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Predicting Distribution and Range Dynamics of Three Threatened *Cypripedium* Species under Climate Change Scenario in Western Himalaya

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Abstract: Climate change and anthropogenic pressure have significantly contributed to the decline of biodiversity worldwide, particularly in mountain ecosystems such as the Himalaya. In addition to being relatively sensitive to disturbances, orchids may also respond more quickly to climate change impacts than other plant species. Because of their complex biology and anthropogenic pressures on their habitat in the Himalayan region, lady's slipper orchids are considered to be a highly vulnerable group of orchids. In the present study, we examine the effect of climate change on the distribution of three threatened *Cypripedium* species (*Cypripedium cordigerum*, *Cypripedium elegans*, *and Cypripedium himalaicum*), utilizing ecological niche modeling for present and future climatic scenarios to identify key environmental determinants and population parameters. A community climate system model (CCSM ver. 4) was used to identify suitable distribution areas for future scenarios. Based on the least correlated characteristics of the species bioclimatic, topographical, and physiological characteristics, the species' climatic niche was determined. According to the results, the true skill statistic (TSS), area under the receiver operating characteristic curve (AUC), and Cohen's kappa provide more reliable predictions. Precipitation during the wettest month and precipitation during the coldest quarter are the primary climatic variables that influence the distribution of suitable areas. A total of 192 km^2 of the area was estimated to be suitable for all three species under current climate conditions. Under future climate conditions, the model predicts a trivial increase in suitable habitat areas with a shift toward the northwest. However, highly suitable habitat areas will be severely diminished. There are currently highly suitable habitats in Tungnath and the Valley of Flowers, but due to climatic factors, the habitats will become unsuitable in the future. Additionally, under future climatic scenarios, viable habitats will be identified for priority conservation to cope with the effects of climate change and anthropogenic activities. In light of these findings, conservation methods for the target species may be designed that will be successful and have the potential to prevent local extinctions.

Keywords: potential distribution; range expansion; anthropogenic pressure; climate change

1. Introduction

As one of the world's Global Biodiversity Hotspots [1,2], the Himalaya is home to more than 10,500 flowering plant species that inhabit a diverse range of eco-climatic zones. Although climate change and other anthropogenic disturbances such as habitat fragmentation, invasion by alien species, and intensive livestock grazing have contributed to the continued disruption the Himalayan ecosystems' structural and functional reliability has been altered [3,4]. Due to the vulnerability of the Himalayan ecosystems to climate change and their socio-ecological importance [5], the National Action Plan on Climate Change (NAPCC) has established sustainable ecosystem utilization to ensure that ecosystem services continue, and biodiversity is conserved [6]. It is particularly important to pay attention and take measures to conserve the climate-sensitive, endangered, threatened, and endemic plant species in the Himalaya.

Due to their specialized reproductive strategies and mycorrhizal selectivity, orchids are considered among the most ecologically sensitive vascular plants. With over 736 genera and 28,000 species, the Orchidaceae family is the second largest and most diverse family of flowering plants in the world [7]. As a result, it is currently facing an unusual process of extinction [8]. The majority of vulnerable orchid species in the world are terrestrial orchids, despite making up a minor percentage of the family. Of the 244 orchid species reported in Uttarakhand, Western Himalaya, 129 species are terrestrial in nature. In the Western Himalayas, there are 14 endemic orchid species, of which 13 are endemic to Uttarakhand [9].

Cypripedium L. is a perennial herb commonly known as Lady's Slipper. This genus consists of about 59 known species (TPL, 2017) and two varieties. According to Jalal et al. [10], there are three species of *Cypripedium* found: *C. cordigerum* D. Don, *C. elegans* Reichb.f., and *C. himalaicum* Rolfe in the Western Himalaya. Considering the scale, the dispersion of these species is affected by a number of biotic and abiotic factors, including territory size, light, and soil conditions [11]. This genus is widely distributed, with populations ranging from 2400 to 3900 m in altitude [12]. It has been reported by the International Union for Conservation of Nature and Natural Resources (IUCN) that the overall population of orchids has decreased. As a result of various factors, such as overgrazing, collection, deforestation, and climate change, suitable habitat has been lost. The three *Cypripedium* species require specific habitat conditions in order to germinate and grow, including the presence of mycorrhizal parasites, nutrient availability, and sufficient sunlight [13]. In light of the significant threat, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) included all *Cypripedium* species in Appendix II. *C. cordigerum* is categorized as Vulnerable (VU), *C. elegans,* and *C. himalaicum* as Endangered (EN) due to declining populations.

An assessment of the potential distribution of threatened species and their habitats can be made with the aid of species distribution models (SDMs). A predictive map of suitable habitats for the species can be created using environmental data and known species occurrences [14]. In addition to guiding targeted surveys, SDMs can help prioritize areas for conservation action and inform land-use planning decisions by identifying areas where threatened species are likely to occur. Furthermore, SDMs can assist in predicting the impacts of climate change on species distributions, enabling proactive management of these impacts to be accomplished.

Characterizing a species' ecological niche gives the essential knowledge required to identify crucial areas that may require prioritization of conservation actions [14] and gives an idea to constantly monitor the status of the growth parameters of various plant species in their natural habitats [15]. Terrestrial endangered species are negatively affected by climate change, and more information about their distribution is required in order to identify and rehabilitate them. Western Himalayan orchids are subject to very scanty information regarding ecological niche dynamics, distribution patterns, and the impact of climate change. *Cypripedium* species have previously been studied primarily in terms of distribution and biology [16]. Keeping in view above, it is imperative to assess their availability and potential zone in the region. Accordingly, the study attempted to clarify the present and future distribution and impact of climate change on *Cypripedium* species in the western Himalaya. The three objectives of our study are (i) to provide present geographical distribution and possible future habitats, (ii) to elucidate the effect of each independent variable in the creation of a model, and (iii) to detect suitable areas for species bestowing to global climate change projections for the years 2050 and 2070. In general, our study will provide valuable insights into climate change's potential impact on the distribution and range dynamics of *Cypripedium* species in the Western Himalayas and assist in the development of conservation strategies that will protect these threatened species for the foreseeable future.

2. Materials and Methods

2.1. Study Area

In the Indian Himalayan region, the Western Himalayas extend across Uttarakhand and Himachal Pradesh [17]. This study examined the vegetation of the cool temperate to alpine regions of Uttarakhand state (Figure 1). Approximately 8990 km^2 of this region is covered by broadleaved forest and sub-alpine coniferous forest, as well as alpine herbaceous/grassy slopes. Extremely varied topography in the alpine zone includes steep slopes terminating at famed summits, deep gorges, extensive moraines, ridges, spurs, upland plateaus, and lakes. Temperatures and rainfall are extreme in the inner dry valleys. As the Trans-Himalayan zones transition to the Greater Himalayas, the aridity increases. Also, the vegetation is sparsely distributed with an increasing cold-dry climate. There are four broad classes of vegetation in the study area: Himalayan moist temperate forests, sub-alpine forests, alpine moist scrubs, and moist alpine meadows. In addition to being habitats for various native species, these formations are unique assemblages of specialized growth forms adapted to particular environmental conditions. Poets, saints, tourists, trackers, mountaineers, researchers, pilgrims, and people from every walk of life are drawn to the region because of its panoramic beauty.

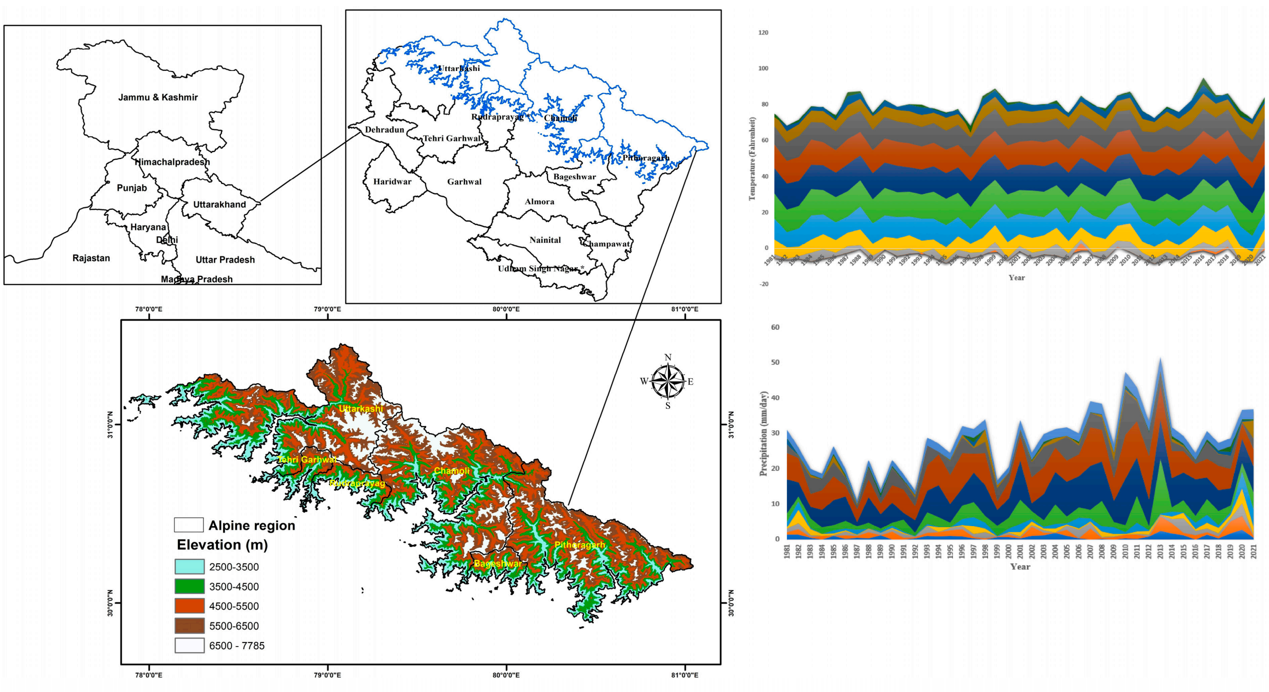

Figure 1. Study area map with decadal climatic data (Temperature, Precipitation).

2.2. Study Species

This study prioritized the conservation of three threatened terrestrial orchid species commonly known as Lady's Slipper orchids, *Cypripedium himalaicum* (EN), *Cypripedium elegans* (EN), and *Cypripedium cordigerum* (VU). Continuous harvesting, habitat destruction, over-grazing, and emerging climate change scenarios are deteriorating their areas of occurrence and leading to a rapid population decline, which reflects its endangered status. In the western Himalayas, the species have a very restricted distribution, and in the state, these species are represented by a handful of populations [10].

2.3. Data Collection

The field surveys were conducted in the regions of high-elevation forests and alpine regions of Uttarakhand during the period 2019–2021. A Global Positioning System (Garmin eTrexH) was used to determine the locations of the target species in the field. A GeoCAT assessment was conducted based on population abundance and coordinates in order to assess the IUCN threat status of the species in the study area [18]. Additionally, distribution data were compiled from global sources such as the Global Biodiversity Information Facility (GBIF.org) and local herbaria such as the Forest Research Institute (DD), Botanical Survey of India (BSD), and Wildlife Institute of India (WII).

2.4. Predictor Variables

In order to determine the impact of climate on species dispersal, several climatic factors were considered. Therefore, gridded climatic data with a spatial resolution of 1 km was acquired from the WorldClim database [19]. A Digital Elevation Model (ASTER, DEM) with a 30 m spatial resolution was used to determine topographic variables, such as slope, aspect, and elevation. Based on Sentinel-2 satellite images and the Random Forest (RF) classification algorithm, a detailed thematic vegetation map of the area was prepared in order to establish the relationship between environmental factors and habitats. Using the nearest neighbor sampling method, all variables' layers were resampled at 1 km grids. The variable with the highest correlation (Pearson correlation coefficient, 0.75) was removed from the analysis by performing a multi-collinearity analysis. Final prediction models were based on only ten variables (from a total of 12).

The future scenarios for *C. himalaicum*, *C. cordigerum*, and *C. elegans* in the region were assessed using environmental predictors (current, 2050, and 2070). The probability distribution modeling was conducted using a total of 22 environmental variables for each period. For the future climatic scenario, 19 bioclimatic variables with a spatial resolution of 1 km were also used. According to the IPCC 5th assessment report, the climatic scenarios for the 2050s and 2070s have been derived from the global climate model (GCM). In order to predict the probable impact of future climate change on the species of interest, we used the community climate system model version 4 (CCSM 4). As a means of assessing potential suitability ranges for species habitation in the 2050s (2041–2060) and the 2070s (2061–2080), the scenarios RCP 2.6 (the lowest GHG emissions scenario) and RCP 8.5 (the highest GHC emissions scenario) were used.

2.5. Predictive Modeling

We created the model using the Maximum Entropy Modeling (MaxEnt) machine learning methodology. For *C. himalaicum*, *C. elegans*, and *C. cordigerum*, 20, 12, and 10 presence records were used. The Jack-knife test was utilized to understand the relative influence of each predictor variable [20]. In addition, the predictive model allows for the creation of replicated runs which are used for cross-ratification, bootstrapping, and repeated subsampling. To prevent over-prediction and reduce model over-fitting, the regularization multiplier was set at 0.1 [20]. Therefore, the presence data is randomly divided into 'training' and 'test' sets [21] in the ratio of 75:25 while maintaining the other values as defaults. A Jack-knife test involves the prediction of a single location that is excluded from the 'training' dataset [22]. The predictive performance of the model was evaluated by (ROC) analysis, true skill statistics (TSS), Kappa statistics, sensitivity (true positive rate (TPR)) and false alarm rate (FAR) (1—specificity). The model's robustness was also assessed by the AUC value. AUC value 0.5 shows a low fit model, 0.5–0.7 indicates lower accuracy of the model, 0.7–0.9 denotes the reasonable performance of the model, and values > 0.9 demonstrate the high performance of the selected model [23].

3. Results

3.1. Habitat Preferences of the Species

Cypripedium populations were recorded between 2500 and 4000 m in different micro-habitat conditions: cool temperate forests, sub-alpine forests, grassy slopes, and alpine moist scrubs. Slopes ranging from 25 to 40 degrees and which are exposed to the south and north characterize the microhabitat condition. There is a significant difference in the distribution of species between different types of habitats. It was found that mixed herbaceous meadows (short forbs), mat-forming shrubs, and tall forbs were the most preferred types of habitats. In warm temperate sub-alpine forests and on the upper edges of alpine meadows, *C. cordigerum* is found sporadically in birch (Betula utilis) forests.

As determined by the Jackknife test, the mean diurnal range (Bio-2), soil type, and bio-3 (isothermality) were the variables that did the best job of predicting suitable habitats when used separately. Cumulatively, these variables contributed 70%. Additionally, altitude, slope, aspect, and temperature seasonality (Bio-4), as well as vegetation type, did not contribute significantly to the weight. As a consequence, they are likely to have a limited impact on the distribution of *Cypripedium* species. Mean daylight range (Bio-2) and aspect were the strongest predictors for *C. himalaicum* distribution, with 44.9% and 25.2%, respectively. Soil type and bio 11 (mean temperature of the coldest quarter) are considered strong predictors for *C. cordigerum* with 30% and 16%, respectively, while isothermally (Bio-3), altitude, and aspect structured the habitat suitability of *C. elegans* with 48.4%, 22.1%, and 8.4%, respectively (Table 1). The combination of all climate and topographic elements structured the distribution pattern of all the *Cypripedium* species.

Table 1. Environmental variable contributions showing their respective percent contribution.

Variables	*C. himalaicum*	*C. cordigerum*	*C. elegans*
Bio-2	44.9	2.5	1.4
Aspect	25.2	14.5	8.4
Bio-12	11.4	3.4	–
Bio-11	9.3	16.6	6.2
Altitude	7.7	1.3	22.1
Bio-3	–	4.9	48.4
Slope	1.1	4.1	–
Vegetation type	–	2.4	–
Bio-4	–	0.4	7.9
Soil type	0.5	30.1	–

3.2. Potential Distribution and Habitat Preferences

Habitat suitability analysis and field surveys revealed that *Cypripedium* species prefer the understory of *Betula* forest, alpine grassy slopes, and moist rocky habitats. *C. himalaicum* showed high suitability in the moist grassy slopes and herbaceous meadows in association with *Danthonia cachemyriana*, *Anemone tetrasepala*, *Aconitum heterophyllum*, *Rhododendron lepidotum*, and *Nardostachys jatamansi*. It is occasionally found under the canopy of *Betula utilis*. Similarly, *C. cordigerum* is mainly distributed in the forested area of *Quercus semecarpifolia*, *Abies pindrow*, and *A. spectabilis*, and *Betula utilis* having gentle to steeper slopes (>35°) in the broken rocky areas and amidst open scrubs. *C. elegans* is showed distribution in moist slopes along 26–34°, and humus-rich soils. It was found to be associated with *Smilacina purpurea*, *Viola biflora*, *Fragaria nubicola*, *Gerbera* sp., *Caltha palustris*, *Clematis* sp., *Ranunculus hirtellus,* and *Selinum vaginatum*. In some places, it forms an association with *Bergenia stracheyi* and *Rhododendron* thickets.

3.3. Habitat Suitability under Current Climatic Conditions

Habitat suitability analysis under current climatic conditions reveals that *C. himalaicum* has a highly suitable habitat of about 209 km^2, whereas the less suitable habitat of 363 km^2. *C. cordigerum* has a highly suitable habitat of about 199 km^2 and a less suitable of about 600 km^2 area, and C. *elegans* showed an area of 215 km^2 as a highly suitable habitat and 315 km^2 as the less suited. All three species showed maximum suitable habitats on grassy slopes (55%) dominated by *D. cachemyriana* and sub-alpine (*Betula utilis*, *Q. semicarpifolia*) forests (40%) and moist herbaceous meadows (5%) (Figure 2).

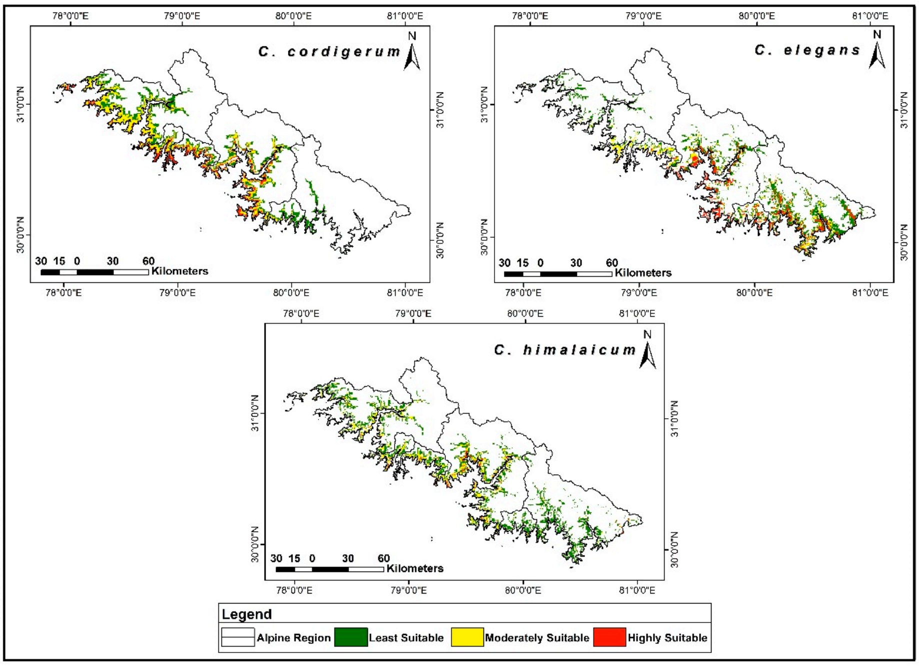

Figure 2. Current habitat suitability of *C. cordigerum*, *C. elegans*, and *C. himalaicum*.

3.4. Distribution Prediction in Future Climate Scenarios

According to RCP 4.5 and RCP 8.5, Figures 3–5 illustrate the projected distributions of each species for 2050 and 2070. The AUC value ranged from 0.70 to 0.92 for predicting the suitability of *Cypripedium* species for future distribution, which indicates that the models performed well. Furthermore, the range of TSS values (0.75 to 0.90) indicated the robustness of the model. As shown in Table 2, Figure 5, the probable area of occurrence for *C. himalaicum* is highest at 2.6% (190.23 km^2) in RCP 2.6 for 2050, while the lowest at 107 km^2) in RCP 8.5 for 2070. The maximum probable zone (97 km^2) for *C. cordigerum* in 2050 was predicted based on RCP 2.6, and the lowest zone (51 km^2) was predicted based on RCP 8.5 in 2070 (Table 3 and Figure 3). Maximum future climatic suitability (199 km^2) for *C. elegans* was in 2070 of RCP 2.6, while the lowest (102 km^2) was in the year 2050 RCP of 2.6 (Table 4, Figure 4)**.**

Annual mean temperature (Bio-1) and annual precipitation (Bio-12) have been highly influential on *C. himalaicum* distributions in 2050. By 2070, the coldest quarter (Bio-19) and the wettest month (Bio-13) will play a significant role. Under RCP 2.6 and 8.6, *C. cordigerum* will be influenced by elevation and annual mean temperature (Bio-1), whereas in 2070, the mean temperature of the coldest month (Bio-6) and precipitation of the wettest month (Bio-13) will determine its distribution. During the 2050 time period, *C. elegans* distribution will be influenced by annual precipitation and precipitation of the wettest month, while the distribution will be influenced by the coldest quarter's precipitation (Bio-19) and annual precipitation (Bio-12).

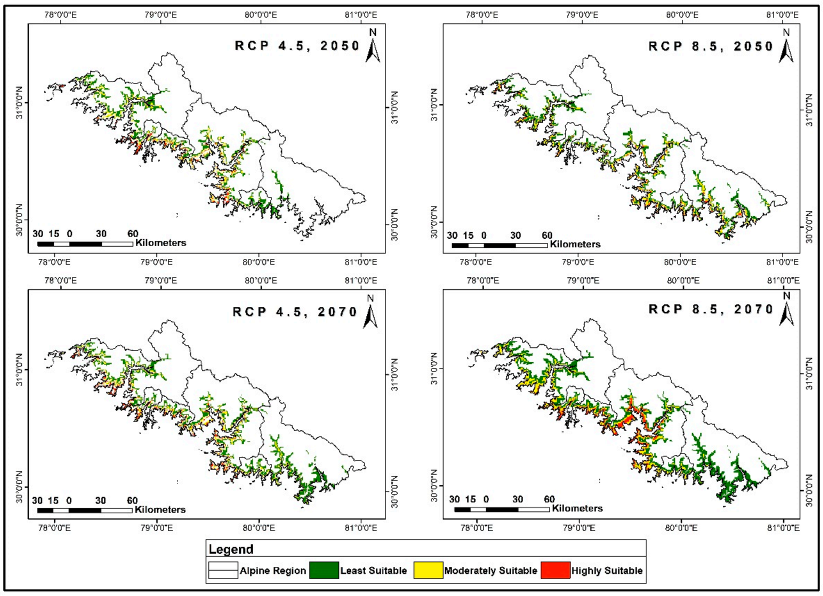

Figure 3. Predicted future habitat suitability for *C. cordigerum*.

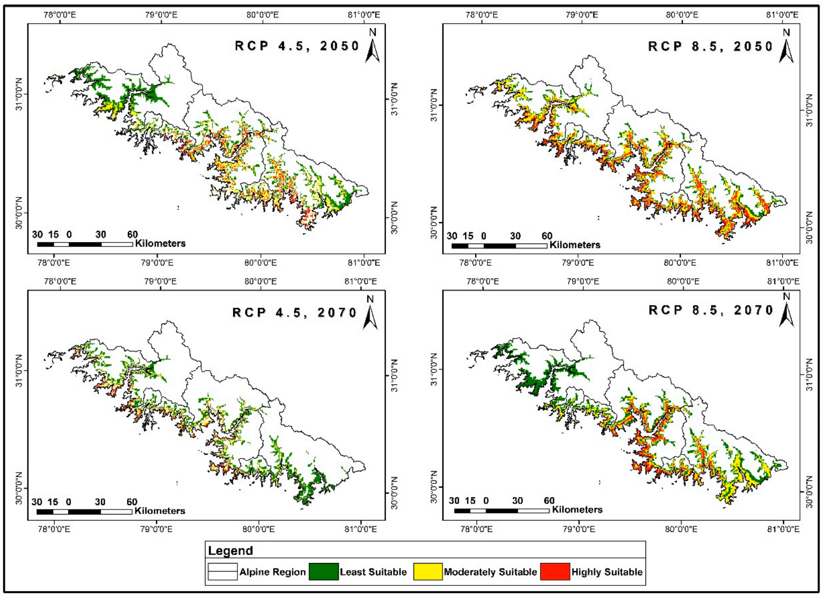

Figure 4. Predicted future habitat suitability for *C. elegans*.

Table 2. Prediction accuracy of *C. himalaicum* species under future climatic scenarios.

	Year 2050				Year 2070			
	RCP 2.6		RCP 8.6		RCP 2.6		RCP 8.6	
AUC value	0.84		0.75		0.92		0.87	
TSS value	0.75		0.81		0.88		0.74	
Percentage of contribution	Bio-1	Bio-19	Bio-12	Bio-6	Bio-19	Bio-1	Bio-13	Bio-6
Value (%)	34	27	41	25	37	24	31	30
Area in km^2 (10th percentile training presence threshold rule)	190		124		140		107	
Percentage of Area	2.6		1.5		1.7		1.3	
Highest probability of species occurrence	0.74		0.65		0.71		0.81	

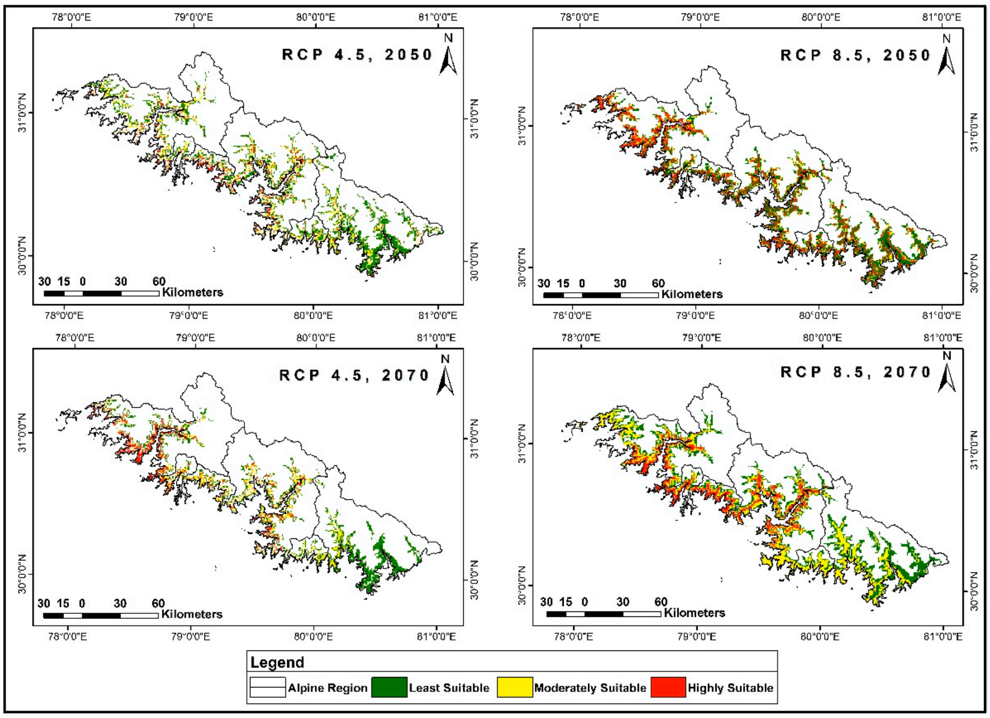

Figure 5. Predicted future habitat suitability for *C. himalaicum*.

Table 3. Prediction accuracy of *C. cordigerum* under future climatic scenarios.

	2050				**Year 2070**			
	RCP 2.6		**RCP 8.6**		**RCP 2.6**		**RCP 8.6**	
AUC value	0.71		0.71		0.81		0.91	
TSS value	0.75		0.81		0.79		0.69	
Percentage of contribution	Altitude	Bio-19	Bio-1	Bio-12	Bio-12	Bio-6	Bio-13	Bio-19
Value (%)	40	21	35	27	23	31	34	29
Area in km^2 ((10th percentile training presence threshold rule)	97		55		86		51	
Percentage of Area	1.2		0.7		1.09		0.6	
Highest probability of species occurrence	0.65		0.71		0.68		0.7	

Table 4. Prediction accuracy of *C. elegans* under future climatic scenarios.

	2050				**Year 2070**			
	RCP 2.6		**RCP 8.6**		**RCP 2.6**		**RCP 8.6**	
AUC value	0.78		0.80		0.89		0.70	
TSS value	0.80		0.82		0.87		0.90	
Percentage of contribution	Bio-12	Bio-19	Bio-13	Slope	Bio-19	Bio-1	Bio-12	Bio-19
value	37	25	34	26	37	24	37	32
Area in km^2 ((10th percentile training presence threshold rule)	102		189		199		154	
Percentage of Area	1.3		2.4		2.5		1.9	
Highest probability of species occurrence	0.61		0.62		0.65		0.59	

3.5. Range Dynamics under Future Climatic Scenarios

According to future scenarios, Tungnath, Panwalikantha, Garbyang, Badrinath, Deodi (Rishiganga valley), Janki Chatti, Tungnath, Yamnotri are predicted to become unsuitable for *C. himalaicum* growth by 2050. Additionally, the Ralam valley, Tungnath, Bajmora, and Dibrugheta areas will no longer be suitable for *C. elegans*. In the future, however, forest-dwelling species of *C. cordigerum* that have a limited distribution in the alpine region will be less affected. In future scenarios, the following areas are likely to be more suitable for all *Cypripedium* species: Kedarnath Wildlife Sanctuary, Valley of Flowers National Park, Kandara, and Har-Ki-Don (Figures 6–8).

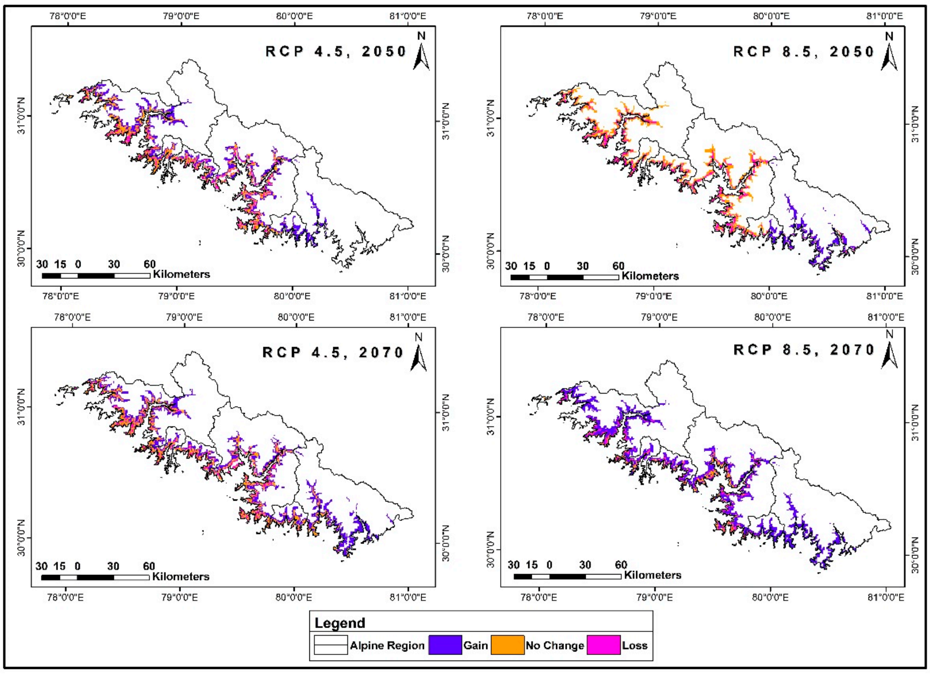

Figure 6. Predicted range contraction for *C. cordigerum*.

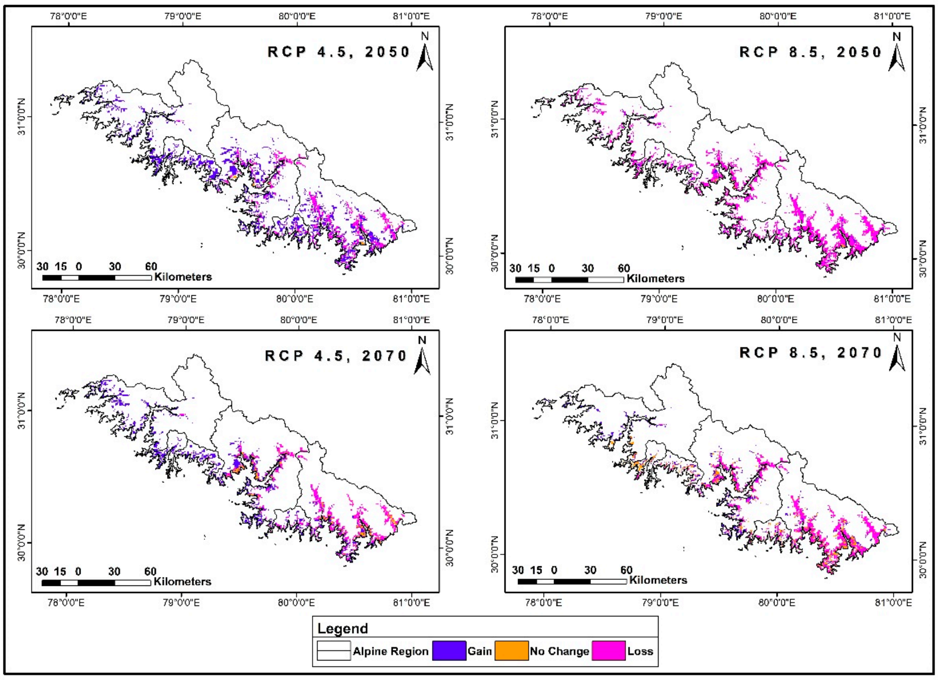

Figure 7. Predicted range contraction for *C. elegans*.

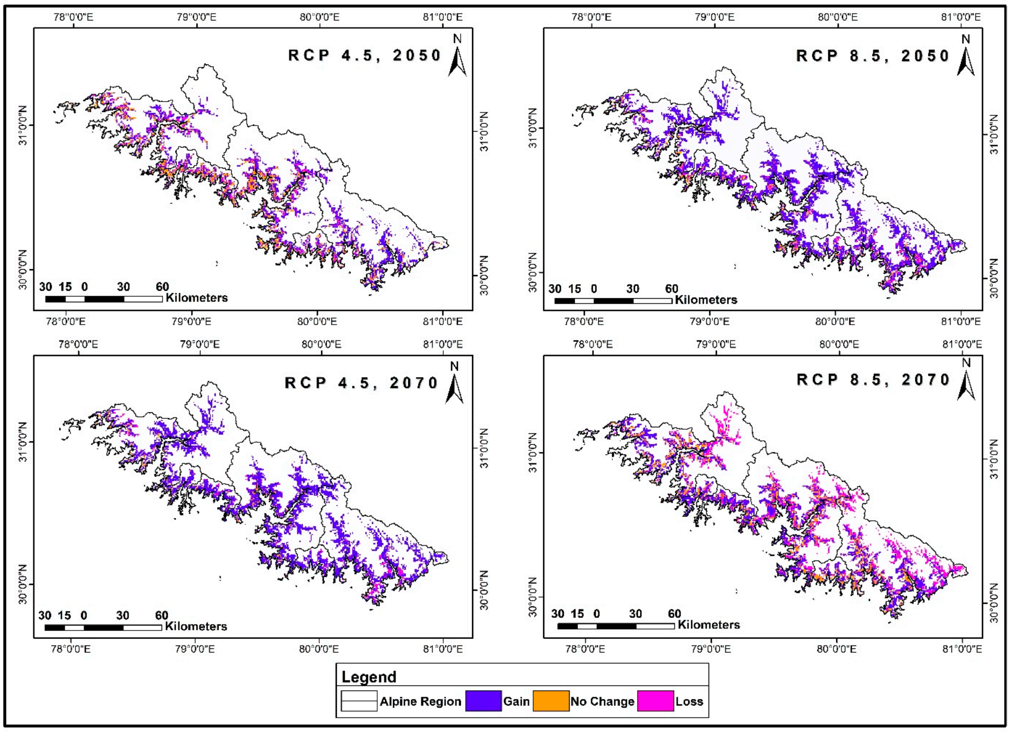

Figure 8. Predicted range contraction for *C. himalaicum*.

On the basis of the distribution trends for two time periods (2050 and 2070), as well as future climate scenarios (RCPs 4.5 and 8.5), a significant decline in the overall habitat is predicted. RCP8.5 (2070) showed moderate habitat declines for all species, with RCP 4.5 (2050) showing an overall decline. According to these future scenarios, 60% of suitable habitats will be damaged and no longer suitable for these species.

4. Discussion

Climate and precipitation play a crucial role in defining species tolerance ranges of distribution, among other environmental factors. A change in global temperatures and precipitation patterns has a detrimental impact on vulnerable species' habitats and distributions [24]. Various methods can be used to evaluate the probable range of species occurrence and population demographics. A gridded dataset of environmental parameters as well as the presence and absence of specific species, is used to develop these methods [25]. An important correlative approach to assessing a species' potential ecological niche and predicting its future distribution is to model its ecological niche using information about its environmental conditions. As a result of correlation niche modeling, conservation and management of rare taxa have been supported and have been encouraged to identify suitable habitats for the long-term maintenance of species populations [26]. They are spatially explicit and can be applied to a wide range of species at a scale that is suitable for conservation purposes [27].

For centuries, scientists have observed and documented consistent relationships between the distribution of species and their physical environment. Since the advent of numerical models, quantitative algorithms are increasingly being used for both the description of patterns and the prediction of future patterns [27]. Mathematical techniques can be applied to a wide range of applications with varying degrees of success. A number of published studies have been used in this study to demonstrate that species distribution models (SDMs) are capable of accurately predicting the natural distribution of species. With the help of high-quality survey data as well as relevant predictors, in addition to being functionally viable, these specific models are capable of providing genuine distribution ranges. They provide both ecological insights as well as a high degree of predictability. As a tool for predicting the existing and future distribution ranges of species, species distribution modeling (SDM) is essential for the development of various strategic management approaches for habitat conservation and management. Technological advancements in SDMs have enabled ensemble modeling to become a viable method due to growing data availability [28].

This study aims to model the current and future distributions of three *Cypripedium* species using a machine-learning approach. This study examines the dynamics of the species niches, both in the present and in the future, and estimates the size and pace of possible range expansions and contractions. Data with a 1 km^2 spatial resolution were used because the current study area is topographically complex. Many applications require data with a high spatial resolution (1 km^2) in hilly and other regions with severe climate gradients in order to capture environmental variation that would otherwise be lost at lower spatial resolutions [19,29].

Climate may still play a significant role in determining how quickly natural populations regenerate and disperse. Many climate prediction models indicate that climate change will be a dominant stressor in the second half of the twenty-first century. It is likely that species with major human threats, a small distribution range, a more compact population structure, and high habitat distinctiveness will be particularly vulnerable to habitat loss and changes in distribution [14,30]. Through the use of species distribution models, it has been possible to find potentially suitable habitats for vulnerable species. Climate change has been shown to have a significant impact on species distributions [31–33] by expanding, changing, or reducing ranges.

Overlaying the modal outputs on satellite images, a moist temperate forest, open *R. anthopogon* scrub, moist-shady areas under Himalayan Birch, Kharsu Oak, and Salix forests had high habitat suitability, while Abies forest in temperate and less disturbed herbaceous meadows had medium to low habitat suitability.

Satellite images showed high habitat suitability of moist temperate forests, open *R. anthopogon* scrub, and moist-shady areas under Himalayan Birch, Kharsu Oak, and *Salix* trees. Abies forests in temperate herbaceous meadows had medium to low habitat suitability.

The climate is one of several abiotic factors that define a species' range limits and determine its ecological niche, which is used in SDM models [34]. It is crucial for the management and protection of vulnerable and endemic species to be able to predict appropriate ecological niches under current and future climatic conditions [35]. Because climatic factors are not the primary determinant of habitat suitability, the real niche of species is often smaller than that suggested by model-based forecasts [36]. In terms of topographic variables, the aspect contributed the highest weight when used alone. Climate predictors such as diurnal range and isothermality (Bio-2 and Bio-3) provide considerable information on the distribution of all *Cypripedium* species. Alpine distribution patterns and community structure are greatly influenced by topographical (elevation, aspect) and bioclimatic factors [37]. There are some species that prefer moist and marshy habitats over open grasslands or rocky terrain, which are crucial factors in alpine biodiversity [38]. There has been rapid climate change in the Himalayas [39]. Species in alpine habitats are more vulnerable to extinction because they have a limited geographic range. Species migrating to high latitudes or elevations are disproportionately affected by climate change [40].

Based on model output, climate scenarios RCP 4.5 and RCP 8.5 indicate climatically acceptable habitats move northerly or northeasterly and become less suitable as elevation decreases. As a result, we hypothesize that north-facing mountain slopes have greater biomass, coverage, height, species diversity, and soil nutrient content than south-facing slopes [41]. Earlier studies in the Himalayan region have also reported species moving north and northeast due to climate change [42–44]. Changing temperatures will displace cold-adapted species with warm-adapted ones, which may result in habitat loss [45]. Northwestern Indian Himalayan rainfall declined similarly, according to Hasan et al. [46]. Changes in climatic conditions contribute to significant declines in precipitation for the driest quartile while increasing precipitation and temperature for the wettest quartile [47]. In the Western Himalayas, winter precipitation has declined, and dry days have increased continuously [48].

Future climate scenarios will influence the distribution of *Cypripedium* species based on average yearly temperatures (Bio-1), precipitation (Bio-12), precipitation of the coldest quartile (Bio-19), precipitation of the wettest month (Bio-13), and topography. RCP 4.5 (2050) would result in fewer suitable habitats for this species than RCP 8.5 (2050 and 2070), indicating that climatic changes and changes in land use patterns due to increasing emission rates would harm habitat suitability. The model predicts that climatic changes will result in new habitat suitability classes (referred to as habitat gains) at lower emission rates (such as RCP 4.5 vs. RCP 8.5), with the biggest gains occurring at lower emission rates. Cypripedium species are likely to benefit more from the RCP 4.5 scenario than from the RCP 8.5 scenario in the northern part of Uttarakhand. In addition, future climatic niche loss may be explained by the warming of lower altitudes or locations where the species are now found.

Based on our ensemble model, we predicted that habitat suitability for these three orchid species would drastically decline under future climate change scenarios, peaking at RCP 8.5 by 2070. Although many of the currently suitable ecosystems will become unsuitable in the future, certain areas with unsuitable climates will be able to adapt to changing climatic conditions. Conservation areas for rewilding and restoration may be established in regions that create appropriate habitats. According to observations, the rapid warming of the climate in the western Himalayas might be one of the major reasons for the significant decline in the niches of species, which is observed to be faster than the projected increases in temperature in other similar ecosystems around the world. Due to lower GHG emissions in RCP 4.5, most of the regions are expected to remain acceptable habitats for both species. According to RCP 8.5, the number of suitable habitats is expected to decline by approximately 55%. It is expected that the Valley of Flowers National Park, Kedarnath Wildlife Sanctuary, Kandara sites, and Har ki Doon will remain suitable for all species. A limited range expansion is also observed at RCPs 4.5 and 8.5 for *C. himalaicum*, *C. cordigerum*, and *C. elegans* in the eastern parts of the Uttarakhand. As a result, the range expansion in western Uttarakhand is greater. The results of this study confirm predictions that many Himalayan plant species will lose habitat as a result of climate change [49]. Under the influence of climate change, increased temperatures and earlier snowmelt may lead to enzymatic dysfunction, inhibiting plant growth and placing limitations on their developmental route [50]. Changing temperature affects plant phenology, which may reduce future habitat appropriateness [51]. There have been significant increases in the yearly average temperature and the average temperature of the wettest quartile of the north-western Himalaya [52].

As well as climate change, habitat loss resulting from excessive grazing, livestock trampling, and various development activities (road construction) have significantly affected the species. In addition to being medicinal, orchids are also horticultural [53,54]. Uncontrolled wild collecting and alien species invasion have put many of these species at risk [16]. A CITES listing of the Orchidaceae family has been imposed due to the impending threat (Appendices II). Western Himalaya showed a contiguous distribution of all three Cypripedium species owing to habitat specificity [55]. Orchids seem to prefer moist, shady, and humus-rich soils, as many of them grow in moist, shady, and humus-rich areas [56]. It has been reported that Pindari valley had the highest density of *C. cordigerum*, *C. elegans*, and *C. himalaicum* [57], respectively, of 0.8, 5.5, and 0.9 individuals/m^2, respectively.

The results of predictive modeling indicate that the species of *Cypripedium* are likely sensitive to changes in Annual mean temperature (Bio-1), annual precipitation (Bio-12), precipitation of wettest month (Bio-13), precipitation of coldest quarter (Bio-19), altitude and aspect. In general, the species' optimal bioclimatic requirements are defined as warm quartile temperatures of 6–7 °C, total precipitation of 1500–1700 mm per month, overall precipitation of 1200–1500 mm, altitude between 2700–3800 m on an east-facing slope.

Substantial alterations in these typical bioclimatic and topographic conditions could have a significant impact on the phenological behavior and the future spread of species. The annual total precipitation is useful in assessing how significant water availability is to a species range because it closely equates to total water intake. When the potential range of a species is impacted by extreme precipitation conditions throughout the year, the wettest month can be useful. While precipitation during the coldest quarter of the year gives total precipitation during the three coldest months of the year, this information can be useful for understanding how such climatic circumstances may affect species' seasonal distributions. The current study gives an overview of habitat suitability and expected changes in response to future climatic scenarios, as well as changes in the species' geomorphological profile. Several conservation activities on a local and regional scale in the Western Himalayas could benefit from the findings of this study. It is important to note that the model was built to predict the fundamental niche of the species rather than its understood niche, which is one of the study's limitations. The species' actual niche might not match what our model predicted. Another obstacle is that biotic elements like plant-mycorrhizal association or plant-pollinator interaction were not taken into account while modeling the habitat appropriateness of *Cypripedium* at different time scales (2050 and 2070). The potential range of the Orchidaceae species might be overestimated due to biotic interactions, especially mycorrhizal interactions [58].

5. Conclusions

In addition to being habitat specific, each of the three threatened *Cypripedium* species are suffering from severe stress and requires immediate attention. Anthropogenic stress and environmental perturbations contribute to additional strain on the species. Consequently, the present study evaluates the habitat suitability of three *Cypripedium* species and predicts the likely effects of climatic warming on their spread in the Western Himalayas in the future. The major predictors were the temperature average over the year (Bio- 1), precipitation average over the year (Bio-12), precipitation during the coldest quarter (Bio-19), and precipitation during the wettest month (Bio-13), as well as topography. There is an ecological niche for the species of approximately 192 km^2, which corresponds to approximately 1.5% of the total geographic area of the alpine region in the state. Climate change is likely to result in a greater loss of habitat for species in the eastern portion of the state. Climate change scenarios (RCP 4.5 & 8.5) will lead to a substantial decline in species habitat suitability compared to current predictions. The most important priority should be the selection and maintenance of a stable ecosystem that is resistant to the effects of climate change based on the predictions of habitat contraction. A number of additional preventive actions may also be undertaken in sensitive areas of the state in order to protect and restore the species. A significant threat to the population arrangement of the selected species is the disruption and alteration of land use/land cover caused by human activities such as the expansion of human habitats, agricultural operations, and animal husbandry. There are a variety of phytosociological features that demonstrate this.

In addition to providing useful information for conservation planning and participatory management, these distribution maps will also enable the identification of other sites not previously documented. Thus, the Valley of Flowers area is crucial for protecting Cypripedium's wild germplasm resources since it is one of the best-preserved tracts of extremely favorable habitat in the world for *Cypripedium* in the future. Several policymaking agencies may benefit from the information generated, including the Department of Forestry, the Board of Biodiversity, the Board of Medicinal Plants (SMPB), and the Ministry of Environment, Forest, and Climate Change (MOEF & CC). Through the incorporation of a Biodiversity Management Committee (BMC), the restoration of existing habitats would be one step forward.

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