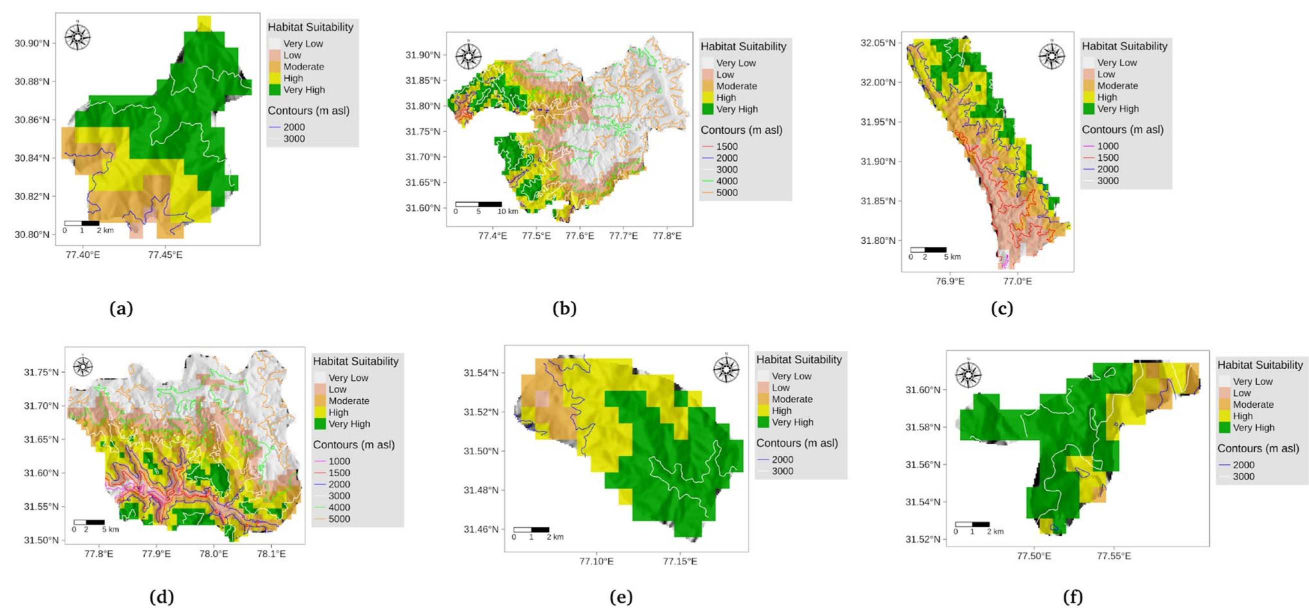

Fig. 9 Habitat suitability map of *Taxus contorta* in protected areas of Himachal Pradesh with a considerable area under the highly suitable category. **a** Churdhar Wildlife Sanctuary, **b** GHNPCA, **c** Nargu Wildlife Sanctuary, **d** Rupi Bhaba Wildlife Sanctuary, **e** Shikari Devi Wildlife Sanctuary, **f** Tirthan Wildlife Sanctuary. The habitat suitability raster has been overlaid over a hillshade created using SRTM 90 m DEM. All the layers have been projected to Lambert Conformal Conic projection

Scientific and Cultural Organization (UNESCO) for its outstanding role in the conservation of Biodiversity (UNESCO,2014). The GHNPCA has a lot of riparian coniferous forests (ASI 2020), which happens to be a very suitable habitat for *T. contorta* (Thomas 2011). The GHNPCA was the only National Park in Himachal Pradesh where Maxent predicted very highly suitable habitats for *T. contorta.* It is an IUCN category II protected area (WDPA 2020) and hence there is no extraction of resources and no grazing is legally permitted (Bawa et al. 2011), which makes it an ideal place to reintroduce *T. contorta*, given its sensitivity to anthropogenic disturbance (Giertych 2000; Perrin et al. 2006; Pant and Samant 2008; Lanker et al. 2010). As is evident from Fig. 9b the western areas of the National Park near the slopes with elevation contours between 2500 and 3000 m asl (white lines) could be the best sites to re-introduce *T. contorta.* The other protected areas, where very high suitability of habitats were predicted, are all wildlife sanctuaries, which are IUCN category IV protected areas (WDPA 2020). In such areas some controlled harvesting is legally permitted (Bawa et al. 2011), therefore any planting of *T. contorta* in such areas would need clear demarcations (including fencing the sites for a certain time period) and discussions with the local communities to maintain grazing free conditions. A considerable area of suitable habitats for *T. contorta* were predicted in Rupi Bhaba, Nargu, Churdhar, Tirthan and Shikari Devi Wildlife Sanctuaries (Table 5). In these wildlife sanctuaries, the best areas for enrichment planting of *T. contorta* could again be the areas between 2500 and 3000 m asl (Fig. 9), the stretches being north-eastern for Nargu Wildlife Sanctuary, north- and south-western for Tirthan Wildlife Sanctuary, central and south-eastern for Shikari Devi Wildlife Sanctuary and distributed in patches at the mountain tops of central and southern areas separated by a valley in the Rupi Bhaba Wildlife Sanctuary. The Kais Wildlife Sanctuary in Kullu district had the highest proportion (92.46%) of its protected area falling under the very highly suitable category, followed by Tirthan Wildlife Sanctuary (Kullu district) and Churdhar Wildlife Sanctuary (Sirmaur and Shimla districts), both having more than 60% of its area as being very highly suitable. These Wildlife Sanctuaries would be very important for concentrated reintroduction of *T. contorta.* In the highly suitable areas predicted for *T. contorta,* any enrichment planting should be done only within the GlobCover land cover categories 40, 70 and 100 following the response curve (Fig. 8). These protected areas would be easy to maintain and may serve as future reserves of genetic stocks of *T. contorta,* if given proper protection from anthropogenic disturbances. The other protected areas of Himachal Pradesh, that are not included in Table 5, did not contain any pixel having a predicted very highly suitable habitat. To completely restore *T. contorta*, concerted efforts are required on the part of both State Forest Department as well as the forest fringe communities and other stakeholders to enact regulations, and to reach agreements to protect the species (Ravikanth et al. 2018). Adequate legal mechanisms must be put in place to manage species especially those where the population size of the species is small so that it can be recovered from the brink of extinction.

Conclusion

The Maxent modelling algorithm was used in the ENM of *T. contorta*. The model output should be reasonable, provided that the AUC value was in the excellent category (Swets 1988). The model could be improved in the future by collecting more occurrence points from the different sites predicted to have high to very high suitability for *T. contorta*, that shall also validate how well the model had predicted the ecological niche of the species. Further research to evaluate the dispersal characteristics of the species and inclusion of disturbance layers could help in predicting the actual distribution of the species. The most important factors that characterize the ecological niche of *T. contorta* are land cover, annual mean temperature (Bio1), temperature seasonality (Bio4) and precipitation of the driest month (Bio14). Land cover had the greatest percent contribution to the model. The response curves using only one variable at a time, predicted the land cover categories: Closed to open (> 15%) broadleaved evergreen and/or semi-deciduous forest (> 5 m), Closed to open (> 15%) mixed broadleaved and needle leaved forest (> 5 m), and Closed (> 40%) needle leaved evergreen forest (> 5 m) to be highly suitable for enrichment planting of *T. contorta.* Additionally, the model predicted that the reintroduction areas for *T. contorta* should have annual mean temperature values (Bio1) between 7.5 and 10 °C, and precipitation of the driest month greater than 25 mm. This research has highlighted the protected areas and the proportion of their areas that are very highly suitable for the establishment of *T. contorta*. The western stretches of the GHNPCA along the elevation contours of 2500–3000 m asl could be the best places for the enrichment planting and for long-term secure preservation of this species in its natural habitat. Wildlife Sanctuaries such as Rupi Bhaba, Nargu, Churdhar, Tirthan and Shikari Devi have also been predicted to be highly suitable for reintroduction of *T. contorta,* but in such areas protection from anthropogenic disturbances, especially grazing would be extremely important. This information shall be potentially beneficial for *in-situ* conservation of this endangered tree species, by demarcating and protecting areas predicted to have very high suitability and for initiating reintroduction operations for *T. contorta* by the state Forest Department and other conservation agencies.

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