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Cover: Common Silverline *Spindasis vulcanus vulcanus* in poster colours adapted from photograph by Kalpesh Tayade. © Pooja R. Patil.

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COMMUNICATION

Species distribution modeling of a cucurbit *Herpetospermum darjeelingense* in Darjeeling Himalaya, India

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Abstract: *Herpetospermum darjeelingense* (C.B.Clarke) H. Schaef. & S.S. Renner is a rare cucurbit found in Darjeeling, Himalaya. It is known for its use as food and medicine with possible pharmaceutical applications. Here we assess the current and future habitat suitability of *H. darjeelingense* in the study area using MaxEnt modeling. In order to obtain accurate results for future models, the ensemble method was used. The current suitable habitat covers only 13% of the study area, while the future models for 2050 and 2070 show zero habitat suitability for the species. This strongly indicates a possible local extinction of the species indicating a need for rapid and decisive conservation efforts.

Keywords: BioClim, climate change, ecology, elevation, ensemble, habitat suitability, MaxEnt, population, taxonomy, vulnerable.

Abbreviations: AUC—Area Under the Curve | CCSM4—Community Climate System Model 4 | CMIP5—Coupled Model Intercomparison Project 5 | GCM—General Circulation Model | GFDL-CM3—Geophysical Fluid Dynamics Laboratory- Climate Model 3 | IPCC—International Panel on Climate Change | LPT—Least Presence Threshold | MIROC5—Model for Interdisciplinary Research on Climate 5 | RCP—Representative Concentration Pathways | ROC—Receiver Operating Curve | SDM—Species Distribution Modeling | SEM—Scanning Electron Microscopy | TSS—True Skill Statistic.

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Author details: D. Boral is a research scholar under the guidance of SM. Her research work focuses on the taxonomy and distribution modeling of rare and threatened plants from Darjeeling Himalaya. Dr. S. Moktan is a faculty in the Centre of Advanced Study, Department of Botany, University of Calcutta. Areas of interest in research include taxonomy, ecology, biodiversity and conservation.

Author contributions: DB—field data collection, data analysis, writing original draft; SM—conceptualization, reviewing, editing and supervision.

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INTRODUCTION

The Himalaya biodiversity hotspot is one of the 36 currently recognised by CEPF (2021). The eastern region of the hotspot stands out in its global significance as it contains several centres of plant diversity (CEPF 2005). The complex landscape of the region has contributed to its floristic diversity, which includes several threatened plants (Kandel et al. 2019). In particular, the political boundary of India harbours an estimated 5,800 species of plants from the eastern Himalaya (Pande & Arora 2014).

The Darjeeling Himalaya is a part of the extension with its characteristic vegetation & landscape (CEPF 2005). Some of the major threats to this region include rapid urbanisation and climate change (Pandit et al. 2014). The impact of climate change on plants results in changes in phenology (Hart et al. 2014) and geographic ranges (Gómez-Ruiz & Lacher Jr. 2019). A distinctive pattern of upward altitudinal shift is also observed in mountainous regions (Dullinger et al. 2012). Another impact of climate change includes invasion by alien species which are hardier and more competitive (Pandit et al. 2014).

As the effects of climate change become more drastic, there is an urgent need to study consequences for significant species such as *H. darjeelingense,* which have vulnerable status. SDM functions on the principle of comparing the environmental conditions of the known location of the species to novel climatic conditions (Pearson 2007). Several different algorithms have been developed to model species distribution, such as MaxEnt (Elith et al. 2011), BIOCLIM (Beaumont et al. 2005), and GARP (Peterson et al. 2007). The accuracy of each modeling system is dependent on the sampling size and ecology of the species. Ultimately, species distribution models are an effective tool that can provide focus to possible practical applications (Hernandez et al. 2006). Among these tools, MaxEnt has been used widely for many different species such as *Picrorhiza kurroa* Royle ex Benth. (Chandra et al. 2021), *Podophyllum hexandrum* (Royle) T.S. Ying (Banerjee et al. 2017), *Rhododendron niveum* Hook.f. (Chhetri & Badola 2017) and including vulnerable species such as *Ornduffia calthifolia* (F.Muell.) Tippery & Les*, O. marchantii* (Ornduff) Tippery & Les (Ball et al. 2020), and *Lavatera acerifolia* Cav. (Villa-Machío et al. 2020). MaxEnt uses presence-only data to create a probability map predicting the distribution of a species across a spatial dimension (Elith et al. 2011). Thus, the objectives of the present study were to: i. characterize the taxonomy and habitat ecology of the taxa in Darjeeling Himalaya and, ii. identify current and future potential habitat and environmental variables determining distribution.

MATERIALS AND METHODS

Study Area

The study encompassed the Darjeeling Himalayan region that extends between 27°13'10"–26°27'05'' N & 88°53'–87° 30'' E covering an altitudinal range between 130–3,636 m in the lap of the eastern Himalaya hotspot. The region is bordered by Bangladesh to the south-east, Nepal to the west, and Bhutan to the east. The region is also flanked by the state of Sikkim (Figure 1).

As an extended part of the Himalayan hotspot, the region boasts several types of vegetation ranging from tropical to sub-alpine (Das 1995). A combination of topography & climate along with its location makes the region floristically diverse. The region harbours vegetation of Indo-Chinese, Indo-Malaysian, and western Himalayan origin including rare species such as *Gastrochilus corymbosus* A.P. Das & Chanda, *Liparis tigerhillensis* A.P. Das & Chanda, *Globba teesta* S. Nirola & A.P. Das to mention a few (Nirola & Das 2017).

The Species

The present study uses MaxEnt to explore the distribution of *Herpetospermum darjeelingense* (C.B.Clarke) H. Schaef. & S.S. Renner, a member of the family Cucurbitaceae in Darjeeling Himalaya (Image 1). The genus *Herpetospermum* comprises of four known species found restricted in the Himalaya and southeastern Asia (POWO 2021), of which three are found in the Darjeeling Himalayan region (Renner & Pandey 2013). *H. darjeelingense* (syn. *Edgaria darjeelingensis* C.B. Clarke) is one of the species found in the eastern Himalaya (Renner & Pandey 2013). The presence of this species has been recorded in Bhutan (Grierson & Long 1991), southern China, and Nepal (Renner & Pandey 2013). In India, the species is distributed sparsely in the states of Sikkim and Arunachal Pradesh. Threat search classified the species as Vulnerable in 2017 (BGCI 2021).

Species Occurrence Data

The occurrence points were gathered through a field study conducted during 2019–2020 within the Darjeeling Himalaya. The coordinate points in the locations were recorded using Garmin eTrex H. The collected coordinates were first converted to decimal degrees and then thinned using spThin package in R in order to

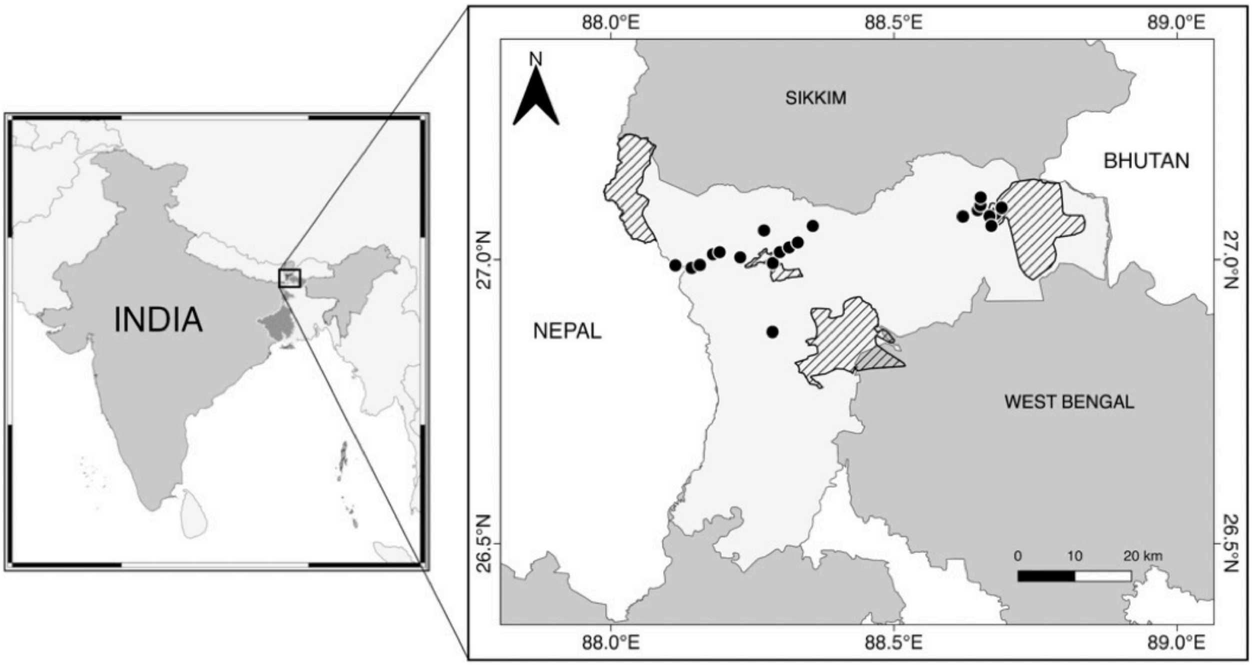

Figure 1. Study area. Shaded area indicates protected areas; black dots indicate occurrence points.

remove duplicates and to remove any coordinates with a distance of less than 1 km between them. The resulting 21 coordinates were used for modeling suitable habitat. The taxonomy of the species was studied through the collection of voucher specimens. Pollen grains were collected from the partially opened bud, and the process of acetolysis was followed (Erdtman 1960) and thereby, SEM observations were made. The population of the species was assessed along with its habitat ecology and the associated species.

Environmental variables

Elevation data were sourced at 30-arc second (~1 km^2) resolution from WorldClim 2.1 (Fick & Hijmans 2017). From this, slope and aspect data were generated using QGIS 3.4 Madeira software in ASCII format. The elevation, slope, and aspect constituted the three topographic predictors used in this paper. The current bioclimatic variables were obtained from WorldClim 2.1 at 30-arc second (~1 km^2) resolution (Fick & Hijmans 2017). The future bioclimatic variables were based on CMIP5, obtained from WorldClim 1.4 (Hijmans et al. 2005). The selected dataset were the GCMs (General Circulation Models) GFDL-CM3 (Griffies et al. 2011; Chaturvedi et al. 2012), CCSM4 (Meehl et al. 2012; Purohit & Rawat 2021) and MIROC5 (Watanabe et al. 2010) for years 2050 & 2070 for three different Representative Concentration Pathways (RCPs), RCP 2.6, RCP 4.5, and RCP 8.5. The RCP 2.6, RCP 4.5, and RCP 8.5 represent three different carbon emission levels (IPCC, 2014). All data were trimmed to the appropriate size and converted to ASCII format using QGIS 3.4 Madeira.

Modeling Procedure

First, highly correlated variables (variables with Pearson's coefficient *r* value > 0.9) were identified and removed using ENM Tools 1.3 (Warren et al. 2010) (Figure 2). The remaining list of environmental variables is given in Table 1. Overall, seven bioclimatic variables and three topographic variables, i.e., elevation, slope, and aspect, were used for modeling. Models were run on MaxEnt ver.3.4.1 (Phillips et al. 2006). As there were merely 21 occurrence points, only linear and quadratic features were applied. Five replicated models were run using the random test percentage of 25% (Srivastava et al. 2018; Qin et al. 2020). For predictions based on future climate, current occurrence data was projected onto future climactic variables. These were from the datasets GFDL-CM3, CCSM4, and MIROC5 for years 2050 & 2070; for RCP 8.5, 4.5 & 2.6. This resulted in 18 different future models to consider. An ensemble approach was applied wherein; the three different models from each GCM for each RCP of a particular year were combined (Araújo & New 2007; Khanum et al. 2013).

Model Validation

The area under the curve (AUC) values were used to assess individual models. Along with AUC, models were

Table 1. Site characteristics of *Herpetospermum darjeelingense* in different habitats.

Latitude (N)	Longitude (E)	Altitude (m)	Aspect	Slope (◦)	Habitat	Population
26.99395	88.28557	2449	SW	0–15	Hilly slope	5
27.00408	88.22867	2176	SE	15–30	Roadside	1
27.05187	88.27033	1830	NE	15–30	Roadside	5
26.98553	88.1428	2246	SE	15–30	Roadside	1
26.99013	88.1141	2170	SW	15–30	Hilly slope	3
26.9908	88.15693	2197	SE	0–15	Hilly slope	3
27.00958	88.17978	2151	SE	15–30	Hilly slope	8
27.01318	88.19185	2188	SE	15–30	Hilly Sslope	23
26.87283	88.28515	1457	SW	15–30	Jhora	1
27.01334	88.29806	2134	SE	15–30	Roadside	2
27.02173	88.31473	1951	SE	15–30	Roadside	4
27.03048	88.3302	1799	SE	30–45	Stream bank, Hilly slope	8
27.0599	88.3569	1628	NE	15–30	Hilly slope	7
27.0764	88.62195	1847	NE	30–45	Hilly slope	2
27.08777	88.64798	2079	SE	15–30	Hilly slope	3
27.08153	88.67965	2219	SE	0–15	Hilly slope	5
27.09168	88.69067	1910	SW	15–30	Hilly slope	1
27.09618	88.6527	2150	NE	15–30	Hilly slope	4
27.10963	88.65315	1938	NE	15–30	Scrub	1
27.07688	88.66888	2090	SW	15–30	Scrub	1
27.06005	88.67223	1772	SW	15–30	Hilly slope	4

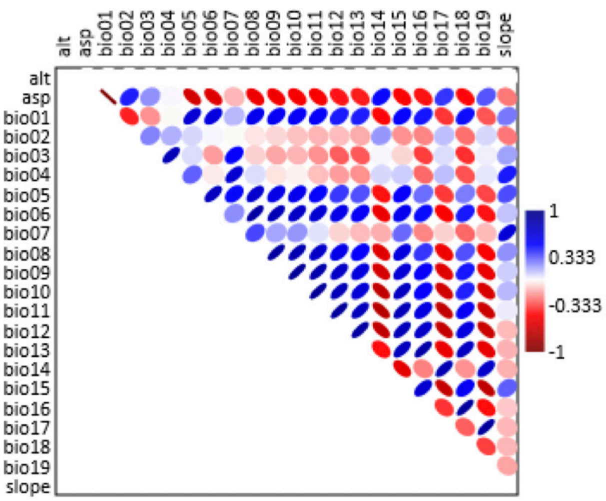

Figure 2. Pearson correlation of independent variables. Dark blue represents correlation > 0.9).

also appraised by true skill statistic (TSS) values (Allouche et al. 2006). TSS values were calculated for each model iteration with the lowest presence threshold (LPT). The value of LPT is equal to the lowest probability at a species occurrence point. LPT thus excluedes all areas that are at least not as suitable as locations where the species occurred (Pearson et al. 2007).

RESULTS

Taxonomy and Ecology of *H. darjeelingense*

H. darjeelingense is described as being an annual with a climbing habit, bifid tendrils, deeply cordate-ovate, and unlobed leaves. The leaves were pubescent with undulate and denticulate margin. The plant is dioecious with male flowers being paired. Bracts are absent or inconspicuous. Both male and female flowers have elongated calyx tube, teeth subulate; corolla is rotate, bright yellow, with deep lobes. Male flowers carry three stamens, anthers connate, single-celled. Female flowers are solitary, with ellipsoid ovary, three stigmas. Fruits are broadly fusiform, carrying about three-six seeds. SEM analysis of the pollen grains revealed that they are spherical, triporate, with distinctly spinous exine (Image 1).

Ecologically, the species is found to grow on roadsides, hilly slopes, stream banks, jhoras, and scrubs

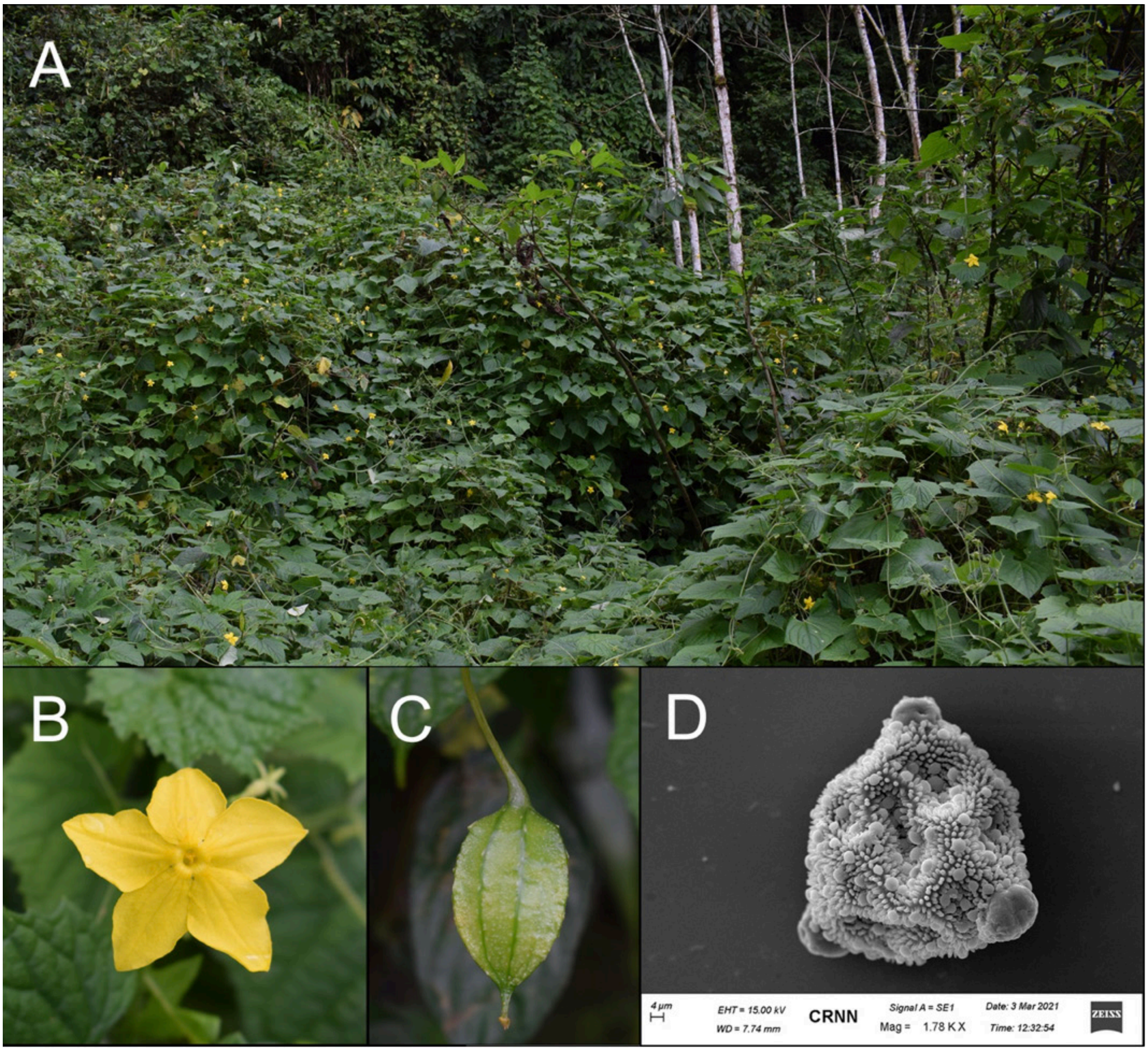

Image 1. *Herpetospermum darjeelingense*: A—Habit and habitat | B—Flower | C—Fruit | D—Pollen grain under SEM. © D. Boral.

Table 2. Variables used for species distribution modeling in MaxEnt.

Variable abbreviation	Variable Name	Units
BIO02	Mean diurnal range	°C
BIO03	Isothermality	%
BIO07	Temperature annual range	°C
BIO11	Mean temperature of coldest quarter	°C
BIO15	Precipitation seasonality	mm
BIO18	Precipitation of warmest quarter	mm
BIO19	Precipitation of coldest quarter	mm
ALT	Altitude	m
ASPECT	Aspect	NA
SLOPE	Slope	(°)

within an elevation range of around 1,400–2,600 m. The associated species in the niche includes major trees like *Magnolia cathcartii* (Hook.f. & Thom.) Noot., *Symplocos glomerata* King ex Clarke, *Alnus nepalensis* D. Don, and *Cryptomeria japonica* (Thunb. ex L.f.) D. Don. The associated undershrubs are *Tetrastigma serrulatum* (Roxb.) Planch., *Aconogonon molle* (D. Don) Hara, *Boehmeria macrophylla* Hornem., *Yushania maling* (Gamble) Majumdar & Karth., *Ageratina adenophora* (Spreng.) King & Rob, *Girardinia diversifolia* (Link) Friis, while the ground covers include *Galium elegans* Wall. ex Roxb., *Strobilanthes divaricata* (Nees) T. Anders., *Persicaria chinensis* (L.) H. Gross, *Drymaria cordata* (L.) Willd. ex Schult., *Pouzolzia hirta* Blume ex Hassk., *Lecanthus peduncularis* (Wall. ex Royle) Wedd., and species of *Pilea*. It is difficult to tally number of individuals of *H. darjeelingense* as it has climbing/creeping habit and thus in some cases forms dense sprawling clumps. The site characteristics revealed 48% of the population was distributed towards south-east, followed by south-west with 28% and north-east with 24% aspect location. Majority of the populations was distributed on the hilly slope with around 15°–30° inclination followed by roadside while only few populations were distributed at steep habitat.

Reportedly, *H. darjeelingense* is used both as food (Mueller-Boeker 1993) and as medicine to treat cattle (Shrestha & Khadgi 2019), traditionally among different communities from the Himalayan belt. A recent study also reports the presence of 13 antioxidants from leaf material, indicating the pharmaceutical potential of the species (Chakraborty et al. 2021). The species is classified as Vulnerable (BGCI 2021) regionally in China. However, information regarding its current status in the study area is scant.

Habitat Suitability for Present Day

The different variables used for predicting suitable habitat for *H. darjeelingense* included temperature,precipitation data, altitude, slope, and aspect. The present-day model with the predicted suitable habitat is shown in Figure 3 along with the ROC curve and the jackknife in Figure 4. The current model performed very robustly with the AUC value at 0.986 and the TSS value 0.948. The potential distribution of *H. darjeelingense* was stretched over an area of 416.25 km^2 (13.21%) after application of LPT. The percentage of contribution is highest for the bioclimatic variable mean temperature in the coldest quarter (BIO11) at 61.2 %, followed by precipitation of seasonality (BIO15) at 24.5%, mean diurnal range (BIO02) at 4.4% and precipitation of warmest quarter (BIO18) at 4.4%. The jackknife also reveals that BIO11 is the most important environmental variable while the other influential variable according to the jackkife is precipitation of seasonality (BIO15) (Figure 4b).

Response to Variables

The species response curve of *H. darjeelingense* to each variable is depicted in Figure 5. The probability of the presence of the species increases with ALT sharply peaking at 2,000 m (Figure 5a) with the range 1,500–3,000 m. The altitude of almost all sample points fell within this range. For aspect, the response increases with an increase in degree (Figure 5b). For BIO02, BIO03, BIO18, response decreases with increase in variable while, the response increases as BIO15 increases. For BIO11, suitable habitat requires a mean temperature ranging from 5°C–12°C in the coldest quarter. For BIO19, suitable habitat required mean precipitation between 40–90 mm for the coldest quarter.

Habitat Suitability for Future Models

The six future ensemble models have an AUC value ranging from 0.99–0.985. The TSS value ranges from 0.903–0.944. The highest percentage of contribution is mean temperature in the coldest quarter (BIO11) for all six ensemble models. Similarly the altitude (ALT) has the highest permutation of importance for both the current and future models. The jackknife shows some difference in the results for the future models where ALT has the highest training gain when used in isolation in some models while mean temperature in the coldest quarter (BIO11) has the highest training gain when used in isolation in other models. The prediction accuracy details of the individual models, along with the ensemble models, are given in Table 3. After the LPT value (0.49) was applied for all future models, probable spatial distribution was 0 km^2 for all.

DISCUSSION

The present study explores the ecological status and assesses the habitat distribution of *H. darjeelingense* in current and future climate scenarios. Previous studies on other species have been conducted using MaxEnt, such as *Angelica glauca* Kitam. (Singh et al. 2020), *Rosa arabica* (Crép. ex Boiss.) Déségl. (Abdelaal et al. 2019), *Ixora* sp. (Banag et al. 2015), *Berkheya cuneata* (Thunb.) Willd. (Potts et al. 2013), *Acer cappadocicum* subsp. *lobelia* (Ten.) A.E. Murray (Sumarga 2011), *Pterocarpus santalinus* L.f. (Babar et al. 2012), *Aglaia bourdillonii* Gamble (Irfan-Ullah et al. 2006). MaxEnt has also been used to explore the distribution of endangered species such as *Dioscorea* sp. (Hills et al. 2019). MaxEnt is one of several modeling algorithms available for species distribution modeling. MaxEnt predicts probable distribution using presence-only data and a set of climatic grids generating output where each grid cell has a value ranging from 0 (least suitable) to 1 (most suitable) (Phillips et al. 2017). MaxEnt is also effective even with small sample sizes making it suitable for studying endangered species (Pearson et al. 2007). Concerning the performance of MaxEnt models, both AUC and TSS values were used. Swets (1988) classified model performance into failing (0.5–0.6), bad (0.6–0.7),

Table 3. Prediction accuracy with important variables of *Herpetospermum darjeelingense* models.

			AUC	TSS	Percentage contribution		Permutation importance		Jackknife training gain	
					Variable	Value	Variable	Value	In isolation	In absence
Current			0.986	0.949	BIO11	61.2	ALT	59.5	BIO11	BIO15
2050	RCP 2.6	CCSM4	0.988	0.946	BIO11	59.9	ALT	66.2	ALT	BIO15
		GFDL-CM3	0.987	0.942	BIO11	63	ALT	46.2	BIO11	BIO15
		MIROC5	0.987	0.933	BIO11	60.3	ALT	61.2	BIO11	BIO15
		Ensemble	0.987	0.94	BIO11	61.1	ALT	57.9	-	-
	RCP 4.5	CCSM4	0.985	0.957	BIO11	63.6	ALT	46.7	BIO11	BIO15
		GFDL-CM3	0.986	0.93	BIO11	63.6	ALT	56.8	BIO11	BIO15
		MIROC5	0.99	0.93	BIO11	57.9	ALT	43.7	BIO11	BIO15
		Ensemble	0.987	0.939	BIO11	61.7	ALT	49.1	-	-
	RCP 8.5	CCSM4	0.989	0.966	BIO11	60.3	ALT	57.8	BIO11	BIO15
		GFDL-CM3	0.989	0.946	BIO11	58.7	ALT	63.1	BIO11	BIO15
		MIROC5	0.985	0.921	BIO11	60.5	ALT	45.5	BIO11	BIO15
		Ensemble	0.987	0.944	BIO11	59.8	ALT	55.5	-	-
2070	RCP 2.6	CCSM4	0.988	0.954	BIO11	61.7	ALT	48.4	BIO11	BIO15
		GFDL-CM3	0.989	0.94	BIO11	56.3	ALT	60.7	BIO11	BIO15
		MIROC5	0.988	0.906	BIO11	61.5	ALT	52.7	ALT	BIO15
		Ensemble	0.988	0.933	BIO11	59.8	ALT	53.9	-	-
	RCP 4.5	CCSM4	0.988	0.926	BIO11	60.9	ALT	32	BIO11	BIO15
		GFDL-CM3	0.989	0.891	BIO11	62.5	ALT	48.9	BIO11	BIO15
		MIROC5	0.986	0.892	BIO11	61	ALT	54.8	BIO11	BIO15
		Ensemble	0.987	0.903	BIO11	61.4	ALT	45.2	-	-
	RCP 8.5	CCSM4	0.985	0.949	BIO11	59.4	ALT	61.6	BIO11	BIO15
		GFDL-CM3	0.988	0.955	BIO11	60.9	ALT	47.4	BIO11	BIO15
		MIROC5	0.988	0.918	BIO11	60.4	ALT	58.6	BIO11	BIO15
		Ensemble	0.987	0.941	BIO11	60.2	ALT	55.9	-	-

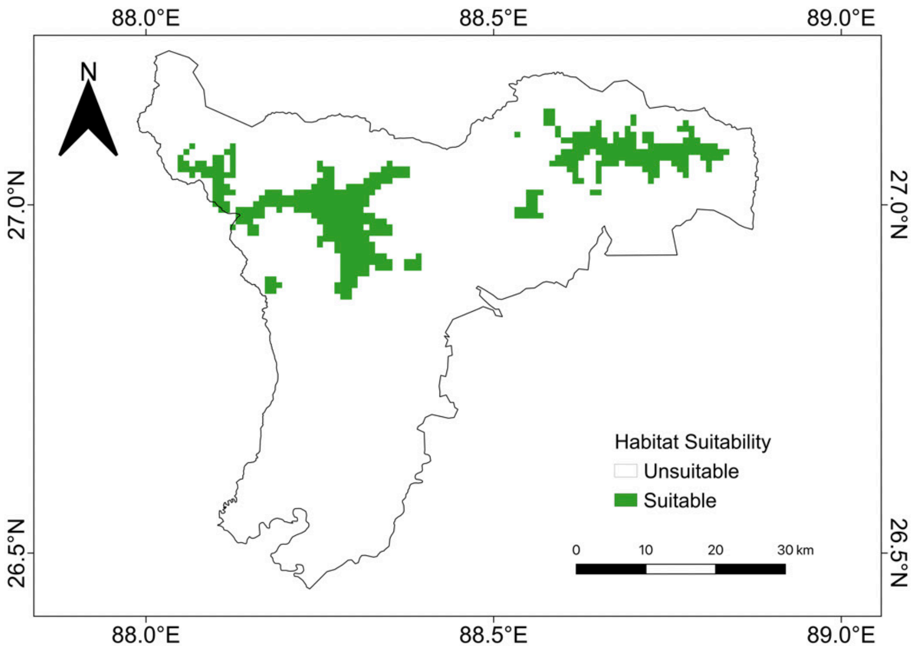

Figure 3. Current climate model of *Herpetospermum darjeelingense* showing potential distribution.

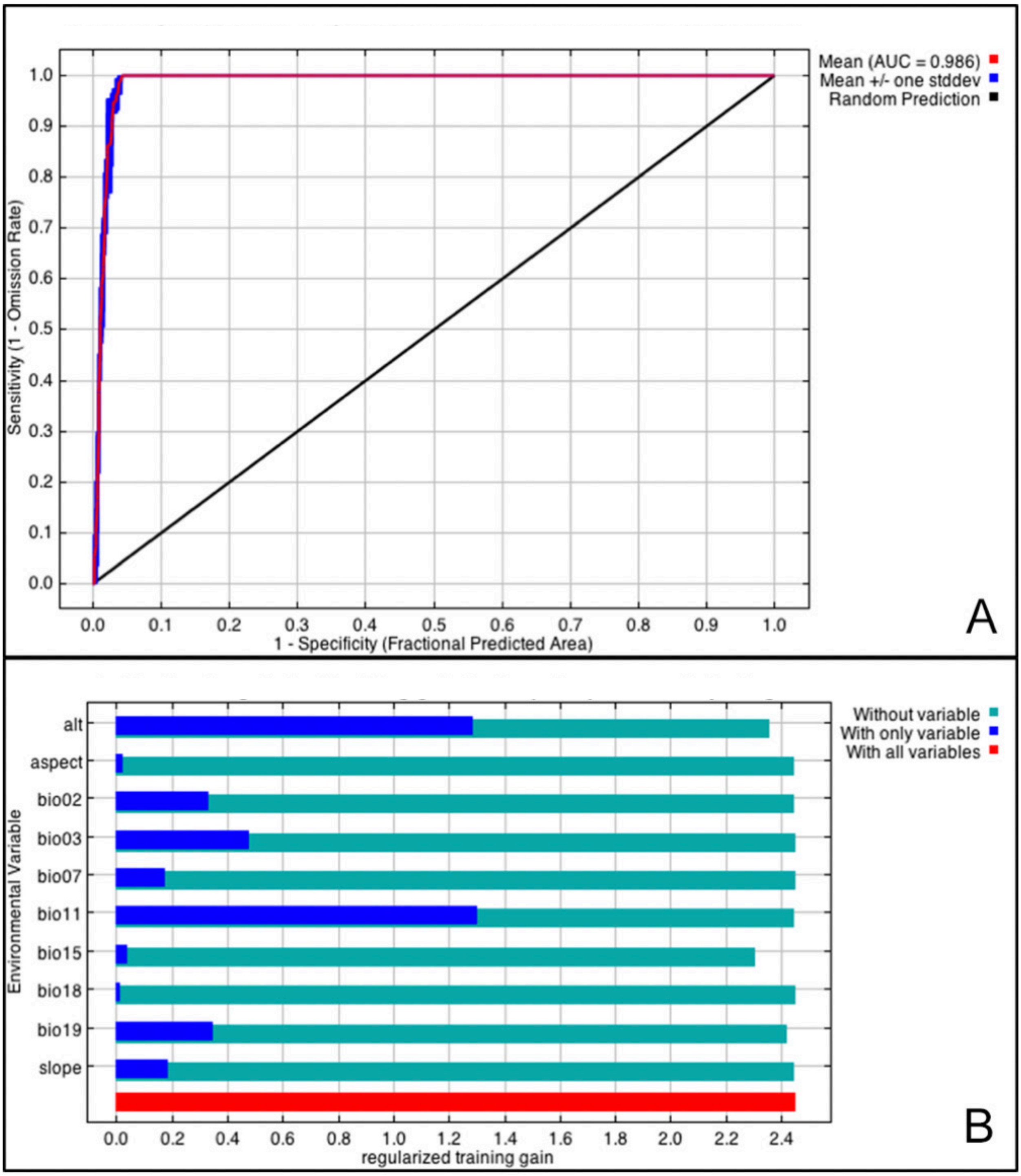

Figure 4. Current climate model of *Herpetospermum darjeelingense*: A—ROC Curve | B—Jackknife of regularized training gain.

reasonable (0.7–0.8), good (0.8–0.9), or great (0.9–1) based on AUC value. Like AUC, TSS also ranges from 0–1, with a higher value indicating a better-performing model (Allouche et al. 2006). The LPT was also used to prevent an over-fitted model. In the current study, only about 13.21% of the total study area was determined to be suitable habitat for *H. darjeelingense*. The current model was well-performing, with high AUC (0.986) & TSS (0.948) values.

The IPCC 5th assessment report (IPCC 2014) presents the projected climate in the future driven by anthropogenic carbon emissions. The report highlights

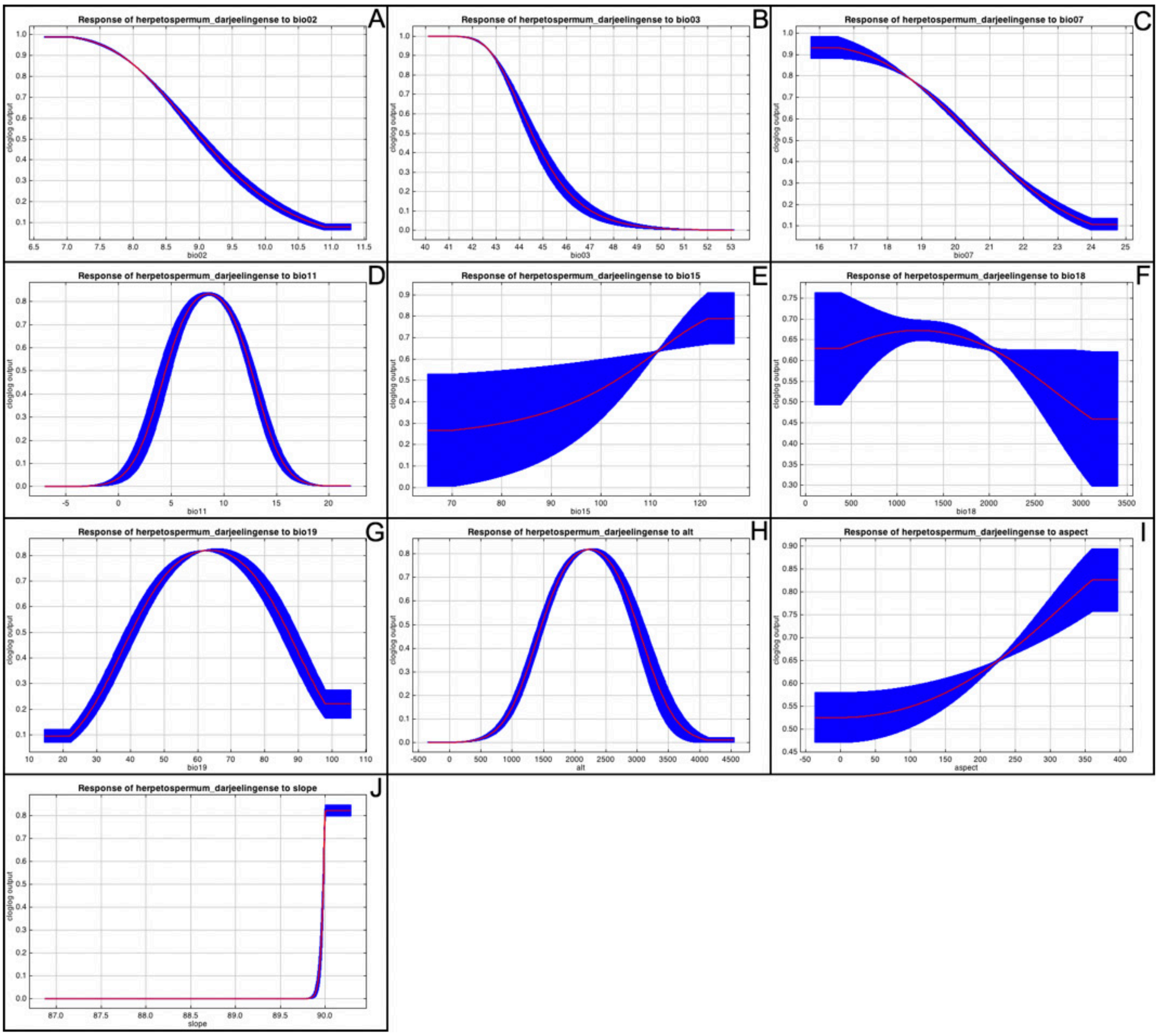

Figure 5. Response curves of *Herpetospermum darjeelingense*: A—BIO02 | B—BIO03 | C—BIO07 | D—BIO11 | E—BIO15 | F—BIO18 | G—BIO19 | H—Altitude | I —Aspect | J—Slope.

the projected scenarios based on the mitigation strategy applied. The RCPs 2.6, 4.5, and 8.5 represents scenarios where either stringent, intermediate or poor implementation of climate strategy occurred. As each GCM is published by separate research groups, it can make modeling future climate change tricky. Hence, the ensemble method as per Khanum et al. (2013) was applied which reduces the ambiguity of using a single GCM. Overall, all future models created using the ensemble method, which combines three different GCMs, show the probable complete disappearance of *H. darjeelingense.* Hence, no matter the climate change mitigation strategy, it is quite possible that the species under study might disappear from the study area by 2050. In the case of endangered species, a complete disappearance from the local environment can indicate further downstream effects on other plants. It should be noted that the results species distribution models, are based on extrapolation from available data and methods (Elith & Leathwick 2009). However, these models can provide valuable awareness of urgent future steps to be taken for the preservation of the species under study.

CONCLUSION

The present study highlights the probable suitable habitat of the cucurbit *Herpetospermum darjeelingense* in the future as well as the present day. The taxon that is often found along roadsides and hilly slopes make its current population vulnerable to habitat destruction due to anthropogenic pressure as well as natural catastrophes. This along with climate change can result in the complete disappearance of the species. MaxEnt modeling of the present-day scenario exhibits a narrow habitat range. Furthermore, future models show that regardless of the climate mitigation strategy, the species faces local extinction. Keeping in mind the availability of limited data on distribution coordinates and population status of the taxa including the rarity of the species in the present study, the taxa should be immediately assigned to Endangered in the IUCN Red List. Furthermore, an urgent requirement to investigate active in situ and ex situ conservation strategies through botanical gardens and local nurseries is of the utmost priority at this juncture because the taxon has both traditional and pharmaceutical potential. One possible method can include the collection of seeds for storage and germination.

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