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RESEARCH PAPER

Population ecology and influence of climate change on the distribution of a critically endangered medicinal plant *Lilium polyphyllum* in the Himalaya

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Abstract

Lilium polyphyllum is a critically endangered medicinal plant found in the Himalaya. Due to the loss of habitat and unregulated collection, the species is facing a serious threat, and there is a need to restore the drastically reducing populations. Therefore, the present study was conducted to assess the populations in the Himalaya and identify suitable habitats of *L. polyphyllum* under projected climate change for conservation. Nine populations/sites (50 × 50 m plot) were studied. The density of *L. polyphyllum* ranged from 0.23 to 2.50 Ind m^{-2}. *L. polyphyllum* density was very low, and it is positively correlated with the altitudinal gradient. In the current study, the MaxEnt algorithm, data on the occurrence of species, and environmental variables were used. Using the SSP370 and SSP245 climate scenarios of MIROC6 and BCC-CSM2-MR climate change models from the CMIP6 project for the period 2081–2100, species future distribution was predicted. MaxEnt predicted that the 2,42,573 km^2 area of the Hindu Kush Himalaya is conducive to the occurrence of *L. polyphyllum*. For both SSPs and GCMs, the distribution area expands as greenhouse gas concentrations rise. The areas where the probability of the species occurrence is highest can be used for in-situ conservation. Decision-makers and policymakers could develop effective management strategies by using the predicted species distribution maps.

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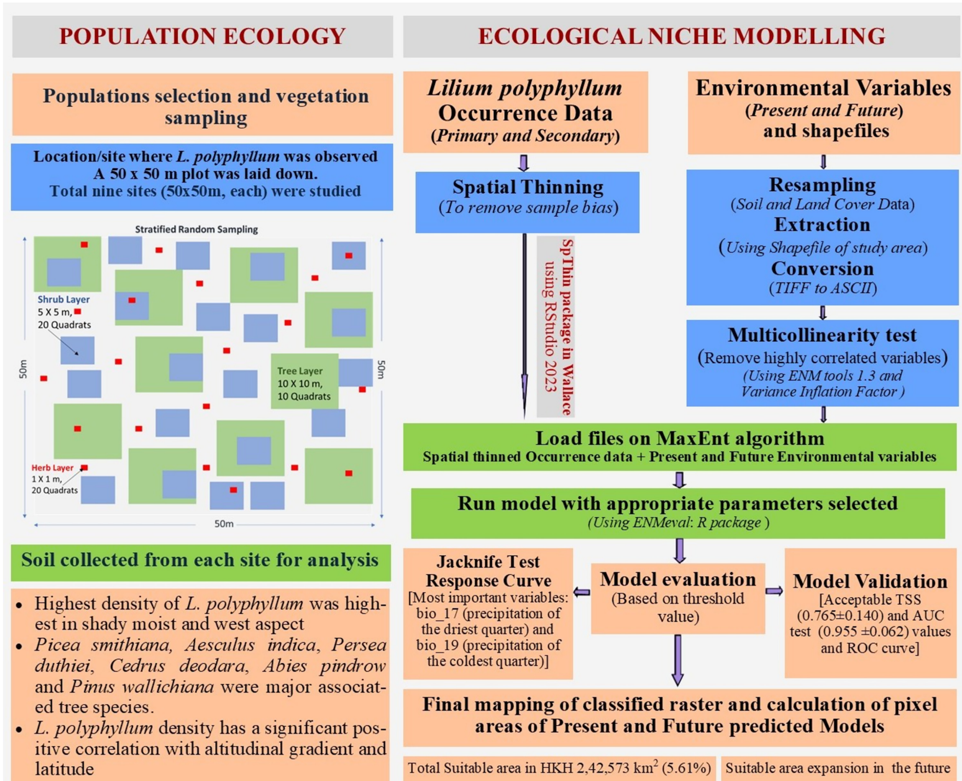
Graphical abstract



Keywords Hindu Kush Himalaya · Diversity · Population ecology · Ecological niche modelling · MaxEnt · Climate change · In–situ conservation

Introduction

Plants have been used by humans as medicine and for sustenance since prehistoric times. The demand for aromatic and medicinal herbs has surged globally with the increasing use of herbal-based treatment. Consequently, these plants are now key raw materials used in the production of both traditional and modern conventional drugs. The Himalaya is renowned for its valuable and rare medicinal herbs (Painuli et al. 2021). Among these medicinal herbs, *Lilium polyphyllum* D. Don (Kakoli, Ksheerkakoli) is a notable species (Fig. 1). *L. polyphyllum* is a Critically Endangered (Saha et al. 2015) medicinal plant that belongs to the family Liliaceae. It is distributed in Afghanistan, India and Pakistan between 1800–3700 m amsl. In the Indian Himalayan Region (IHR), this species has been reported from Jammu and Kashmir Union Territory (Khoja et al. 2023), Himachal Pradesh (Rana and Samant 2011b) and Uttarakhand (Phondani et al. 2009). The bulbs of *L. polyphyllum* possess astringent, anti-inflammatory and soothing properties. The preparations are used as antipyretic, aphrodisiac, refrigerant, diuretic, expectorant, galactagogue, tonic and for the treatment of cough, intermittent fever, respiratory disorder, seminal weakness, urinary hesitancy, vitiated conditions, vomiting of blood, burning sensation, chronic rheumatic pain and weakness (Devi et al. 2024; Khoja et al. 2022; Pant and Samant 2010; Rana and Samant 2011a, 2011b; Samant et al. 2007; Sourabh et al. 2018). The population status of *L. polyphyllum* has been studied by Rana and Samant (2011b) in Manali Wildlife sanctuary, Dhyani et al. (2018) in Uttarakhand; and distribution modelling by Rana et al. (2017) in Nepal, Sourabh et al. (2018) in Himalayan region and Mir et al. (2020a) in Jammu & Kashmir Union Territory under current environmental condition. Dhyani et al. (2021) projected a distribution map of the species in the Western Himalayan region using IPCC Representative Concentration Pathways (RCPs) 8.5 (harsh climatic conditions) and RCP 2.6 (less harmful) for the years 2050 and 2070. It is categorized as Critically Endangered by IUCN (Saha et al. 2015) and threatened by the Red Data Book of Indian Plants (Nayar and Sastry 1990) due to loss of habitat and unregulated collection. The fungus *Botrytis cinerea*, which causes

Fig. 1 Habitat, bulb and mature plants of *Lilium polyphyllum*

grey mould, is also affecting *L. polyphyllum* populations (Dhyani et al. 2012).

The identification of suitable regions for an organism under present and future circumstances is crucial for the protection of species, restoration of habitats, prevention of invasions, and anticipation of future consequences (Thuiller 2024). In general, there are three primary requirements, *i.e.*, successful dispersion over its biogeographic past, environmental factors that affect the species to inhabit a particular location that can sustain a population, and biotic conditions (absence of strong competitors and availability of resources) that promote species survival. Ecological niche models (ENMs) provide an efficient method for estimating species ranges, either by interpolating or extrapolating. Statistical and machine learning techniques are used to establish a connection between the observations of a species and environmental predictor factors. Based on the calculated species–environment connection, the probable distribution of the species can then be predicted when digital maps of the environmental factors are available (Zurell and Engler 2019).

The global distributions and shifts in the distributions of many species have been precisely predicted using ENM. By using correlative or mechanistic approaches to correlate geographical occurrence data with environmental parameters, the ENM can predict the ecological niches of species. Over the past ten years, there has been a substantial increase in the application of correlative ecological niche models (Dolci and Peruzzi 2022). In ENM, a variety of algorithms are available with a variety of data demands, user-friendliness and statistical techniques. Among them, the MaxEnt (Maximum–Entropy) algorithm is one of the most often used ENM tools (Campos et al. 2023). It is a machine-learning approach that needs both presence-only data and environmental predictors (Lhamo et al. 2023). Compared to other algorithms for modelling, it performs better with fewer sample sets. To ascertain the relative relevance of each predictor, MaxEnt produces response curves for each predictor variable and offers a Jackknife option (Li et al. 2022). The aforementioned studies suggest that the MaxEnt algorithm outperforms other models in terms of species distribution prediction accuracy. Therefore, in the present study, we predicted the *L. polyphyllum* distribution modelling using the MaxEnt algorithm.

The majority of research, especially for this species, is limited to ethnobotany or indigenous uses; some studies are available on the phytochemical analysis (Chinmay et al. 2011; Dhyani et al. 2023; Mir et al. 2021), but only a few research have looked into the species population ecology (Dhyani et al. 2018; Rana and Samant 2011a) and habitat suitability modelling for conservation (Dhyani et al. 2021; Mir et al. 2020; Sourabh et al. 2018). Mir et al. (2020)

studied habitat suitability modelling of *L. polyphyllum* for a small geographical region (*i.e*., Jammu & Kashmir, UT) of the Himalaya. Sourabh et al. (2018) predicted suitable habitats under present environmental conditions, and Dhyani et al. (2021) used the old Community Climate System Model and Representative Concentration Pathways (RCPs). Therefore, keeping in view the importance of species for mankind, the present study was conducted to; assess and map the populations of the species; study the physico-chemical properties of the soil; and develop Ecological Niche Model to generate predictive map of species distribution under changing climatic conditions. The study will help in understanding population status, major associated plant species, environmental conditions suitable for the occurrence of the species, and changes in area under changing climatic conditions, ultimately in developing strategy for conservation.

Material and methods

Study area

The present research on the quantitative assessment of the populations of *L. polyphyllum* was carried out in the state of Himachal Pradesh, India, from 2015 to 2020. The vegetation was surveyed and sampled in Kullu (05 populations), Lahaul & Spiti (03 populations) and Chamba (01 population) districts across 03 habitats (shady moist, grassland and rocky), between 31.570504 to 33.09132°N latitudes and 76.43053 to 77.44639°E longitudes, with topographic slope range from 30 to 55° and altitudes ranging from 2103–3316 m amsl (Table 1 and Fig. 2).

Population assessment

From 2015 to 2020, nine (9) *L. polyphyllum* populations were studied. At a location/habitat where the occurrence of *L. polyphyllum* was observed, a 50 × 50 m plot was laid out. To identify habitats, physical characteristics were used. We used randomly placed ten, 10 × 10 m quadrats to sample trees, shrubs with twenty, 5 × 5 m quadrats, and herbs with twenty, 1 × 1 m quadrats (Curtis and McIntosh 1950; Singh and Samant 2020). Standard ecological methods were used for data collection. Field data were analyzed to determine density, relative density, frequency, abundance and Basal Area (Misra 1968; Mueller-Dombois et al. 1974). The relative density of the selected species was used to identify the major associated species. Species diversity was calculated by using Shannon–Wiener's Information Statistic (H′) (Shannon and Weaver 1963) and Concentration of dominance (Cd) by Simpson's Index (Simpson 1949). The Circumference at Breast Height (CBH) of each tree was measured from 1.37 m above the ground. Individuals were considered as trees (31.5 cm and above), saplings (10.5–31.4 cm), and seedlings (10.5 cm), based on CBH. Samples of each and every species collected from each site were identified using the regional floras (Polunin and Stainton 1984; Singh and Rawat 2000).

Soil analysis

During the vegetation surveys and samplings in each plot, 5 soil samples (1 from the centre and four from the corners) were randomly obtained, mixed, and in airtight polythene bags, a composite sample of the homogenised soil weighing 200 g was collected and brought to the laboratory. The pH was measured with a pH meter in a 1:4 (w:v) suspension of soil in water. The Walkley and Black method was used to determine carbon and organic matter. Following digestion with concentrated H_2SO_4, total nitrogen (%) was determined using the Kjeldahl procedure (Singh et al. 2005). The physico-chemical characteristics (soil pH, moisture content, organic carbon, available phosphorus, available potassium and total nitrogen) of the soil for each populations were analysed using three replicates from composite samples by following Allen (1974).

Table 1 Site characteristics and dominant species of the *L. polyphyllum* populations in Himachal Pradesh, North Western Himalaya

Site	Habitats	Altitude (m)	Latitude (°N)	Longitude (°E)	Slope (°)	Aspect	Dominant species
Ratoli	Shady Moist	2853	32.7404	76.6195	50	North–West	*Picea smithiana* & *Cedrus deodara*
Salpat	Grassland	2625	32.7312	76.6385	45	North	*Viburnum cotinifolium* & *Rosa webbiana*
Rahuli	Grassland	2519	32.8152	76.4305	40	North–West	*Indigofera heterantha*
Takwas	Shady Moist	3316	33.0913	76.4519	40	West	*Viburnum cotinifolium*
Lapah	Shady Moist	2169	31.7831	77.4464	30	North–East	*Aesculus indica* & *Picea smithiana*
MWLS	Shady Moist	2319	32.2511	77.1663	40	North	*Picea smithiana*
KhWLS	Rocky	2312	31.8589	77.0981	55	North–West	*Picea smithiana*
Hirb -1	Shady Moist	2103	31.5747	77.3728	50	North–East	*Machilus duthiei*
Hirb- 2	Shady Moist	2235	31.5705	77.3780	40	East	*Aesculus indica*

m meter, *N* North, *E* East, ° degree

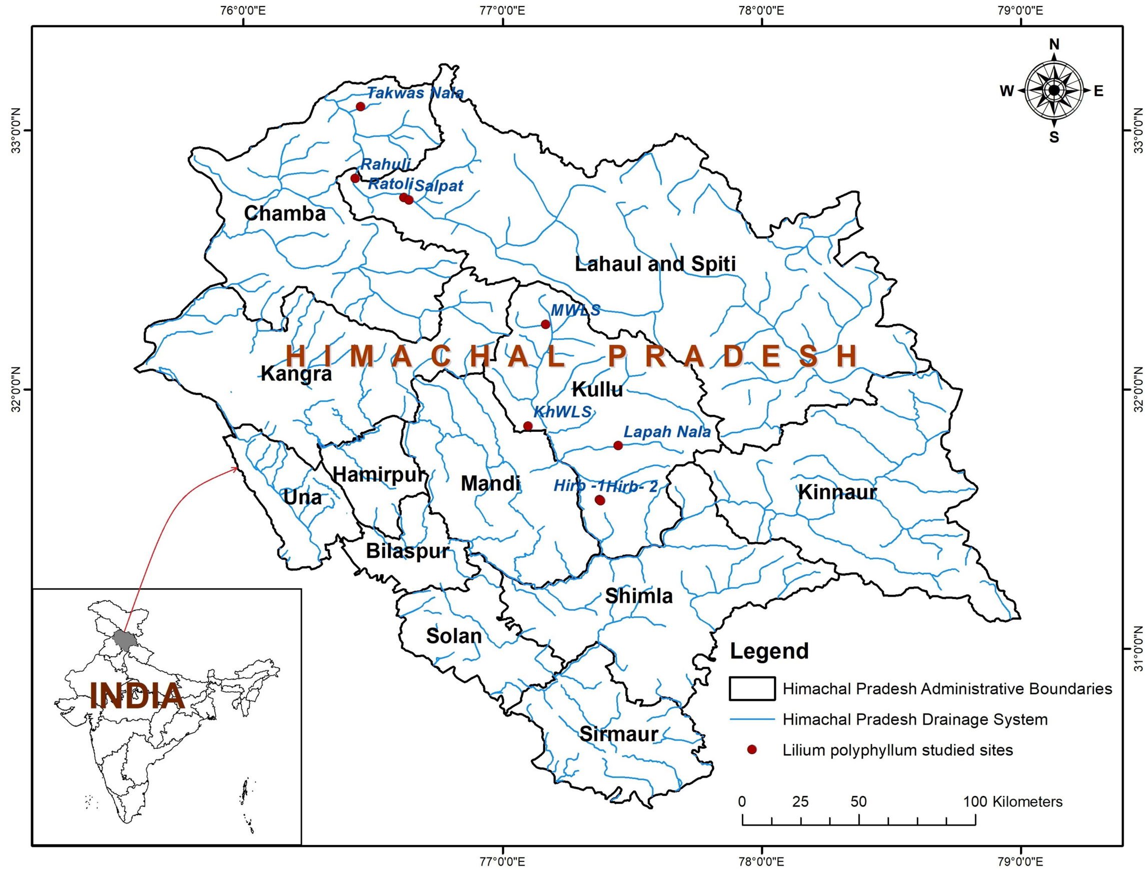


Fig. 2 Map showing study sites/populations of *Lilium polyphyllum* in Himachal Pradesh, North Western Himalaya

Ecological niche modelling

The current ecological niche modelling of *L. polyphyllum* has been carried out for the Hindu Kush Himalayan (HKH) region, characterized by its mountainous topography and varied regional climate, which spans eight nations; China, Afghanistan India, Pakistan Nepal, Bhutan, Bangladesh and Myanmar and covers an area of ~ 4.3 million km^2 (Gyamtsho 2021).

Species occurrence data

A literature review (Pragya et al. 2015; Dhyani et al. 2023), field surveys, and the Global Biodiversity Information Facility website (GBIF.org 2023) yielded a total of 43 distributional data points for the species (primary 9 and secondary 34). ArcGIS 9.2 was used to convert the gathered occurrence points into a KMZ (Keyhole Markup Language Zipped) file, which was then loaded into Google Earth, and duplicate and illogical points were removed. The Wallace(v2.0.5) SpThin package (Johnson et al. 2022) was used to spatially thin the 43 occurrence points to eliminate sampling bias (Chandora et al. 2023). This was done using RStudio 2023.06.0 Build 421 and R version 4.2.2 as the running base (Harman et al. 2024). Only 39 data points were left after SpThin at a 5 km distance that were used for ENM (Fig. 2).

Environmental variables

The Digital Elevation Model (DEM) and present (19 bioclimatic variables) and future climate data at the resolution of 30 arc-seconds (~ 1 km^2) were obtained from the www.Worldclim.org website (Fick and Hijmans 2017). For future climate data, we used two GCMs (Global Climate Models) *i.e.*, MIROC6 (Model for Interdisciplinary Research on Climate—Sixth version) and BCC-CSM2-MR (Beijing Climate Centre Climate System Model version 2) under two Shared Socioeconomic Pathways (SSPs) i.e., middle-of-the-road (SSP370) and optimistic (SSP245) climate scenarios for 2081–2100 period. The previous studies have demonstrated that these GCMs are most frequently applied in South Asia and exhibit the best performance in the Indian monsoon region (Bisht et al. 2016; Sun et al. 2021; Kunwar et al. 2023; Paul et al. 2023; Vinod and Agilan 2024). SSP245 and SSP370 were selected as two Shared Socio-economic Pathways (SSPs) to represent a medium-to-high scenario of future greenhouse gas emissions and to evaluate how diverse societal actions may result in differing climate change consequences (Kaky et al. 2020).

Data on slope and aspect were obtained from DEM using ArcGIS 9.2. Soil Data (30 arc-seconds) was obtained from the FAO soil portal (https://www.fao.org/soils-portal/). Data on land cover global (300 m) was obtained from the European Space Agency GlobCover Portal (Arino et al. 2012). Using the nearest neighbour interpolation approach in ArcGIS 9.2, soil and land cover data were resampled to the bioclimatic variables' resolution (30 arc-seconds). Finally, all these variables have been clipped to the HKH region shapefile and converted to MaxEnt-compatible ASCII format using ArcGIS 9.2. Under climate change, no gap vegetation projections were available, we considered the vegetation to be unchanged over this period. Because topographical data (slope, aspect and elevation) were considered stationary, the same data were utilized in future datasets (Paul and Samant 2023; Paul et al. 2023).

The autocorrelation of environmental layers was examined using ENMtools_1.3. In addition, Variance Inflation Factor (VIF) values were also calculated to decrease multicollinearity among the variables using GRASS GIS 8.4 (Petty et al. 2012) (Supplementary Table 1). Eleven environmental variables remained for modelling after the variables with cross-correlation values larger than ± 0.80 and more than five VIF values were eliminated from the analysis (Fig. 3a). The finalized variables included soil, land cover, slope, aspect, annual mean temperature (bio_1), precipitation seasonality (bio_15), precipitation of wettest quarter (bio_16), precipitation of driest quarter (bio_17), precipitation of warmest quarter (bio_18), precipitation of coldest quarter (bio_19), mean diurnal range (bio_2), and Isothermality (bio_3).

Modelling parameters

To predict distribution maps, the most popular ENM tool is MaxEnt (Merow et al. 2013). In the present study, the MaxEnt version 3.4.4 k algorithm was used for predicting *L. polyphyllum* distribution maps *(*Steven et al. 2022). To handle the model complexity, we applied ten replicate effects, a cross-validated replicate run type, a maximum number of background points of 10000, a default prevalence of 0.5, a Jackknife test to calculate the variable's importance, created response curves of each selected variable and a threshold rule of ten percentile training. Prior research indicates that overfitting may result from utilizing default settings in the MaxEnt model simulation, which lowers prediction accuracy and transferability (Hernandez et al. 2006). To overcome this issue, ENMeval: An R program package was used to modify the MaxEnt's feature combination (FC) and regularization multiplier (RM). For this study, we selected Linear as the FC with an RM of 3 (Muscarella et al. 2014). Ten percent occurrence records was utilized for testing and ninety percent for model training (López-Martínez et al. 2016).

Model validation

MaxEnt's output produced potential present and future distribution maps for *L. polyphyllum*. The model's accuracy was verified with ROC (Receiver Operating Characteristic) curve, TSS (True Skill Statistic), and AUC (Area Under Curve) test values. The TSS was calculated by following Allouche et al. (2006). TSS values fall between -1 to $+1$, and values above 0.5 indicate acceptable model quality. Based on a 10-percentile training presence threshold value of 0.3373, we further divided distribution areas into four groups: Unsuitable (0.00-threshold value), marginal (0.3373–0.50), moderate (0.50–0.70), and highly suitable (0.70–1) (Amiri et al. 2022; Paul and Samant 2024). The shift in range and direction of species expansion and decrease have been calculated by subtracting the present predicted map from the maps of future distribution under various climate scenarios (Veera et al. 2019).

Results

Population assessment

A total of 09 sites/populations of *L. polyphyllum* were surveyed in Lahaul & Spiti, Chamba and Kullu districts of Himachal Pradesh, India across 03 habitats. The detailed site characteristics of each population/site are presented in Table 1 and Fig. 2. The shady moist habitat represented 06 sites, followed by grassland (2) and rocky (01) habitats between 2103 and 3316 m amsl. Among aspects, the highest number of sites was in the north-west aspect (3), followed by north and north-east (2, each) and east and west (01, each) aspects between 31.570504 to 33.09132°N latitudes and 76.43053 to 77.44639°E longitudes with topographic slope range from 30–55°.

Overall, Species richness in *L. polyphyllum* studied populations ranged from 19 to 48, maximum species found in the Hirb-1 (48) population, followed by Hirb-2 (46), Lapah (42) and Takwas Nala (34) populations. Tree richness ranged from 0–7, maximum trees were recorded in Lapah (07) population. Shrubs richness ranged from 2–10, with the maximum shrubs recorded in the Hirb-2 (10) population. Herbs richness ranged from 11–35, with maximum herbs recorded in the Hirb-1 (35) population. The Total Trees Density (TTD) ranged from 0–430 Ind ha^{-1}. Maximum TTD was noted in the Hirb-1 (430 Ind ha^{-1}) population. The total basal area (TBA) ranged from 0–71.36 $m^2\ ha^{-1}$, and the maximum TBA was noted in the Hirb-2 (71.36 $m^2\ ha^{-1}$) population.

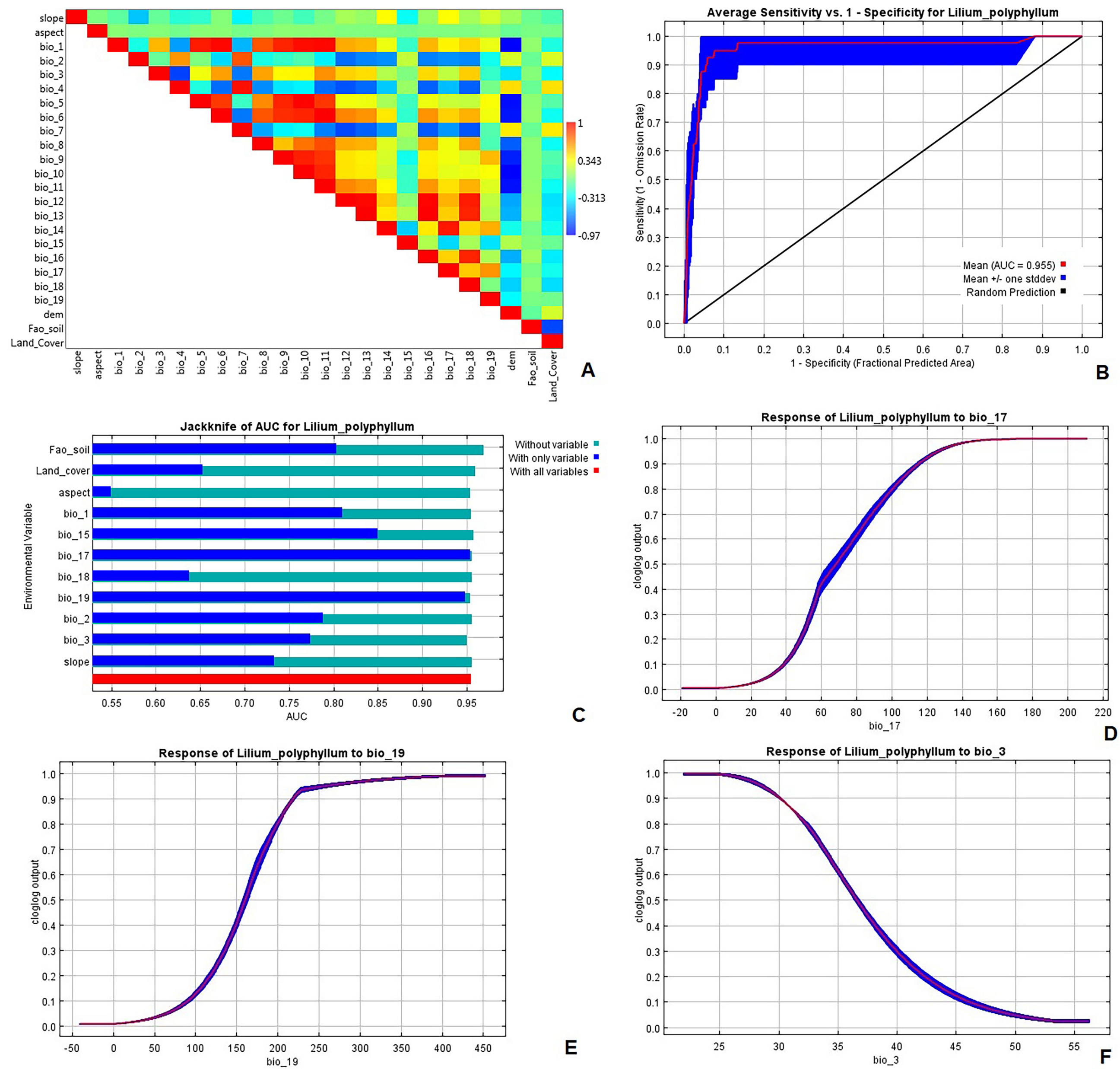


Fig. 3 **A** Matrix of correlations between bioclimatic variables, **B** ROC curve, **C** Jackknife evaluation outcomes, and **D**–**F** Key bioclimatic variables' predicted response curves

The Total Shrubs Density (TSD) ranged from 400–3880 Ind ha^{-1}. Maximum TSD was noted in Lapah (3880 Ind ha^{-1}) population, followed by the Hirb-2 (2230 Ind ha^{-1}) population. The Total Herbs Density (THD) ranged from 17.20–86.20 Ind m^{-2}. Maximum THD was noted in Salpat (86.20 Ind m^{-2}) population, followed by Hirb-1 (82.75 Ind m^{-2}) and Hirb-2 (77.10 Ind m^{-2}) populations.

The density of *L. polyphyllum* ranged from 0.23–2.50 Ind m^{-2}. The highest density of *L. polyphyllum* was recorded in Takwas (2.5 Ind m^{-2}) population, followed by Rahuli (0.80 Ind ha^{-1}), Ratoli (0.70 Ind m^{-2}), and Salpat, Hirb-2 MWLS and Lapah (0.5 Ind m^{-2}, each) populations. The remaining populations had <0.5 Ind m^{-2} *L. polyphyllum* density, and it was recorded as minimum in the Hirb-1 (0.23 Ind m^{-2}) population. Relative density of *L. polyphyllum* ranged from 0.27–7.33%, maximum relative density of *L. polyphyllum* recorded in Takwas Nala (7.33%) population, followed by Ratoli (4.07%), MWLS (1.90%) and KhWLS (1.64%) populations. The remaining populations had < 1.64% relative density, and it was recorded as a minimum in the Hirb-1 (0.27%) population. In the studied populations of *L. polyphyllum*, 138 species (18 trees, 25 shrubs and 95 herbs) were recorded.

Species diversity (H′) for trees ranged from 0–1.77, the maximum of trees was noted in Lapah (1.77) population. Species diversity for shrubs ranged from 0.65–1.78, maximum H′ of shrubs noted in the MWLS (1.78) population. Species diversity for herbs ranged from 1.19–3.30, the maximum H′ of herbs was recorded in the Hirb-1 (3.30) population. The Concentration of dominance (Cd) for trees ranged from 0.19–0.71, maximum Cd of trees noted in the Hirb-1 (0.71) population. Cd for shrubs ranged from 0.20–0.54, the maximum Cd of shrubs was noted in Salpat (0.54) population. Cd for herbs ranged from 0.05–0.53, the maximum Cd for herbs was noted in Salpat (0.53) population, and it was recorded minimum in Hirb-1 and Hirb-2 (0.05) populations (Table 2).

Among habitats, the highest *L. polyphyllum* density was in shady moist (0.80 Ind/m^2) habitat, followed by grassland (0.65 Ind/m^2) and rocky (0.35 Ind/m^2) habitats. In terms of aspects, the highest *L. polyphyllum* density was noted in the west (2.50 Ind/m^2) aspect, followed by north-west (0.62 Ind/m^2), east and north (0.50 Ind/m^2, each) and north-east (0.31 Ind/m^2) aspects (Table 3).

Picea smithiana (30.20%), *Aesculus indica* (15.44%), *Persea duthiei* (13.95%), *Cedrus deodara* (8.03%), *Abies pindrow* (5.57%) and *Pinus wallichiana* (5.29%) were the major associated tree species. *Viburnum cotinifolium* (19.52%), *Sarcococca pruniformis* (16.43%), *Indigofera heterantha* (9.96%), *Desmodium elegans* (8.74%), *Rubus ellipticus* (7.89%), *Rosa webbiana* (7.24%), *Hedera nepalensis* (4.48%) and *Berberis aristata* (4.22%) were the major associated shrub species. *Poa annua* (21.00%), *Fragaria nubicola* (4.25%), *Bergenia stracheyi* (3.52%), *Thalictrum foliolosum* (2.62%), *Viola canescens* (2.55%), *Poa alpina* (2.47%) and *Caltha palustris* (2.28%) were the major associated herb species recorded in the *L. polyphyllum* studied populations (Table 3).

Soil sampling and analysis

In *Lilium polyphyllum* studied populations, soil moisture content ranged between 3.15 ± 0.05—38.33 ± 1.28%; pH, 5.75 ± 0.00—7.32 ± 0.01; total nitrogen, 0.19 ± 0.01—0.84 ± 0.08%; organic carbon, 1.39 ± 0.00—3.46 ± 0.05%; organic matter, 2.39 ± 0.00 -5.97 ± 0.09%; available phosphorous, 0.94 ± 0.02—8.62 ± 1.02 kg/ha; and available potassium, 100 ± 5.20—627 ± 10.50 kg/ha. Soil pH, moisture content, organic carbon, available phosphorus, available potassium and total nitrogen analysed for each population are provided in Table 4.

Ecological niche modelling

Present distribution area of *L. polyphyllum*

The test of the MaxEnt model calibration for *L. polyphyllum* provided satisfying results (TSS = 0.765 ± 0.140 and AUC test = 0.955 ± 0.062) (Fig. 3b and Table 1). Based on permutation importance and percent contribution, bio_17 and bio_19 are the most significant variables influencing *L. polyphyllum* distribution (Table 5). The results of the Jackknife test indicate that bio_17 has the largest gain when utilized alone. As a result, it appears to contain the data that is most significant. When bio_3 is removed, the gain is reduced the most; therefore, it contains the most information not found in other variables (Fig. 3c). According to the response curves, locations with precipitation in the driest quarter exceeding 100 mm, and precipitation in the coldest quarter more than

Table 2 Species richness, Total Basal Area, Density, Relative density, Species diversity and Concentration of dominance of tree, shrub and herb layers in *L. polyphyllum* sites, Himachal Pradesh, North Western Himalaya

Sites	Tree layer					Shrub layer				Herb layer				*L. polyphyllum*	
	R	D	TBA	H′	CD	R	D	H′	CD	R	D*	H′	CD	RD%	D*
Hirb-1	4	430	24.78	0.62	0.71	9	1680	1.68	0.26	35	82.75	3.30	0.05	0.27	0.23
Hirb-2	5	280	71.36	1.13	0.43	10	2230	1.50	0.32	31	77.10	3.13	0.05	0.65	0.50
KhWLS	5	250	17.79	1.43	0.27	4	720	1.32	0.28	20	21.30	2.65	0.09	1.64	0.35
Lapah	7	330	2.48	1.77	0.19	7	3880	1.49	0.32	28	47.10	2.85	0.08	0.85	0.40
MWLS	4	200	10.04	1.09	0.42	7	1720	1.78	0.20	18	26.25	2.43	0.13	1.90	0.50
Rahuli	–	–	–	–	–	3	400	1.03	0.38	24	75.60	2.22	0.23	1.06	0.80
Ratoli	4	170	2.2	1.18	0.36	4	680	1.38	0.25	11	17.20	1.70	0.29	4.07	0.70
Salpat	–	–	–	–	–	2	560	0.65	0.54	17	86.20	1.19	0.53	0.58	0.50
Takwas	–	–	–	–	–	4	1216	1.22	0.33	30	34.10	2.99	0.08	7.33	2.50

D* = Density (Ind m^{-2}); D = Density (Ind ha^{-1}); CD = Concentration of Dominance; H′ = Species Diversity; KhWLS = Khokhan Wildlife Sanctuary; MWLS = Manali Wildlife Sanctuary; R = Species Richness; and TBA = Total Basal Area (m^2/ha)

Table 3 Habitat and aspect wise Species richness, Total Basal Area, Density, Relative density, Species diversity and Concentration of dominance of tree, shrub and herb layers in *L. polyphyllum* sites in Himachal Pradesh, North Western Himalaya

	SR	Trees					Shrubs				Herbs				LP
		R	D	TBA	H′	CD	R	D	H′	CD	R	D*	H′	CD	RD
Habitats															
GR	2	–	–	–	–	–	3	480	0.84	0.46	21	81	1.71	0.38	0.65
RO	1	5	250	18	1.43	0.27	4	720	1.32	0.28	20	21	2.65	0.09	0.35
SM	6	5	282	22	1.16	0.42	7	1901	1.51	0.28	26	47	2.73	0.11	0.80
Aspects															
W	1	–	–	–	–	–	4	1216	1.22	0.33	30	34	2.99	0.08	2.50
NW	3	3	140	7	0.87	0.21	4	600	1.24	0.30	18	38	2.19	0.20	0.62
E	1	5	280	71	1.13	0.43	10	2230	1.50	0.32	31	77	3.13	0.05	0.50
N	2	4	200	10	1.09	0.42	5	1140	1.21	0.37	18	56	1.81	0.33	0.50
NE	2	6	380	14	1.20	0.45	8	2780	1.59	0.29	32	65	3.08	0.06	0.31

SM = Shady Moist; RO = Rocky; GR = Grassland; E = East; N = North; NW = North–West; NE = North–East; W = West; and LP = *Lilium polyphyllum*; R = Richness; SR = Site Representative; D* = Density (Individual/m^2); D = Density (Individual/ha); H′ = Species Diversity; Cd = Concentration of Dominance; and RD = Relative Density (%)

Table 4 Physical and chemical properties of soils in *L. polyphyllum* populations

Population	TN%	AP (kg/ha)	AK (kg/ha)	OC %	OM%	pH	MC%
Hirb-1	0.35 ± 0.02	0.94 ± 0.02	100 ± 5.20	2.7 ± 0.10	4.65 ± 0.17	6.56 ± 0.00	6.97 ± 0.06
Hirb-2	0.84 ± 0.08	1.7 ± 0.10	627 ± 10.50	3.46 ± 0.05	5.97 ± 0.09	6.75 ± 0.01	38.33 ± 1.28
KhWLS	0.33 ± 0.00	8.62 ± 1.02	340 ± 18.50	1.52 ± 0.04	2.62 ± 0.07	6.78 ± 0.01	18.5 ± 1.17
Lapah	0.42 ± 0.01	5.71 ± 0.40	323 ± 4.51	2.52 ± 0.10	4.34 ± 0.17	5.75 ± 0.00	31.00 ± 1.53
MWLS	0.37 ± 0.01	6.05 ± 0.24	132 ± 16.50	2.75 ± 0.08	4.74 ± 0.14	6.36 ± 0.01	20.5 ± 0.50
Rahuli-1	0.37 ± 0.03	3.81 ± 0.40	134 ± 3.51	1.86 ± 0.12	3.2 ± 0.21	6.77 ± 0.01	19.99 ± 1.00
Ratoli	0.19 ± 0.01	8.06 ± 0.24	227 ± 5.08	1.62 ± 0.10	2.79 ± 0.17	6.91 ± 0.02	13.9 ± 0.10
Salpat	0.28 ± 0.03	5.38 ± 1.20	206 ± 4.59	1.39 ± 0.00	2.39 ± 0.00	6.76 ± 0.00	3.15 ± 0.05
Takwas	0.28 ± 0.00	1.79 ± 0.10	146 ± 12.50	1.89 ± 0.05	3.26 ± 0.09	7.32 ± 0.01	23.5 ± 1.32

TN = Total Nitrogen; AP = Available Phosphorous; AK = Available Potassium; OC = Organic Carbon; OM = Organic Matter; and MC = Moisture Content; Values are mean ± standard deviation of three replicates

Table 5 Statistical values of *L. polyphyllum* distribution model performance and accuracy

Global Climate Models	Period	Area Under Curve Value	True Skill Statistic value	Permutation importance of key variable	Percent contribution of key variable
	Present	0.955 ± 0.062	0.765 ± 0.140	bio_19 (49.2)	bio_17 (50.3)
BCC-CSM2-MR	SSP245, 2081–2100	0.948 ± 0.066		bio_17 (63.8)	bio_17 (51.0)
	SSP370, 2081–2100	0.944 ± 0.066		bio_17 (51.8)	bio_17 (46.2)
MIROC6	SSP245, 2081–2100	0.948 ± 0.076		bio_17 (55.4)	bio_17 (46.3)
	SSP370, 2081–2100	0.950 ± 0.060		bio_17 (49.4)	bio_17 (52.9)

200 mm should be ideal for the distribution of *L. polyphyllum* (Fig. 3).

Based on the MaxEnt model output, in the HKH region for the occurrence of *L. polyphyllum,* the highly suitable class encompasses 1,11,943 km^2 (2.59%), the moderate suitability 53,349 km^2 (1.33%), and the marginal suitability class encompasses 73,281 km^2 (1.69%) of the area. Overall, 2,42,573 km^2 (5.61%) of the area is suitable for *L. polyphyllum* occurrence (Fig. 4; Tables 6 and 7). There are highly suitable habitats in Afghanistan, India, and Pakistan within

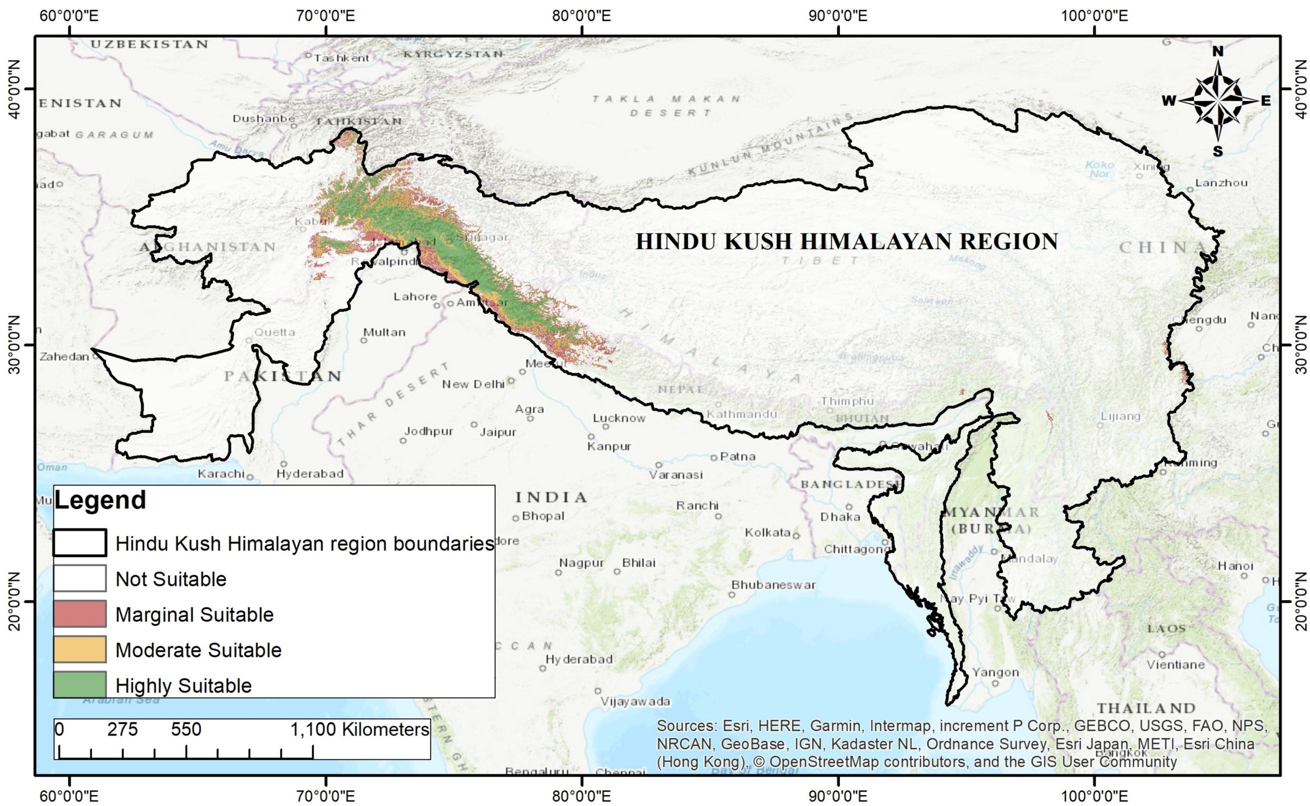


Fig. 4 Potential suitability map of *L. polyphyllum* in the Hindu Kush Himalaya

Table 6 Estimated suitability area of *L. polyphyllum* in the Hindu Kush Himalaya

Global Climate Models	Period	Probability class's area (Area changed compared to present, km^2)			
		Marginal	Moderate	Highly Suitable	Total Suitable area
	Present	73281	57349	111943	242573
BCC-CSM2-MR	SSP245, 2081–2100	226994 (+153713)	96318 (+38969)	124683 (+12740)	447995 (+205423)
	SSP370, 2081–2100	228519 (+155238)	97104 (+39755)	126101 (+14158)	451724 (+209152)
MIROC6	SSP245, 2081–2100	108874 (+35593)	65480 (+8131)	98979 (– 12964)	273333 (+30761)
	SSP370, 2081–2100	331031 (+257750)	119001 (+61652)	133968 (+22025)	584000 (+341428)

the altitudinal range of 1800–3500 m amsl. In Afghanistan, high-suitability areas were in the Nuristan, Kunar, Laghman, Nangrahar, Paktya, and Khost provinces. In India, high-suitability areas were in Jammu & Kashmir Union Territory (Doda, Kupwara, Baramulla, Srinagar, Pulwama, Anantnag, Gandarbal and Bandipora districts), Himachal Pradesh (Lahaul valley in Lahaul & Spiti district, Dhauladhar range of Kangra district, higher elevation ranges of Solan, Sirmour, Chamba, Kullu, Mandi, Kinnaur and Shimla districts) and Uttarakhand (Uttarkashi, Tehri Garhwal and Chamoli districts), Muzaffarabad area of Azad Kashmir/Pakistan-Occupied Kashmir (POK). In Pakistan, high-suitability areas were in Khyber Pakhtunkhwa province (Fig. 4).

The future distribution of *L. polyphyllum*

Under SSP245 and 370 climate scenarios for the 2081–2100 period, the TSS and AUC test values for both GCMs were satisfactory (Table 5). Suitability areas in different classes have been provided in Tables 6, 7 and Fig. 5 for selected SSPs and GCMs. Based on the climate scenarios SSP 245 and SSP 370 for the 2081–2100 period, the suitable area for the BCC-CSM2-MR model was 4,47,995 km^2 (10.36%) and 4,51,724 km^2 (10.45%), respectively. Similarly, it was 2,73,333 km^2 (6.32%) and 5,84,000 km^2 (13.50%) for the MIROC6 model, respectively (Tables 6 and 7). For the SSP245 climatic scenario in the 2081–2100 period, the suitability area for *L. polyphyllum* has been predicted to increase

Table 7 Changes (%) in *L. polyphyllum* suitability areas under different climate scenarios in the Hindu Kush Himalaya

Global Climate Models	Period	Probability class's area (Area changed compared to present, %)			
		Marginal	Moderate	Highly Suitable	Total Suitable area
	Present	1.69 (0.00)	1.33(0.00)	2.59(0.00)	5.61(0.00)
BCC-CSM2-MR	SSP245, 2081–2100	5.25 (+3.56)	2.23 (+0.90)	2.88 (+0.29)	10.36 (+4.75)
	SSP370, 2081–2100	5.28 (+3.59)	2.25 (+0.92)	2.92 (+0.33)	10.45 (+4.84)
MIROC6	SSP245, 2081–2100	2.52 (+0.83)	1.51 (+0.18)	2.29 (− 0.30)	6.32 (+0.71)
	SSP370, 2081–2100	7.65 (+5.96)	2.75 (+1.42)	3.1 (+0.51)	13.50 (+7.89)

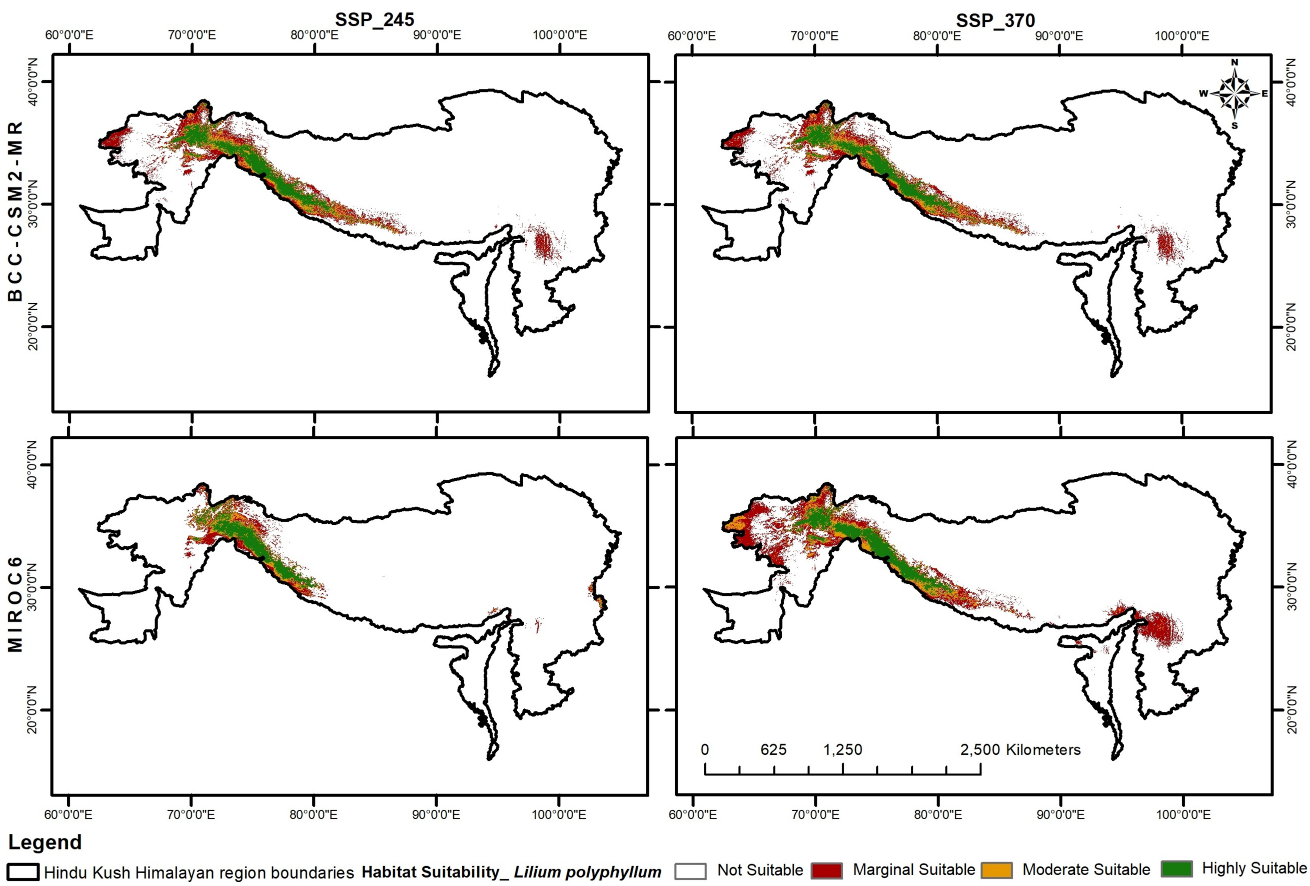


Fig. 5 Predicted distribution of *L. polyphyllum* under climate change scenarios in the Hindu Kush Himalaya

by 4.75% and 0.71% for the BCC-CSM2-MR and MIROC6 models, respectively, compared to the present forecasted model. Similarly, it is predicted that the total suitable area will rise by 4.84% and 7.89%, respectively, under the SSP 370 scenario (Tables 6 and 7 and Fig. 6).

Discussion

Understanding the patterns of species spatial distribution, the factors affecting the abundance of species, and the reasons why certain regions have more species or individuals than others are some of the primary research questions in biogeography and ecology. In addition to constituting the foundation of scientific research in the fields of ecology and evolution, these concerns have crucial implications for the conservation and management of biodiversity (Thuiller 2024). The people residing in the Himalaya utilize plants for many purposes, including medicines, food, fodder, and tools for agriculture (Dhiman and Muthanarasimha 2023). Many species have suffered devastating declines in populations during the past few decades as a result of human activity, including habitat destruction, overexploitation, changing environmental conditions and natural disasters (Shrestha et al. 2021). Among

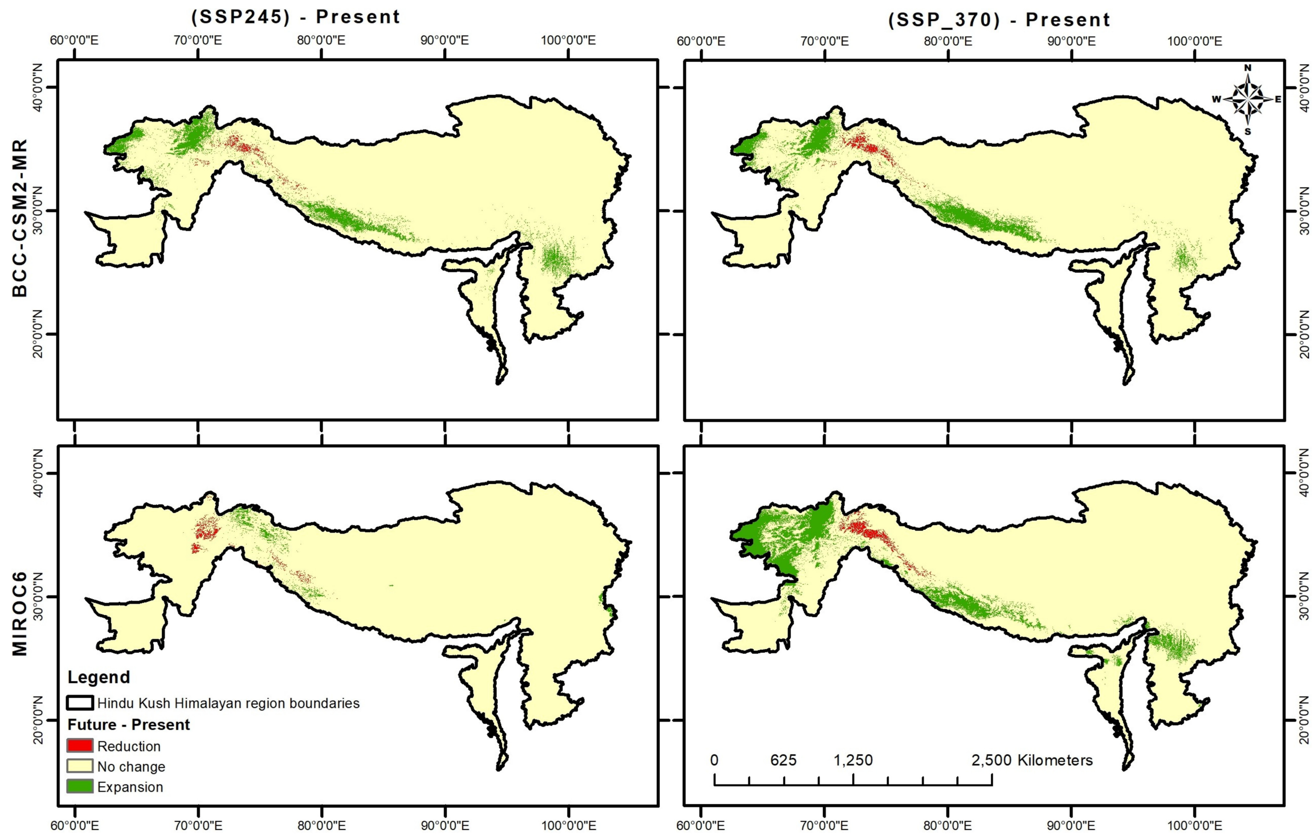


Fig. 6 Effects of climate change on the spatial distribution of *L. polyphyllum* in the Hindu Kush Himalaya

these, *L. polyphyllum* is particularly popular due to its therapeutic and aesthetic properties. To conserve this species, it is imperative to identify suitable habitats and study its population ecology.

In the studied populations, *L. polyphyllum* has been reported from shady-moist forests, rocky and grassland habitats. The highest density of *L. polyphyllum* was found in the shady-moist forest, indicating that the forests provide favourable conditions for the species' overall growth. Past studies in the Manali Wildlife Sanctuary also showed that *L. polyphyllum* density was maximum in the shady-moist habitat (Rana and Samant 2011b). In general, the soil's pH was slightly acidic, which suggests that species liked the slightly acidic soil for growth. In the studied populations, the density of *L. polyphyllum* was very low and it was comparatively higher than the earlier reported values from Manali Wildlife Sanctuary and the Garhwal region (Dhyani et al. 2018; Rana and Samant 2011b).

L. polyphyllum density displays a significant positive correlation with altitudinal gradient ($r = 0.880$, $p < 0.01$ and $n = 9$) and latitude ($r = 0.677$, $p < 0.05$ and $n = 9$). This indicates that the topographical gradients play an important role in species distribution. Also, it has a significant inverse relationship with total tree density ($r = -0.852$, $p < 0.01$ and $n = 9$) in the studied populations. The relative density of *L. polyphyllum* displays a significant positive correlation with altitude ($r = 0.898$, $p < 0.01$ and $n = 9$) and a negative correlation with total tree density ($r = -0.827$, $p < 0.05$ and $n = 9$). TBA had a significant positive correlation with available potassium ($r = 0.781$, $p < 0.05$ and $n = 9$), total nitrogen ($r = 0.894$, $p < 0.01$ and $n = 9$) and organic matter and carbon ($r = 0.746$, $p < 0.05$ and $n = 9$) present in the soil (Fig. 7). Additionally, we calculated the Extent of Occurrence (EOO) and Area of Occupancy (AOO) based on a cell width of 2 km and from the ground-point data only, in GeoCAT (Geospatial Conservation Assessment Tool), to check the threat status of the species in the Himalaya. The AOO value was 160 km^2 and falls within the endangered extinction risk category. The EOO value was 2,55,972 km^2 and falls within the Least Concern extinction risk category of IUCN (Supplementary Fig. 1).

AUC and TSS values and ROC curves are used to evaluate predicted models. The calibration test for the *L. polyphyllum* model produced acceptable AUC test values (Thuiller et al. 2005) and TSS value (Allouche et al. 2006). Developed models outperformed random in terms of TSS values, which exceeded 0.5. According to Pearson (2007), accurately predicted models provide ROC curves near the left and top axes

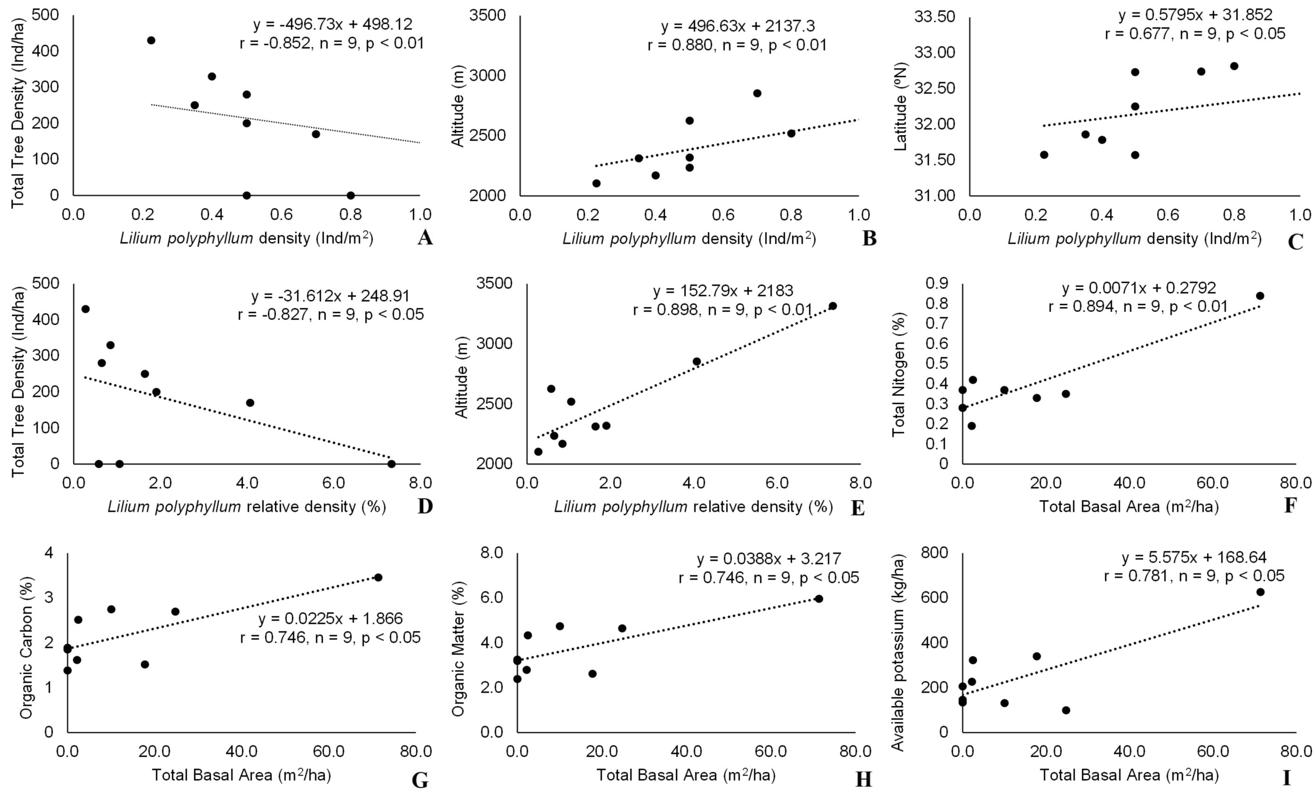


Fig. 7 Correlations between: **A** Density of *L. polyphyllum* and total trees density; **B** density of *L. polyphyllum* and altitude; **C** density of *L. polyphyllum* and latitude; **D** relative density of *L. polyphyllum* and total trees density; **E** relative density of *L. polyphyllum* and altitude; **F** total basal area and total soil nitrogen; **G** total basal area and soil organic carbon; **H** total basal area and soil organic matter; and **I** total basal area and available potassium in soil

of the graph, but a problematic model would exhibit a 1:1 line. Because the ROC curves were located far from the 1:1 line and toward the left and top axes, the models were found to be appropriate. Results from the Jackknife evaluation, permutation importance and per cent contribution revealed that the driest quarters and the coldest quarter's precipitation, and annual mean temperature were the most crucial factors in identifying *L. polyphyllum*'s distribution area.

A prior study also found that precipitation of the coldest quarter (bio_17) was one significant variable for the prediction of the potential distribution map of *L. polyphyllum* in the western Himalaya (Sourabh et al. 2018). The two selected GCMs (MIROC6 and BCC-CSM2-MR) perform well in the Himalayan region (Kushwaha et al. 2024). Therefore, for the period 2081–2100, the distribution of *L. polyphyllum* under SSP245 and SSP370 scenarios has been predicted using these two GCMs in the present research. When the present distribution map has been subtracted from future maps, an expansion in the high suitability area is observed (Figs. 5 and 6). When comparing the future distribution with the present, suitability areas expand with increasing greenhouse gas in both GCMs. Based on MaxEnt's prediction, the distribution of *L. polyphyllum* was most significantly influenced by the driest/coldest quarter's precipitation, suggesting that this species was the most precipitation-sensitive. Climate change may cause expansion in the area of the occurrence of *L. polyphyllum*. The expansion of suitable habitats under SSP scenarios indicates potential resilience to climate change. However, anthropogenic pressures, such as overharvesting, may counteract these benefits. In general, all GCMs under SSP245 scenarios using CMIP6 climate change scenarios anticipate a considerable decline in precipitation during the monsoon in the upper Gangetic region. However, future predictions indicate a significant rise in precipitation after the monsoon and during the winter. The post-monsoon period is expected to have the highest rise in seasonal precipitation (Singh et al. 2022). It indicates that the Western Himalayan region has high post-monsoon and winter precipitation (driest period), which may be the reason for the increase in *L. polyphyllum* suitability region under scenarios of climate change.

Although the species distribution might be predicted with success using the MaxEnt model, the prediction model possessed errors and uncertainty problems (Guisan and Thuiller 2005). Some of the shortcomings with present habitat suitability modelling include an absence of components like functional features, biotic interactions and migration patterns or changes in land use (Keith et al. 2008). However, a review of the literature indicates that the majority of these abiotic and biotic interactions are mostly caused by variations in precipitation and temperature (Pearson and Dawson 2003). Thus, when these parameters are considered, the model predicted reflects such interactions implicitly (Manish et al. 2016). Land use/land cover change and climate change have drawn a lot of attention as the two primary causes of plant habitat loss. This variable could be included in future research.

Some suggestions for conserving *L. polyphyllum* are: (1) The species can be conserved by utilizing its predicted suitable habitat models. (2) To reduce the effects of factors that encourage habitat loss, it is possible to track and monitor the regions where future climate change scenarios are likely to alter potentially suitable habitats for *L. polyphyllum*. (3) The identification of MPCDAs (Medicinal Plants Conservation and Development Areas) for *L. polyphyllum* required. (4) Development of cultivation protocols to reduce dependency on wild populations required. (5) For mass multiplication of the species, cultivation techniques must be strengthened. (6) Notify/Establish protected areas in highly suitable regions required to minimize anthropogenic disturbances. (7) Development of a participatory approach, such as forming Medicinal Plant Conservation Committees to promote medicinal plant cultivation.

Conclusion

The population status, along with the potential distribution map of *L. polyphyllum* in the Himalaya under the predicted climatic change, is presented in the present research. Based on the results of this study, the predicted highly suitable areas are likely to have a significant influence on the species' conservation status. In the Himalaya, projected climatic conditions would expand the total suitability area of *L. polyphyllum*. The most probable areas for the occurrence of *L. polyphyllum* can be used for *in-situ* conservation. The driest quarters and the coldest quarters' precipitation and annual mean temperature were the most crucial factors for the distribution of *L. polyphyllum*. Shady-moist habitat provides favourable conditions for the species' overall growth, and species prefer slightly acidic soil for growth. Decision-makers and policymakers can use the predicted distribution maps to devise an appropriate management strategy. Mass production of this highly traded medicinal plant using various propagation techniques, educating locals of its importance, and supporting active community participation are all important factors in ensuring the survival and conservation of this plant.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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