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CURRENT TOPICS IN PLANT RESEARCH

Modeling the impact of climate change on wild *Piper nigrum* (Black Pepper) in Western Ghats, India using ecological niche models

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Abstract The center of diversity of *Piper nigrum* L. (Black Pepper), one of the highly valued spice crops is reported to be from India. Black pepper is naturally distributed in India in the Western Ghats biodiversity hotspot and is the only known existing source of its wild germplasm in the world. We used ecological niche models to predict the potential distribution of wild *P. nigrum* in the present and two future climate change scenarios viz (A1B) and (A2A) for the year 2080. Three topographic and nine uncorrelated bioclim variables were used to develop the niche models. The environmental variables influencing the distribution of wild *P. nigrum* across different climate change scenarios were identified. We also assessed the direction and magnitude of the niche centroid shift and the change in niche breadth to estimate the impact of projected climate change on the distribution of *P. nigrum*. The study shows a niche centroid shift in the future climate scenarios. Both the projected future climate scenarios predicted a reduction in the habitat of *P. nigrum* in Southern Western Ghats, which harbors many wild accessions of *P. nigrum*. Our results highlight the impact of future climate change on *P. nigrum* and provide useful information for designing sound germplasm conservation strategies for *P. nigrum*.

Keywords *Piper nigrum* · MaxEnt · Niche centroid · Future climate · Centres of diversity

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Introduction

Anthropogenic climate change is one of the major drivers altering species distribution, abundance, range shifts and increasing extinction risks for a number of species (Beltramino et al. 2015; Thomas et al. 2004). As per the current projections, twenty first century will face a rapid climate change that could affect different levels of biodiversity. The Intergovernmental Panel on Climate Change (IPCC) estimates a high risk of extinction for 20–30 % of species with a rise of 2–3 °C in global temperatures (Stocker et al. 2014; Warren et al. 2013). It is also estimated that, by 2080 about 58 % of plants will lose their niche, under their current dispersal rates (Warren et al. 2013).

In the onset of climate change, wild relatives of domesticated crop plants are of particular interest due to their economic importance and being a major source of its gene pool. In recent years, a number of studies have used current and future climate change scenarios to understand the impact of climate change on wild crop diversity (Jarvis et al. 2008; Russel et al. 2014). Substantial change in climate has been shown to cause niche shift or reduction in the habitat, which could lead to isolation and loss of genetic diversity of wild relatives of crop species. Prompt mitigation measures are suggested to avoid these range losses and improve adaptation mechanisms (Warren et al. 2013).

Ecological niche models (ENM) are used extensively to understand the impact of future climate change

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on biodiversity, and improve conservation planning of wild crop diversity (Priti et al. 2016; Russel et al. 2014; Shivaprakash et al. 2013). Ecological niche models use the present distribution data to predict the ecological niche of species for a given set of environmental variables. ENMs are useful to understand several biological phenomena ranging from species delimitations (Nag et al. 2014), predicting species invasions (Peterson et al. 2009; Sarma et al. 2015) and to identify the effect of climate change on biodiversity (Thuiller et al. 2008; Warren et al. 2013).

Piper, is a large genus with nearly 2,000 species of herbs, shrubs and lianas (Wanke et al. 2007), many of which are economically important. *Piper nigrum* L. (Black pepper), is an economically and medicinally important species, largely used as spice all over the world (Jaramillo and Manos 2001; Sen et al. 2010). *Piper nigrum* is naturally distributed in the wet evergreen and occasionally in the moist evergreen forests of the Western Ghats biodiversity hotspot in India. Wild forms of *P. nigrum* are usually dioecious while the flowers of cultivated ones are bisexual in nature (Ravindran 2000).

The Western Ghats are presumed to be the center of diversity of *P. nigrum* and the only remaining source of its wild germplasm. *Piper nigrum* is cultivated widely in India, Brazil, China, Africa, Sri Lanka, Vietnam, Malaysia and Indonesia). With Brazil being the largest exporter (Ravindran 2000). As per Food and Agriculture Organization of the United Nations (FAO), *P. nigrum* is the second most widely traded spice in the world, with 445,900 tons being traded in 2009 valuing about 929 million US dollars (Gordo et al. 2012).

Wild relatives of crop plants are important sources of genetic material harboring genes/traits related to pest resistance and drought tolerance (Hoisington et al. 1999). These wild relatives can be crossed with domesticated ones to produce new varieties. The Western Ghats holds most of the related species of *P. nigrum* and especially the Southern Western Ghats harbors the highest cultivar diversity (Ravindran 2000). In recent years, Western Ghats has been subject to intense land use changes and habitat alterations resulting in extinction of many wild populations of *P. nigrum* (Mathew et al. 2003). Though several studies have been carried out on *P. nigrum* to understand its phytochemistry, distribution and molecular characterization for crop improvement, very few have examined the impact of climate change on the wild relatives of this species (Nazeem et al. 2007; Pradeepkumar et al. 2001; Ravindran et al. 1992; Ravindran 2000). Wild relatives of several crop plants including *P. nigrum* are under severe threat and there is an urgent need to conserve these valuable resources (Nayar 2011).

In this context, the main objectives of our study were to: (1) develop the ecological niche model of wild *P. nigrum* for both present and two future climate change scenarios; (2) quantify the area suitable of *P. nigrum* within Western Ghats in present and future scenarios and (3) estimate the magnitude and direction of niche centroid shifts in the future climate change scenarios.

Materials and methods

Study area and species occurrence data

This study was conducted in the Western Ghats in South India, where wild relatives of *P. nigrum* are distributed naturally from 8°–15° latitude The Western Ghats is one of the biodiversity hotspots of the world (Myers et al. 2000). The study area was divided into 932,815 cells of 1 × 1 km resolution. 52 non-overlapping occurrence points were collected from the field during 2011–2014 and from reliable herbarium records of Tropical Botanical Garden and Research Insitiute (TBGRI), Trivandrum. The species was identified using floras and confirmed by taxonomists to avoid any ambiguity in identification. Since genus *Piper* is known for its taxonomic complexity (Sen et al. 2010), immense care was taken while including secondary data from herbarium records.

Spatial autocorrelation is reported to be a known issue in distribution models (Elith and Leathwick 2009; Ranjitkar et al. 2014). Spatial autocorrelations among the occurrence points were accounted by calculating Moran's I (Moran 1950) using R (package 'ape', Paradis et al. 2004). The occurrence points used for final model building were further separated by 20 km to reduce the effect of spatial autocorrelation due to geographic clustering using R (package spThin, Aiello-Lammens et al. 2015) (Fig. S1). The choice of filtering the occurrence points by 20 km were not arbitrary, but at this distance we found non significance in Moran's I for the chosen predictors. Hence, the final distribution points after filtering consisted of 27 occurrence points, which spread across the entire range of the species. The filterd dataset is available as online supplement.

Bioclimatic variables

Environmental layers were downloaded from global climate data (http://www.worldclim.org) which conisted of 19 bioclim variables and altitude. Slope and aspect of the study area were calculated using ArcGis V9.0. For the future projections we used climatic layers from the general circulation model HADCM3 for two SRES emission scenarios A1B and A2A. All layers were at a resolution of 30 arc seconds (Hijmans et al. 2005). Pearson's correlation (Supporting file No 2) and variance inflation factors (VIFs) were calculated to check for multi collinearity among the selected predictor variables. The VIFs of predictor variables were calculated using R (package usdm, Naimi 2014). VIF is a measure of the inflated variances of a regression coefficient due to multi collinearity. Variables with high VIFs are known to affect the model bulidng adversely (Ranjitkar et al. 2014). Hence, for the final analysis we chose the variables with VIFs <5 which is also biologically relevant to include in the model (Table S1).

Ecological niche modeling

We used Maximum Entropy (MaxEnt) method to develop the ecological niche models. The maximum entropy (MaxEnt) approach estimates a species environmental niche by finding a probability distribution of a species occurrence that is based on a distribution of maximum entropy (with reference to a set of environmental variables) (Philips et al. 2006). MaxEnt was used with default settings with the following changes; 10 replicates of cross validation tests were done by changing the regularization multiplier from 0.5 to 2.5 (totally building five different models for the present conditions), maximum number of background points were set to 10,000. We did 5,000 iterations with convergence threshold set to 1×10^{-6}. Jackknife test was performed to evaluate the variable importance. We chose minimum training presence as the logistic threshold, since all the occurrence points used for the final model building were from primary data source. Model performances were evaluated using AUC (Area under curve). AUC is a threshold-independent metric that is used to measure the models ability to distinguish between random and background points, which is the area under the curve (AUC) of the receiver operating characteristic plot (ROC). The ROC plot has the false-positive error rate on the x axis (i.e. 1—specificity) versus the true positive rate on the y axis (Sensitivity) based on each possible value of threshold probability. It can range from 0.5 to 1.0 where a value of 0.5 can be interpreted as random predictions and values above 0.5 indicate a performance better than random. The best performing model for the present scenario was chosen to do projections for the future climate change scenarios. Future projections were made for the two scenarios A1B and A2A for the year 2080.

Data analysis

The effect of predicted climate change on P. nigrum distribution

For the future climate change prediction, we chose A1B and A2A scenarios (Nakicenovic et al. 2000). A2A is characteristic of scenarios with higher rates of greenhouse gas emissions in combination with higher sulphur and other aerosol emissions, whereas A1B scenario proposes a balanced technological change in the energy system (IPCC 2001).

We used the spatial analyst tool in ESRI ArcMap 9.0 to measure the niche centroid from present to future climate change scenarios. The distance and azimuth from niche centroid of the present scenario to the two climate change scenarios was measured using an online tool for finding terminal coordinates available with http://www.fcc.gov. For estimating the niche breadth, the inverse concentration method (Levin 1968) was used, and the niche overlap (Schoener's D as per Schoener 1968) was calculated using the software ENM Tools v1.3 (Warren et al. 2010). We also calculated the number of pixels predicted to be suitable by MaxEnt modeling algorithm in three different scenarios across different latitudes. The final maps were developed using the software ArcMap V.9.0. The graphs were created using the packages *ggplot2* and *grid* in R software (R core team 2012, see supplementary file for the scripts). A multivariate environment similarity surface (MESS) analysis was perfomed to check the realiablity of future predictions, which suggests where the future models can be most uninformed (Elith and Leathwick 2009). Simlarly, the most dissimilar variables (MOD) analysis was perfomed to determine the variable leading to the prediction of novel climatic conditions.

Results

Model performance and importance of predictor variables

The final set of variables after VIF tests consisted of 6 bioclimatic and 4 topographic variables. The bioclim variables are mean temperature of coldest quarter (Bio11), precipitation seasonality (Bio15), precipitation of driest quarter (Bio17), precipitation of warmest quarter (Bio18) and precipitation of coldest quarter (Bio19). The four topographic variables consists of altitude, slope, northness (cosine) and eastnesss (sine) of the aspect variable. All the variables used for this analysis were treated as continous variables.

Jackknife tests illustrate that temperature seasonality (Bio 4) had a major contribution to the models (Fig. 1). The response curves in Fig. 2 illustrates the change in occurrence probability values of *P. nigrum* with respect to key climatic and topographic variables (top contributing variables are represented in Table 1). The habitat suitability was found higher towards lower values of temperature seasonality (Bio 4) (Fig. 2a), which suggests that highly suitable areas of *P. nigrum* are in climatically stable areas of Western Ghats. Similarly, probability values also peaked around higher values of precipitation of coldest quarter (Bio19), precipitation of the driest quarter (Bio17) and precipitation of the warmest quarter (Bio18) (Fig. 2b, c, d), which indicates the importance of precipitation in determining the distribution of *P. nigrum* in the Western Ghats. Precipitation seasonality (Bio15) (Fig. 2e) also had an influence on the model.

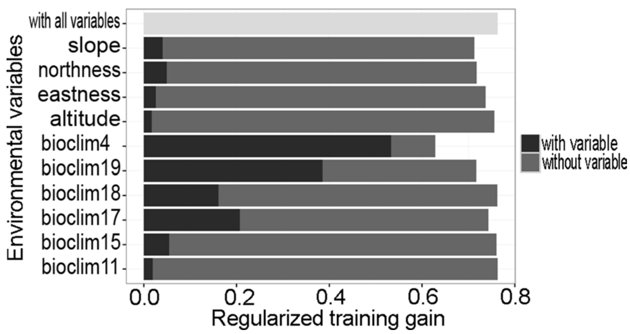

Fig. 1 Jacknife test of regularized training gain for *P. nigrum*

Predicted range of *P. nigrum* in current and future scenarios

Based on the cross validations tests, the model which had a default regularization multiplier was chosen as the best performing model due to its low omission rates (0.14) and also after a visual inspection of the MAXENT maps and the response curves. The best model had AUC values >0.75 ($AUC_{TEST} = 0.89$ (±0.009) $AUC_{TRAIN} = 0.75$ (±0.3)) for 10 replications, which suggests that the models are potentially useful (Phillips and Dudík 2008) (See supporting information figure S4). The final models were converted to distribution maps where the light shade to the darker shades corresponds to different habitat suitability categories (Fig. 3).

Fig. 2 Marginal response curves illustrating how the major environmental variables affect the suitability predictions for *P. nigrum*

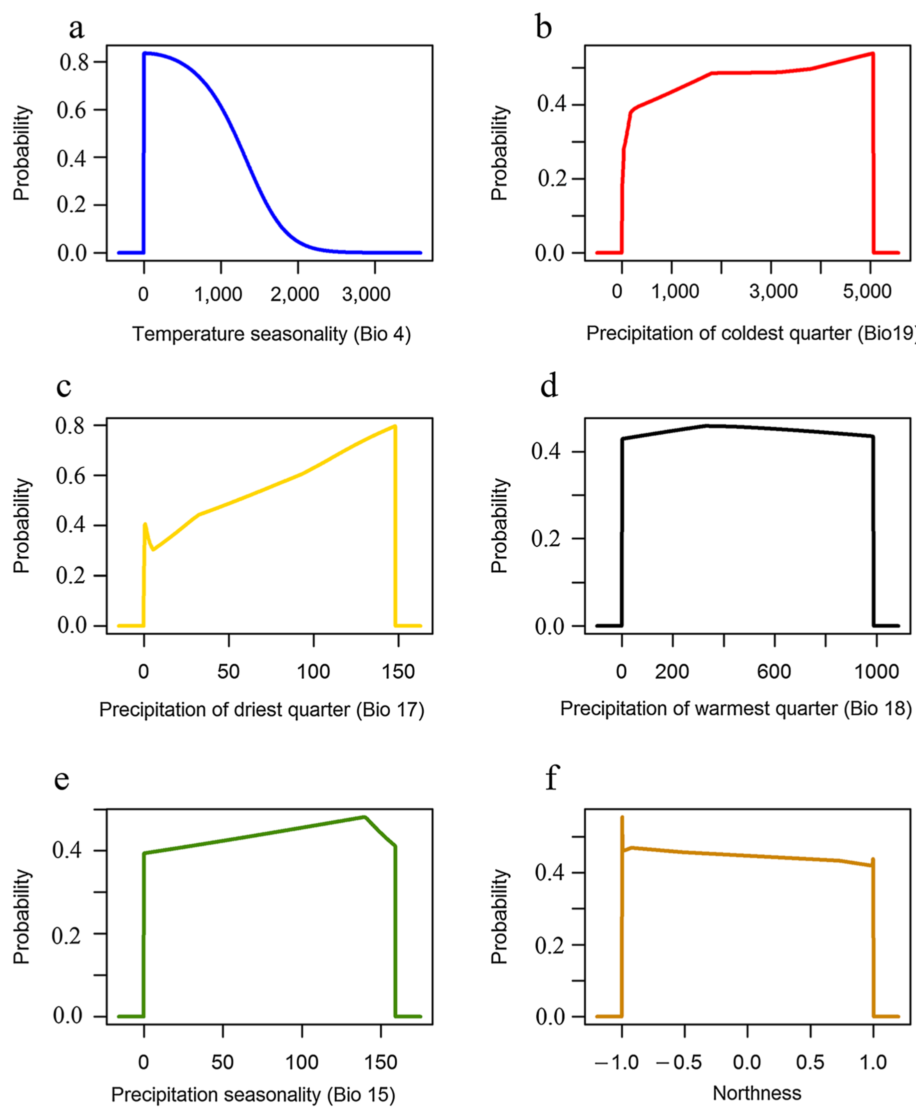

Table 1 Derived bioclimatic and topographic layers with its percent contribution and permutation importance to the selected model

Sl. no	Variable	Percent contribution	Permuataion importance
1	Altitude	1.1	4.4
3	Precipitation of coldest quarter	**53.3**	**7.7**
4	Temperature seasonality	**19.1**	**60.5**
5	Precipitation of driest quarter	**6.9**	**6**
6	Precipitation seasonality	0.8	1.4
7	Precipitation of warmest quarter	0.7	0.6
8	Mean temperature of coldest quarter	0.3	0
10	Slope	**6.8**	**9.1**
11	Northness	**7.1**	**5.4**
12	Eastness	3.9	4.1

Values of top five variables with maximum contribution are in bold

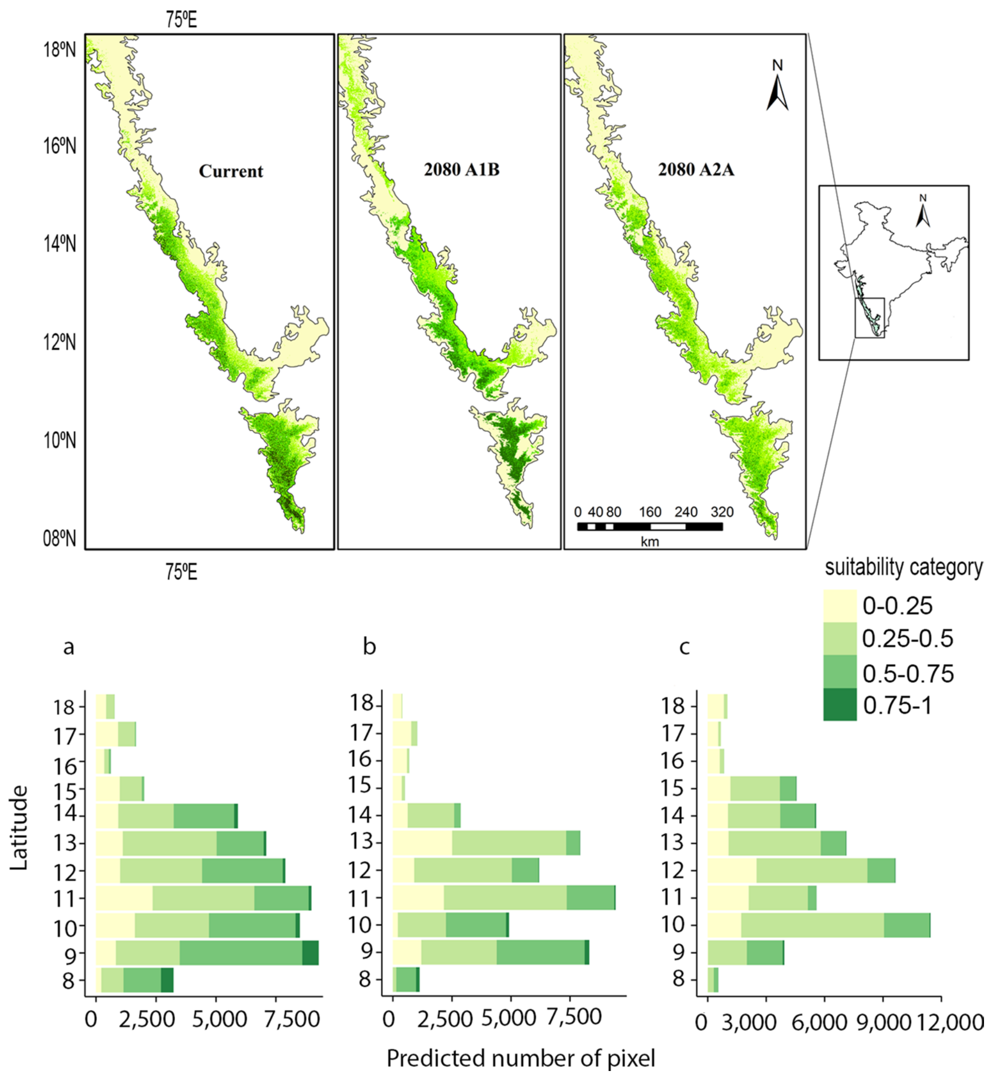

Fig. 3 Habitat suitability maps of *P. nigrum* in different climate change scenarios **a** present **b** A1B scenario **c** A2A scenario. Graphs adjacent to the maps (*a*, *b*, *c*) represent the predicted number of pixels across latitude under different suitability category

In the present scenario, the model predicted a total suitable area of 55,985 km^2 for *P. nigrum* while a reduction in the overall suitability area were observed in both the future scenarios. Under the A1B scenario, the model predicted 43,443 km^2 (reduction of 12,542 km^2 in the total area from present), A2B scenario predicted 50, 927 km^2 (reduction of 5,058 km^2 in the total area from present). The niche centroid of *P. nigrum* will undergo a directional change in both the

Table 2 Change in niche centroid, azimuth, niche breadth, distance from the niche centroid of the present scenario to both the future scenarios and niche overlap of *P. nigrum*

Scenario	Latitude	Longitude	Azimuth	Niche breadth	Distance (km)	Niche overlap
Present	11.967	76.002	0	14.51	0	1
A1B	12.130	76.0645	166.84	16.4	99.8	68.7
A2A	12.66	75.681	155.89	15.85	159.28	71.7

A1B scenario and A2A scenario from the present centroid as per the models. The niche overlap was found to be 68 and 71 percent, respectively for the future scenarios A1B and A2A compared to the present. The area with most favourable climate was found to be in Southern Western Ghats (Fig. 3; Table S2). The models also predicted an increase in niche breadth from present to both the future scenarios suggesting that the future climate change scenarios have an impact on the distribution of wild *P. nigrum* (Fig. 1 and Table 2). MESS surface predicted only few areas with noval climate across the range and the (most dissimilar variable) MOD map shows that, the novel climate conditions found was due to precipitation seasonality (Bio 15) and temperature seasonality (Bio 4).

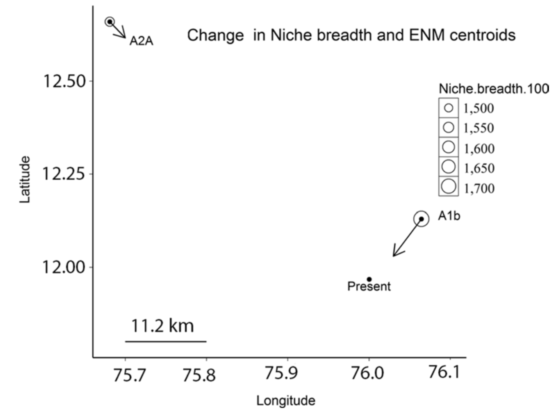

Fig. 4 Changes in niche breadth and ENM centroid. The points correspond to the position of the niche centroid in A1B and A2A scenarios for 2080. The size of *circles* is proportional to the niche breadth. The *arrows* represent the direction of centroid shifts in future scenarios from the present

Discussion

The ecological niche models developed in this study, suggested a reduction in the highly suitable habitats in the Southern Western Ghats in both the future climate change scenarios for the year 2080. There is also a directional shift in the niche centroid of *P. nigrum* in both the future scenarios. The shift was towards northeastern direction in the A1B scenario and towards northwest direction in the A2A, distance between the centroid varied in both the scenarios. A2A exhibited a greater shift compared to A1B as expected (Fig. 4). A meta analysis by Warren et al. (2013) had demonstrated that without proper mitigation strategies, larger range contractions can be expected even in the commonest and widespread species, which can create a substantial loss in global biodiversity. *Piper nigrum* is known as the king of the spices, and is one of the most important and widely used spices in the world (Ravindran 2000). The Western Ghats is reported to be the center of origin of *P. nigrum* and the region has high varietal diversity (Ravindran 2000). It is projected that the global consumption of black pepper could reach up to 280,000 m tonnes by 2020 (Ravindran 2000). Given this scenario, conserving wild varieties of *P. nigrum* would be important for utilizing the genetic resources for the future breeding programs. Effective conservation measures can be taken by using the model prediction in conjunction with the distribution map of wild varieties of *P. nigrum*. Understanding spatial genetic structure and gene flow patterns of wild *P. nigrum* can further improve conservation efforts.

A marginal increase in rainfall is predicted in the A2A and A1B scenarios within the Western Ghats (Krishna Kumar et al. 2011; Lal et al. 2001; Rupa Kumar et al. 2006). Our models also show the importance of different precipitation variables in determining the distribution of *P. nigrum* in the present and future climate change scenarios. In this context, the predicted increase in rainfall in the Western Ghats in the future and variability in the monsoon (Shukla 2003) can be very decisive in the future distribution of *P. nigrum*. Our study suggest that there are variations in habitat suitability of *P. nigrum* across latitudes in the future scenarios, which need to be investigated in further detail.

Comparison of present day plant distributions with future predictions is useful for formulating conservation strategies in understanding the responses of species to anthropogenic climate change (Russel et al. 2014; Warren et al. 2013). Areas of habitat loss can be targets for collection, characterization and estimation of existing and new wild genotypes of *P. nigrum*. Our study demonstrates the impact of climate change on distribution of wild populations of *P. nigrum* and this must be considered before developing protocols for conservation or ecological restoration (Gaston and Gracia-Vinas 2013; Geviz-Gelviz et al. 2015; Harris et al. 2006). However, our conclusions must be taken cautiously considering the shortcomings of the ENMs. Even though MaxEnt is effective in predicting the niche of a species using presence only points (Baldwin

2009), some caveats exist. They are issues in over-fitting and not using known absence records (Peterson et al. 2007). Land use change is one factor, which will affect species distribution synergistically along with the climate change induced niche shifts (Visonti et al. 2011). We also acknowledge that there are several levels of uncertainities while developing the climatic layer which can influence the conclusions of the study (Lal et al. 2001). Overall, based on the current study we recommend detailed surveys for mapping of valuable domestication traits in the predicted suitable areas in the Western Ghats.

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