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Predicting suitable habitats of *Podophyllum hexandrum* under a climate change scenario in Nepal

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Abstract

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Podophyllum hexandrum Royle is a perennial herb with high medicinal significance. Due to high demand, rhizomes are being harvested unsustainably. Besides, climate change has become another prevalent threat to its population. In Nepal, the information on the suitable habitats of *Podophyllum hexandrum* is inadequate. Therefore, the present study modelled suitable habitats of *Podophyllum hexandrum* under current and future climate change scenarios using MaxEnt probabilistic modelling. Nine bioclimatic and two topographic variables with 36 occurrences of *Podophyllum hexandrum* were used in the model. Furthermore, response curves for each selected predictor variable were generated, and a jackknife test was conducted to estimate the effect of individual predictors on habitat suitability. The model output indicated that about 24.36% of Nepal's total area was suitable for the occurrence of *Podophyllum hexandrum.* Out of the total current suitable area, 2.31% constitute high, 6.14% mid and 15.91% constitute low probability regions. The highest potential distribution was predicted in eastern and central Nepal, whereas the western region has low suitability under the current climatic scenario. In addition, the future suitability projection showed that the suitable range would decline in 2050 and 2070 under SSP-245 and SSP-585 trajectories, respectively. Altitude and precipitation seasonality (Bio 15) were the important environmental factors affecting the spatial distribution. Overall, this study identified potential habitats for *Podophyllum hexandrum* under current and future climatic scenarios in Nepal, providing a framework for its conservation planning and habitat management.

Keywords: altitude, conservation, distribution, endangered species, MaxEnt modelling, precipitation.

INTRODUCTION

Climate has been considered to have a dominant control over the geographic distribution of Himalayan medicinal plants, threatening their survival by altering habitat, distribution, ecology, and phenology (Hamann & Wang, 2006; Singh et al., 2014; Shrestha et al., 2022b; Kunwar et al., 2023). Given the impact that climate change is projected to have on threatened plants, it is essential to predict the potential distribution or habitat suitability of such plants in response to climate change scenario for the restoration of their declining populations in their natural habitat as well as artificial introductions (Kumar & Stohlgren, 2009; Rana et al., 2017; Pramanik et al., 2018). The identification of such suitable habitats and environmental factors influencing species distribution is often done through spatial distribution modelling (Rana et al., 2017; Maharjan et al., 2019). It is a modelling technique that models existing habitats of occurrence; therefore, it provides areas of high, mid, and low suitability, as well as areas with no suitability, for the rescue and recovery of threatened species (Rana et al., 2017; Maharjan et al., 2019).

Species distribution models serve as valuable computational tools for estimating where species are likely to occur by integrating occurrence records with environmental factors and assessing how those factors shape their distributions (Elith & Lethwick, 2009; Rana et al., 2017; Maharjan et al., 2019). However, distribution data on threatened and endangered species are often sparse, clustered and incomplete, making commonly used habitat modelling approaches difficult (Engler et al., 2004; Gogol-Prokurat, 2011). In such case, among the various modelling techniques used in species distribution models, the maximum entropy (MaxEnt) is the most commonly used and is highly efficient for delineating species distribution probability because of its high predictive accuracy, precisely involving presence-only data and limited occurrence records (Philips et al., 2006; Phillips & Dudik, 2008; Merow et al., 2013; Yackulic et al., 2013; Rana et al., 2017).

The maximum entropy (MaxEnt) is a general-purpose machine learning technique, developed by Phillips et al. (2006), that can be applied to presence-background data to generate habitat suitability predictions using environmental variables. This method allows the prediction of species' potential ranges, changes in their distribution, future trends, and the development of effective biodiversity conservation strategies (Phillips & Dudik, 2008; Rana et al., 2017). Furthermore, MaxEnt modelling is highly valuable for biodiversity data collected from herbaria and museum collections, which typically contain information about where a species has been recorded rather than absence data (Novoseltseva, 2024).

Podophyllum hexandrum, a highly valued medicinal herb, is under pressure from overharvesting and a climate change scenario (Banerjee et al., 2017). Owing to their high medicinal value and high trade potential, the rhizomes are being unsustainably collected in large quantities from the wild (Nadeem et al., 2000; Lama et al., 2001; Kunwar et al., 2014; O'Neil et al., 2017; Shrestha et al., 2022b). The plant has been considered threatened due to overexploitation, long dormancy, low natural regeneration, restricted distribution and slow growth (Kala, 2005; Dogra et al., 2013). To curb overharvesting and illegal trade of this plant, effective conservation actions are essential, beginning with identifying its core distribution areas and suitable habitats.

Several medicinal and aromatic plants from the Nepal Himalayas have been studied to assess the area of their probable distribution from a conservation perspective (Shrestha & Bawa, 2014; Rana et al., 2017; Rana et al., 2020; Shrestha et al., 2022b; Kunwar et al., 2023). However, information on the spatial distribution, current suitable habitats of *Podophyllum hexandrum*, and how its distribution will change with future climate change is greatly lacking in Nepal. Therefore, the present work aims to map the suitable regions of occurrence of *Podophyllum hexandrum* using MaxEnt probabilistic modelling, which answers the following questions: (a) what are the suitable habitats or potential distribution range of *Podophyllum hexandrum* in Nepal under current and future climatic scenarios? and (b) what are the most important variables determining the distribution *of Podophyllum hexandrum* in Nepal? The predictive maps generated by this study can provide foundational data for developing effective conservation strategies aimed at restoring the species' natural habitat in the highly and moderately suitable regions of Nepal.

MATERIALS AND METHODS

Study area

The study area for modelling occupies the whole country of Nepal covering the area of 147 516 km^2 (Department of Survey, 2024) (Fig. 2). The country has wide elevational range from 59 m to 8 848.86 m above sea level and high geographic diversity, which has provided Nepal with extremely rich plant diversity with nearly 5820 species of flowering plants reported with around 2069 species of medicinal plants (Shrestha et al., 2022a).

Study species

Podophyllum hexandrum Royle (Berberidaceae) is a high-elevation perennial herb of great medicinal importance (Nag et al., 2015; Chalise et al., 2021)

(Fig. 1). The plant is distributed from the Indian Himalayas to Bhutan, Pakistan, Afghanistan, Nepal, Taiwan and China (Tabassum et al., 2014; Chauhan, 2024). The species prefers to grow in shady and moist sub-alpine forest floors, forest openings and margins, and alpine slopes within an elevation range from 2000 m to 4600 m along East, Central and West Nepal (Airi, 1997; Lama et al., 2001; Xiong et al., 2013; Shrestha et al., 2022a; Chauhan, 2024). It is a 15–60 cm tall plant bearing alternate, long-stalked, and often purple-spotted, round leaves in groups of one to three. Flowers are large, cup-shaped, bisexual, actinomorphic, gamosepalous, and white or pink in colour. The fruit is a berry with numerous seeds (Airi, 1997; Banerjee et al., 2017).

It is a slow-growing species that typically propagates by seed. Still, seedling establishment is limited because seeds undergo prolonged dormancy caused by both the seed coat and the endosperm. This limits the regenerative capacity of *Podophyllum hexandrum* (Dogra et al., 2013). The species requires five to seven years to reach an economically viable size (Singh et al., 2021). Xiong et al. (2013) have found that the floral visitors to Himalayan May Apple were very rare. As a nectar-less plant that blooms early in the high Himalayan regions, *Podophyllum hexandrum* often faces a shortage of pollinators. This scarcity delays self-pollination and fruit development, which in turn influences seed production (Xiong et al., 2013).

The rhizome of the plant contains several compounds, such as podophyllotoxin, podophyllin, and many secondary metabolites, which have cytotoxic, antioxidant, anti-inflammatory, and anti-tumour properties and several pharmacological applications (Tabassum et al., 2014). Traditionally, *Podophyllum hexandrum* has been used in folk medicine to treat gynaecological diseases, menstrual disorders, kidney diseases, skin diseases, cough, fever, septic wounds, diabetes, constipation, and many other ailments (Lama et al., 2001; Negi et al., 2019). The species is threatened mainly due to human alterations such as destructive harvesting because of its high trade value as well as because of poor natural regeneration, low genetic diversity, low population density, lack of cultivation protocols and climate change impacts (Kala, 2005; Maqbool, 2011; Nag et al., 2015; Banerjee et al., 2017).

Fig. 1. *Podophyllum hexandrum* in sub-alpine habitat. Photograph by N. Pandey.

Species occurrence data

Species occurrences were compiled from different field surveys, herbarium specimens housed at the National Herbarium and Plant Laboratories (KATH) and published literature (Rawal et al., 2009). Occurrence records were also gathered from the online databases Global Biodiversity Information Facility (GBIF, 2024). Altogether, 42 georeferenced points were collected and checked for spatial autocorrelation to reduce model bias and overfitting (Boria et al., 2014). Spatial thinning was performed in ArcMap 10.8 by randomly selecting a single occurrence point within 10 × 10 km^2 grid cells placed over all occurrence points (Rana et al., 2017; Rana et al., 2020). Finally, 36 presence records of *Podophyllum hexandrum*, covering its distribution in Nepal, were selected and used in ecological niche modelling under current and future climate scenarios (Fig. 2).

Environmental variables

To identify the current and future ecological niche of *Podophyllum hexandrum,* nineteen grid-based bioclimatic variables for the current (1970–2000) and future climate projections were collected from the WorldClim dataset at a spatial resolution of 30 arc seconds (approximately 1 × 1 km resolution) (Fick & Hijmans, 2017). Bioclimatic variables for future climate projections for the time periods 2050 (2041–2060) and 2070 (2061–2080) were obtained from the MIROC6 models for interdisciplinary climate research. Models for interdisciplinary research on climate were considered more appropriate and selected because this global circulation model captures the seasonal rainfall cycle well and provides a consistent outlook for rainfall projections in the Indian subcontinent (Babar et al., 2015). Also, it shows better skills in reproducing precipitation climatology and performs better simulations in future projections than other global circulation models for the South Asian region (Chen & Sun, 2013). Out of four shared socioeconomic pathways (SSPs), shared socioeconomic pathways-245 (SSP-245) and shared socioeconomic pathways-585 (SSP-585) were chosen for the years 2050 and 2070 for modelling. We selected these two shared socioeconomic pathways scenarios because they cover the full range of predicted out-

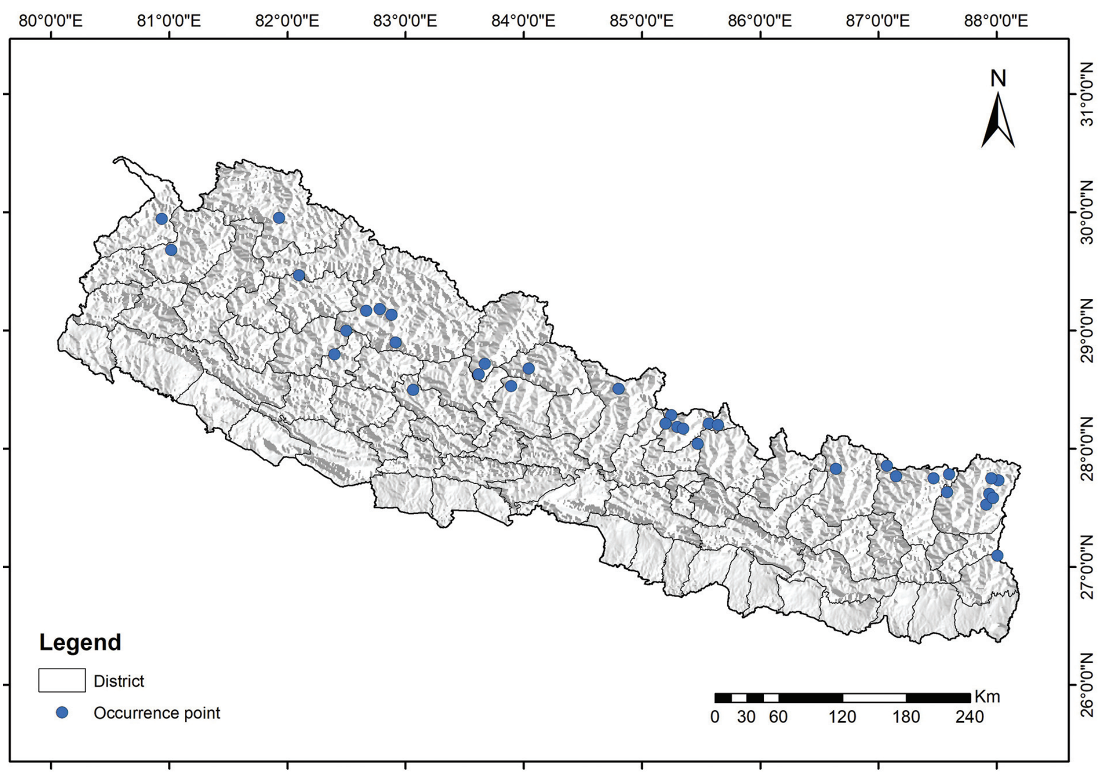

Fig. 2. Distribution of *Podophyllum hexandrum* in Nepal.

comes, from low to highly complex climate systems (Babar et al., 2015; Kunwar et al., 2023).

To identify the significant variables that have the most independent impact on the distribution, a correlation matrix was built in ArcMap 10.8 using the band collection statistics tool, and a Pearson correlation coefficient (r) ≥ ± 0.80 was used as the cut-off threshold to exclude highly correlated variables (Pramanik et al., 2018). Hence, out of nineteen, remaining nine bioclimatic variables, i.e. Bio2 (mean diurnal range), Bio3 (isothermality), Bio4 (temperature seasonality), Bio9 (mean temperature of driest quarter), Bio12 (annual precipitation), Bio15 (precipitation seasonality), Bio16 (precipitation of wettest quarter), Bio18 (precipitation of warmest quarter), Bio19 (precipitation of coldest quarter) and two topographic variables, i.e. altitude and aspect (shuttle radar topography mission digital elevation model global 30 arc second) were selected for current distribution modelling and potential distribution of *Podophyllum hexandrum* into future 2050 and 2070.

Distribution modelling and evaluation

An open-source software, MaxEnt 3.4.4, was used to predict the current and future distribution of the target species (Phillips & Dudik, 2008). The model was run, generating response curves for each selected predictor variable and a jackknife test to estimate the influence of individual predictors on habitat suitability (Khanum et al., 2013; Rana et al., 2017). In the model, occurrence points were used as species presence data, and logistic output was used; the random test percentage was set to 25, and the training percentage was 75%. The model was run in subsample replicate mode with 5000 maximum iterations, 10 replicates, a regularisation multiplier = 1, convergence threshold = 0.00001, maximum number of background points = 10,000, and linear, quadratic, product, threshold, and hinge features were used (Rana et al., 2017). Model accuracy was determined using the area under the receiver operating characteristic (ROC) curve (Khanum et al., 2013; Shrestha & Bawa, 2014; Rana et al., 2017; Lepcha et al., 2019). The area under the curve ranges between 0 and 1; values below 0.7 were considered poor, 0.7–0.8 moderate, 0.8–0.9 good, and > 0.9 extremely good (Hanley & McNeil, 1982). The MaxEnt prediction map was then used to reclassify into four classes of habitat suitability: unsuitable (0–25%), the low (25%–50% probability of occurrence), the medium (50%–75% probability of occurrence) and the high (> 75% probability of occurrence). The area of unsuitable and each suitability class was determined by multiplying the number of presence grids in each class by the unit area (total area of Nepal (km^2) divided by the total number of grid cells of all classes) (Rana et al., 2017).

RESULTS

Current suitable habitats

The total suitable distribution area predicted by the MaxEnt model for *Podophyllum hexandrum* in Nepal was 35 931.36 km^2, which is 24.36% of the country's total land. Out of the total suitable area, about 3406.66 km^2 was predicted as highly suitable; about 9058.84 km^2 as moderately suitable and 23,465.85 km^2 as a low suitable area. Furthermore, 111 584.64 km^2 of area was predicted as unsuitable for *Podophyllum hexandrum* in Nepal, representing 75.64% of the country's total area. The unsuitable area predicted covers mostly low -elevation regions of Nepal (Table 1). The MaxEnt model showed the current highest potential distribution in the eastern and central high -elevation regions of Nepal. However, western Nepal has areas with low suitability for *Podophyllum hexandrum* under the current climatic scenario (Fig. 3).

Future projection

The predicted distribution map of *Podophyllum hexandrum* for the year 2050 and 2070 under climatic scenarios SSP-245 and SSP-585 in Nepal found considerable reduction in the climatically suitable areas (Table 1; Fig. 4). Compared to total suitable area under current climate occupying 35 931.36 km^2 (24.36%), total suitable area for *Podophyllum hexandrum* in Nepal was projected to decline to 24 674.3 km^2 (16.72%) by 2050 in SSP-245 and declining to about 18 555.8 km^2 (12.58%) area in SSP-585 (extreme climate change scenario). Similarly, by 2070, the suitable area continues to decrease to about 28 806.5 km^2 (19.52%) in SSP-245 and 27 674.7 km^2 (18.75%) in SSP-585.

The current high climatically suitable distribution range for *Podophyllum hexandrum* (2.31%) was

Table 1. Projected suitable areas of *Podophyllum hexandrum* under current and future climate change scenarios (SSP-245 and SSP-585) with low, medium and high suitability values in Nepal

Time period	Suitability	Unsuitable (0– 25%)		Low (25– 50%)		Medium (50– 75%)		High (>75%)		Total suitable area	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Current	Current	111585	75.64	23466	15.91	9058.8	6.14	3406.7	2.31	35931	24.36
2041–2060	SSP-245	122842	83.27	17816	12.07	5102.9	3.46	1755.5	1.19	24674	16.72
	SSP-585	128960	87.42	13136	8.9	4264.5	2.9	1155.5	0.78	18556	12.58
2061–2080	SSP-245	118709	80.47	20951	14.2	6507.8	4.41	1347.8	0.91	28807	19.52
	SSP-585	119841	81.24	19641	13.31	7057.1	4.78	976.77	0.66	27675	18.75

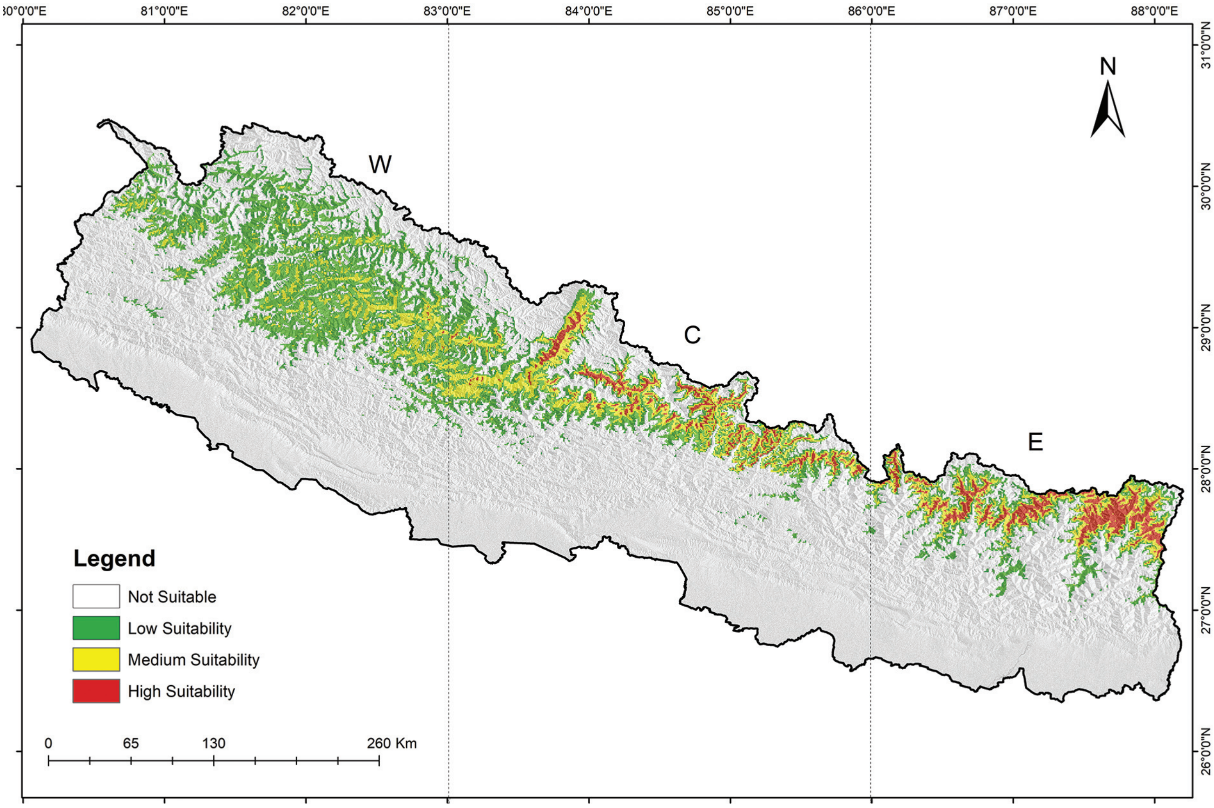

Fig. 3. Predicted potential distribution and habitat suitability of *Podophyllum hexandrum* in Nepal under current bioclimatic conditions.

contracted to just 1.19% in SSP-245 and 0.78% in SSP-585 future scenarios in 2050. The area ultimately declined to just 0.66% in SSP-585 by 2070 (Table 1). Compared to the current data, the medium and low-suitable area of *Podophyllum hexandrum* has declined in 2050 across both shared socioeconomic pathways, but there is some fluctuation in the area in 2070, with a slight expansion of low- and mid- suitable areas in both SSP-245 and SSP-585. According to future projections, eastern Nepal will have the most suitable habitat for the species under future climate change scenarios (Fig. 4).

The model's accuracy was indicated by the area under the receiver operating characteristic curve, with an average test area under the curve of 0.841, suggesting that the selected variables describe the model well for predicting the species distribution (Fig. 5).

Of the 11 predictor variables used, altitude and precipitation seasonality (Bio 15) were the two most important factors in determining suitable habitats for *Podophyllum hexandrum*, each contributing over 55% (Table 2).

The MaxEnt-generated response curve showed

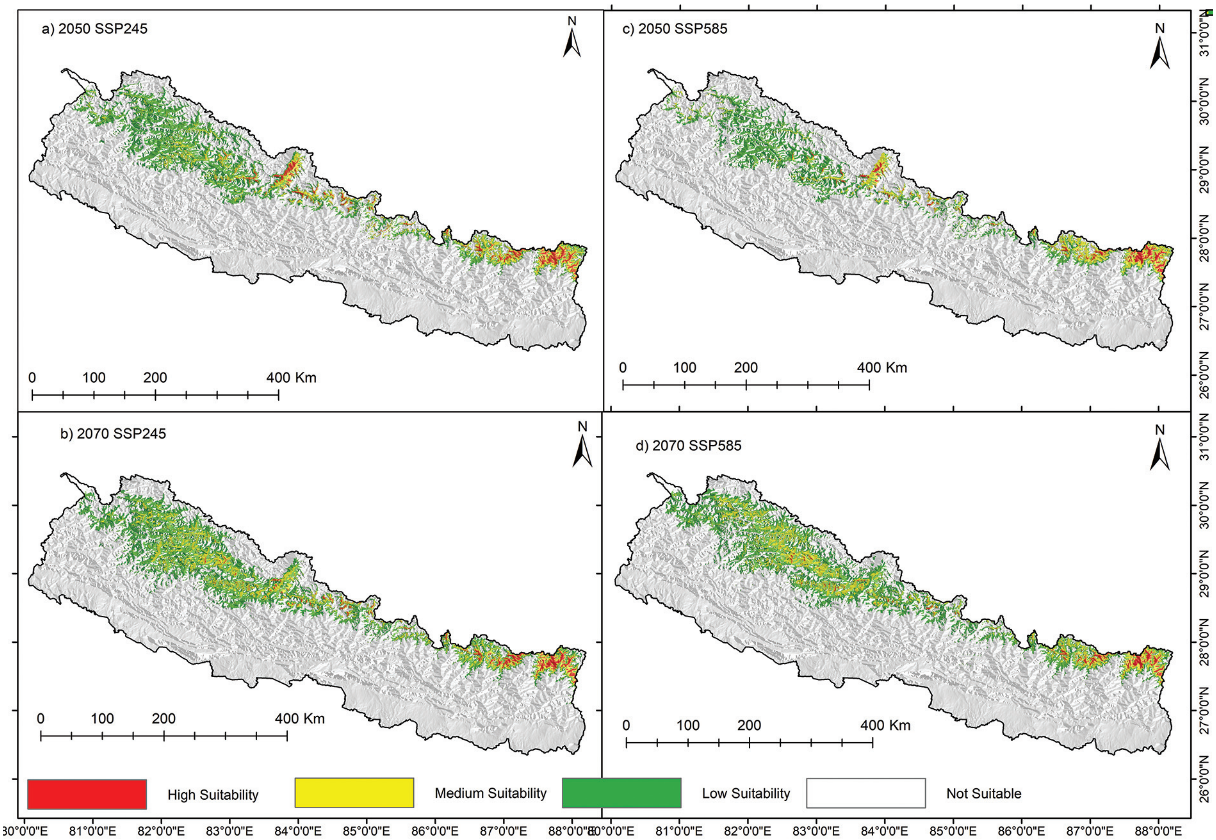

Fig. 4. Habitat suitability of *Podophyllum hexandrum* in Nepal under future bioclimatic conditions for the years 2050 and 2070 under two SSP trajectories (a, b = SSP-245 and c, d = SSP-585).

that the highest suitable area (> 0.5 probability of presence) for *Podophyllum hexandrum* was at altitudes ranging from 3500 m to 4000 m (Fig. 6a). The distribution of the species sharply declined with increasing altitude above 4000 m. Similarly, the probability of presence is high when precipitation seasonality (Bio 15) is up to 80 mm and thereafter sharply decreases (Fig. 6b). The relationship between Bio 9 (mean temperature of the driest quarter) and presence probability appeared unimodal (Fig. 6c).

Furthermore, the MaxEnt Jackknife test of variable importance also showed that the environmental variable with the highest gain when used in isolation was altitude, which is the main factor governing the distribution of *Podophyllum hexandrum* and appears to have the most useful information by itself, followed by precipitation seasonality (Bio 15). The environmental variable that resulted in the decrease in regularised training gain when omitted was precipitation of the coldest quarter (Bio19), followed by aspect (Fig. 7).

Table 2. MaxEnt-derived per cent contribution of different variables

S.N.	Variables	Per cent contribution (%)
1	Altitude	29.6
2	Bio 15 (Precipitation seasonality)	26.7
3	Bio 9 (Mean temperature of driest quarter)	9.5
4	Bio 3 (Precipitation of wettest month)	7.7
5	Bio 18 (Precipitation of warmest quarter)	5.8
6	Aspect	5.8
7.	Bio 19 (Precipitation of coldest quarter)	5.6
8	Bio 4 (Temperature seasonality; standard deviation ×100)	3.5
9	Bio 12 (Annual precipitation)	3.3
10	Bio 16 (Precipitation of wettest quarter)	2.1
11	Bio 2 (Annual precipitation)	0.3

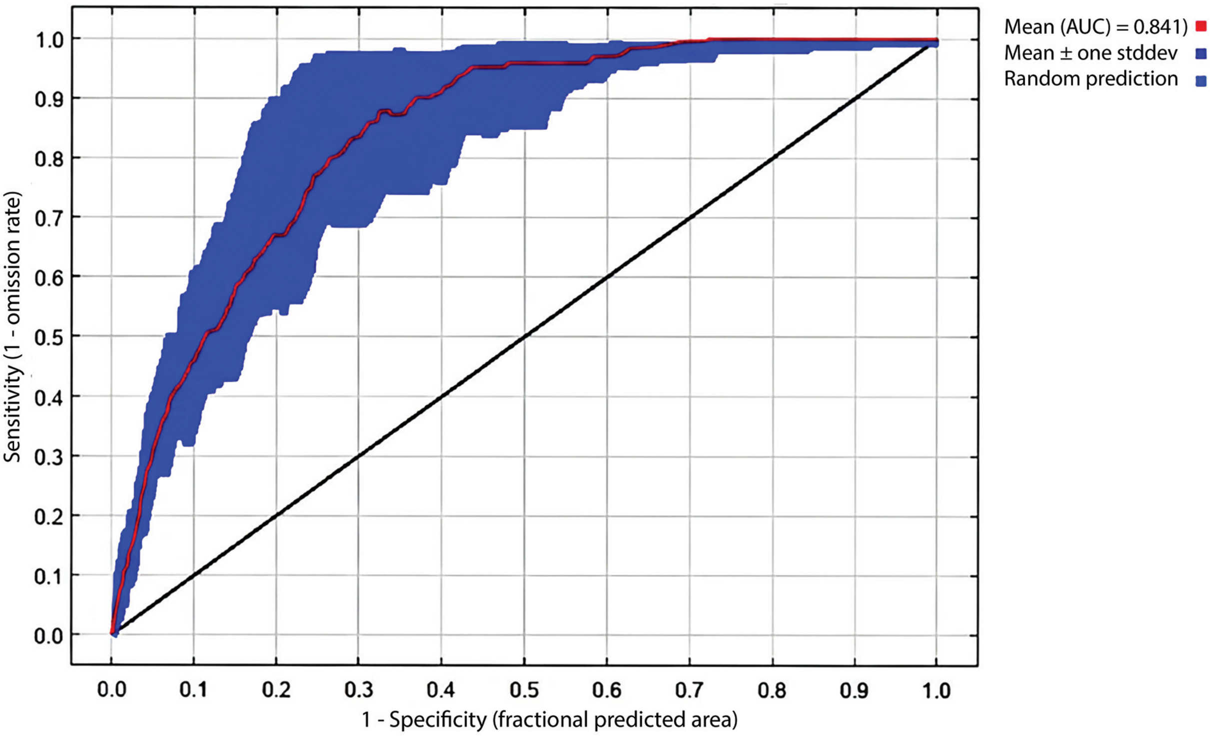

Fig. 5. Receiver operating curve showing the predictive performance of the species distribution model for *Podophyllum hexandrum*, with mean sensitivity plotted against 1-specificity across replicated runs.

DISCUSSION

The prediction of the climatically suitable niche of threatened medicinal plants is imperative for their conservation and sustainable management (Rana et al., 2017). Our model performed well, achieving the selected variables and an area under the curve of 0.841 for predicting species distribution. As the area under the curve ranges from 0.8 to 0.9, this is considered good (Hanley & McNeil, 1982). The current model predicted that only 24.36% of the country's total land is suitable habitat for the target species, whereas 75.64% of the area is unsuitable for *Podophyllum hexandrum.* A similar observation was made by Guo et al. (2014), who found that across the seven provinces in western China, 27.57% of the area was identified as suitable habitat, and 72.43% as unsuitable habitat.

To be precise, the eastern and central high-elevation regions of Nepal have the most suitable ecological niche for *Podophyllum hexandrum*. However, western Nepal has areas with mid- to low- suitability for *Podophyllum hexandrum* under the current climatic scenario. One probable reason for the low suitability in western Nepal might be declining precipitation trends, and the high mountains in central and eastern Nepal receive much more rainfall than the western region (Rana et al., 2017; Pokharel et al., 2019). Less precipitation in the western high mountains could reduce soil moisture, affecting seed germination and recruitment and leading to a low- suitability region for the species. A similar result has been reported by Banerjee et al. (2017), who mapped 18.76% of the Western Himalayan region (Himachal Pradesh, India) as suitable for *Podophyllum hexandrum*. Furthermore, the relationship between Bio 9 (mean temperature of the driest quarter) and presence probability appeared unimodal, indicating reduced suitability with increasing temperature, suggesting that chilling temperature regulates growth in *Podophyllum hexandrum* as revealed by Yang et al. (2016).

Regarding the future habitat suitability of *Podophyllum hexandrum* in 2050 and 2070 under the climatic scenarios SSP-245 and SSP-585, considerable reductions were observed in the climatically suitable areas. This result was similar to that of Shrestha et al. (2022b), which revealed that the suitability of *Podophyllum hexandrum* in Nepal will decline in the

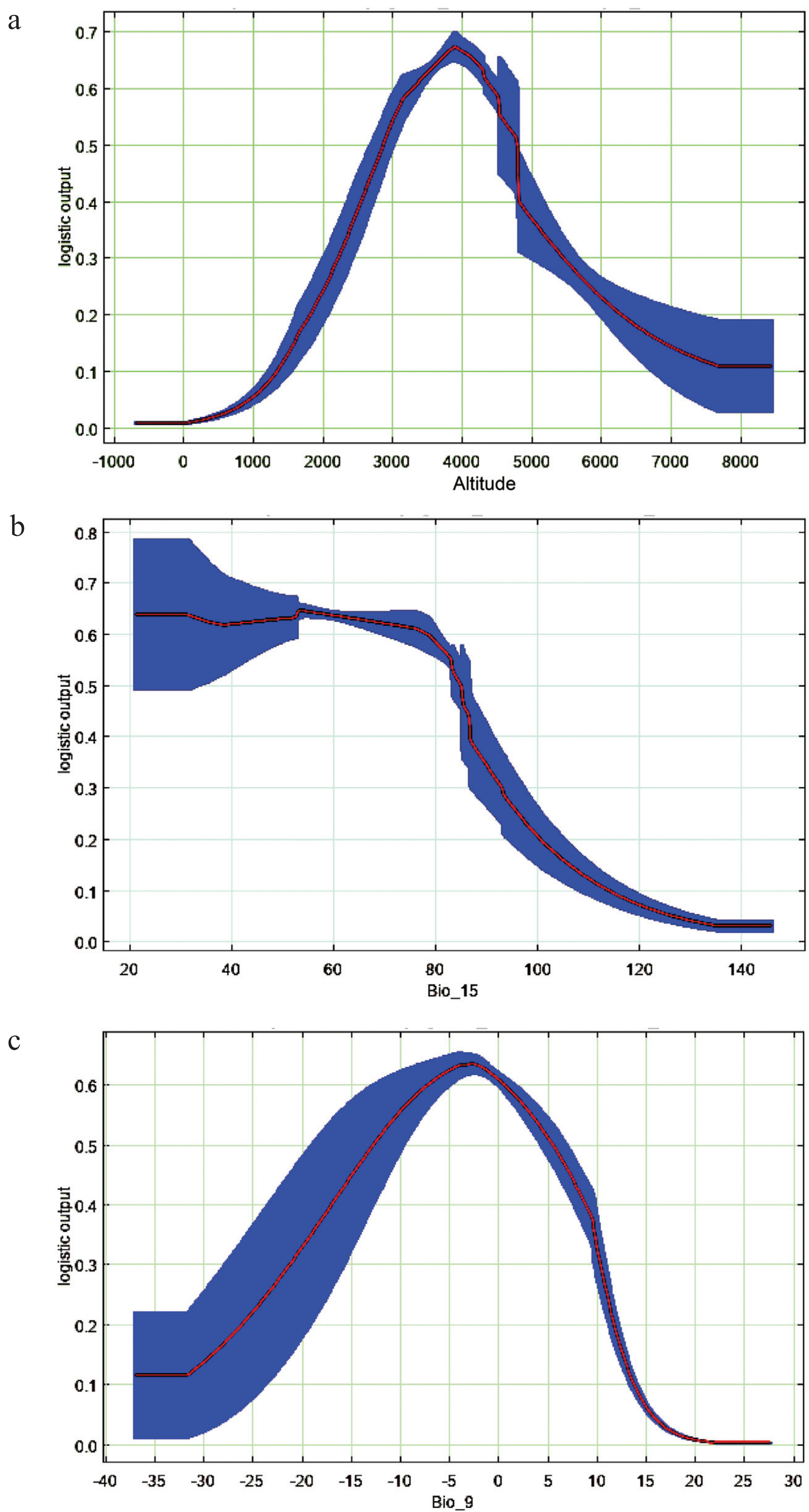

Fig. 6. Response curve of predictor variables showing logistic output (probability of presence) along the y-axis (a = altitude; b = Bio15; c = mean temperature of the driest quarter). Temperatures are expressed in °C, precipitation in mm and altitude in m. Red curves show the average response, and blue margins indicate ± SD from 10 replicate runs.

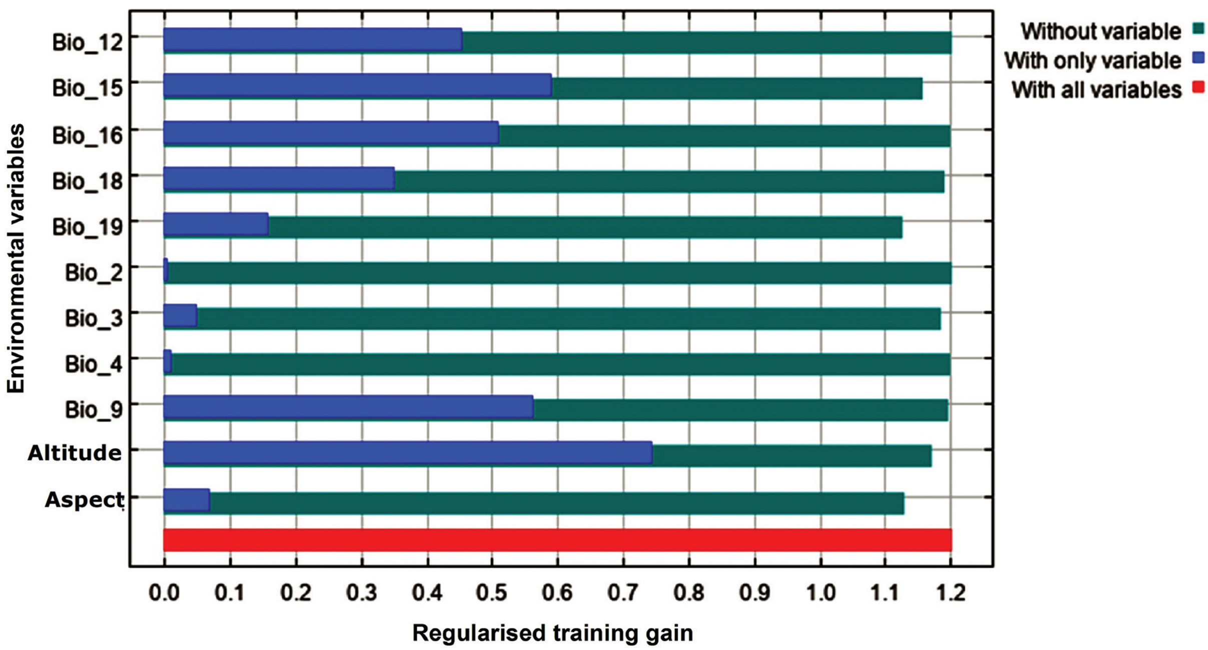

Fig. 7. Jackknife evaluations (average regularised training gain) of the relative importance of predictor variables for 10 replicates.

future, with a > 50% reduction, underscoring the threats posed by climate change to the distribution of *Podophyllum hexandrum*.

Compared to the current data, the medium and low-suitable areas of *Podophyllum hexandrum* have been constrained in 2050 and 2070 in both SSPs. However, there is some fluctuation in 2070, with a trend of a moderate increase in the low- and mid-suitable areas compared to 2050. Nevertheless, compared to the current suitable distributional area, climatic conditions seem unfavourable for *Podophyllum hexandrum* in 2070 as well, indicating a decline in the target species' suitable habitat in the future.

The natural distributions of species are determined primarily by their environmental requirements (Woodward, 1987). Changes in temperature and precipitation are altering plants' habitats, distributions, ecology, and phenology (Rana et al., 2020; Kunwar et al., 2023). In the present study, the assessment of variable importance conducted using MaxEnt-derived per cent contributions of variables and the jackknife method, proved to be strong indicators for selecting variables for model reliability. The analysis of environmental factors in the model revealed that altitude and precipitation seasonality (Bio 15) are the main factors affecting the distribution of target species. *Podophyllum hexandrum* is reported to be distributed from the middle mountains to the high Himalaya zone from 2300 m to 4600 m in Nepal (Shrestha et al., 2022a). Likewise, the MaxEnt model prediction in this study showed a suitable climatic space for *Podophyllum hexandrum*, mostly in the high mountain zone, with altitudes ranging from 3500 m to 4000 m above sea level, under the current climatic scenario. The photosynthetic activities and podophyllotoxin content in *Podophyllum hexandrum* rise as altitude increases (Alam & Naik, 2009; Vats & Kumar, 2006). Therefore, the areas within the predicted suitable altitude range can be prioritised for cultivation, reintroduction, sustainable harvesting, and conservation of *Podophyllum hexandrum*. The predicted high-probability areas were high mountain regions representing the country's temperate and sub-alpine ecological zones, similar to the observations of Banerjee et al. (2017). The model-predicted unsuitable area covered mostly low-elevation regions. The unsuitability predicted in the lowlands of Nepal might be due to *Podophyllum hexandrum's* natural habitats being high-elevation regions with extremely low temperatures (Kushwaha et al., 2008; Kumari et al., 2014; Shrestha et al., 2022a). The microclimatic conditions in the region may not be suitable for the growth of the target species, and the natural habitats of *Podophyllum hexandrum* are at high elevations.

Species distribution models often select both precipitation amount and precipitation seasonality as main predictors of plant ranges (McMahon et al., 2021). The probability of the presence of *Podophyllum hexandrum* was found to be high when precipitation seasonality (Bio 15) is up to 80 mm, and thereafter sharply decreased as the higher precipitation seasonality means more extreme differences between wet and dry periods, which could exert significant influences on regional water resources availability, affecting plant survival.

Podophyllum hexandrum is a rare medicinal plant with a low population density, and is declining each year in most of its occurrence zones (Chauhan, 2024). In addition to environmental variables influencing distribution, biological factors and anthropogenic disturbances such as low rates of natural regeneration or seed germination, prolonged dormancy, and habitat fragmentation, as well as unsustainable harvesting, also cause a decline in population size (Kala, 2005; Banerjee et al., 2017). Moreover, despite the plant being protected under the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) Appendix II and prioritised for research and management by government of Nepal, *Podophyllum hexandrum* continues to decline in wild (Sharma et al., 2004; Kunwar et al., 2014; Joshi et al., 2017; Shrestha et al., 2022b) and the species is also currently listed as globally endangered in the IUCN Red List of Species. Therefore, conservation strategies that protect existing natural populations of *Podophyllum hexandrum* and reintroduce it into suitable habitats through community-based cultivation and management programmes can aid its conservation.

This study predicts the potential distribution of *Podophyllum hexandrum* based on existing occurrence data and environmental variables. The study concluded that the existing population appears confined to a small area suitable for its occurrence, and the species faces severe survival challenges, resulting in a contraction of suitable habitats due to climate change, coupled with poor seed germination, limited natural regeneration, and overexploitation. The projected suitability map can serve as a baseline for implementing management strategies for *Podophyllum hexandrum* in Nepal. It can help plan land-use management around existing populations, discover new populations, identify top-priority survey sites, or set priorities for restoring its natural habitat for more effective conservation. Since this is a pioneering study assessing the distributional range of *Podophyllum hexandrum* in Nepal, we recommend conducting additional research on population decline rates, market dynamics, and measures to encourage sustainable cultivation. Efforts such as community-based conservation, sustainable harvesting practices, and habitat protection should also be prioritised.

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Author contributions. NP: concept or design of the article (lead); data collection (lead); data analysis (lead); methodology (lead); writing original draft (lead); review and editing (lead). BDP: data collection (supporting), data analysis (equal); methodology (equal); writing original draft (supporting); review and editing (equal). Both authors have read and approved the final version of the article.

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