SPECIES

Ensemble modeling of *Rhododendron arboreum* distribution in Nepal: Assessing current patterns and projecting future changes

Samit Kafle[1*], Divya Thapa[2], Keshav Ghimire[3], Jeetendra Gautam[1]

To Cite:
Kafle S, Thapa D, Ghimire K, Gautam J. Ensemble modeling of *Rhododendron arboreum* distribution in Nepal: Assessing current patterns and projecting future changes. *Species* 2023; 24: e81s1590
doi: https://doi.org/10.54905/disssi.v24i74.e81s1590

Author Affiliation:
[1]Agriculture and Forestry University, Faculty of Forestry, Hetauda 44100, Nepal
[2]Institute of Science and Technology, Tribhuvan University, Kathmandu 44618, Nepal
[3]Forest Research and Training Centre, Kathmandu 44618, Nepal

[*]Corresponding author
Agriculture and Forestry University, Faculty of Forestry, Hetauda 44100,
Nepal
Email: samitkafle67@gmail.com
ORCID: 0009-0004-6830-3443

Peer-Review History
Received: 29 July 2023
Reviewed & Revised: 02/August/2023 to 03/October/2023
Accepted: 06 October 2023
Published: 12 October 2023

Peer-Review Model
External peer-review was done through double-blind method.

Species
pISSN 2319–5746; eISSN 2319–5754

ABSTRACT

This research article presents a comprehensive analysis of the distribution patterns of *Rhododendron arboreum* in Nepal, encompassing the current distribution and future projections. We employed an ensemble approach by combining eight selected models with AUC > 0.8. Resulting ensemble model demonstrated remarkable predictive accuracy, achieving an AUC value of 0.97 and a TSS value of 0.77. Our analysis unveiled that within total land area of Nepal, approximately 115,317.1 km2 were deemed unsuitable for *Rhododendron arboreum*, while 32,198.89 km2 were identified as suitable habitats. Future projections for 2050 and 2070 under the SSP2-4.5 and SSP5-8.5 scenarios showed significant changes in habitat suitability. By 2050, under SSP2-4.5, 10,710.39 km2 were projected to be lost, while 4,792.78 km2 were gained. Under SSP5-8.5, more significant loss of 14,237.64 km2 and a smaller gain of 5,696.41 km2 were anticipated. In 2070, further losses in suitable habitat were projected under both scenarios. A consistent upward movement in the suitable habitat elevation range was observed from the current period to the projected years of 2050 and 2070. These findings underscore the urgency of implementing proactive conservation measures to safeguard *Rhododendron arboreum* in the face of climate change. The research provides valuable insights for informing conservation strategies and emphasizes the ecological significance of this species in Nepal. Considering distribution patterns and elevation shifts, our study contributes to a comprehensive understanding of the species dynamics and supports effective conservation planning.

Keywords: Biomod2; Climate change; Ensemble modeling; Rhododendron arboreum; Species distribution modeling

DISCOVERY SCIENTIFIC SOCIETY

1. INTRODUCTION

Over the last century, global temperatures have been discernible increased by approximately 1°C, with a particularly accelerated rise observed in the past three decades (Zhao et al., 2021). This significant shift in climate patterns has profoundly impacted the spatial distribution of plant species. The dynamic nature of climate change has influenced and continues to shape the geographical distribution of plants on a global scale. The current magnitude of climate change poses such a significant threat that even the most stringent measures implemented to mitigate its detrimental effects would prove insufficient (Chhetri et al., 2021; Pachauri et al., 2014). The global climate shift poses a significant threat to Earth's biological diversity. As a result, the global climate shift has the potential to significantly impact the species distribution, leading to the loss of suitable habitats for some of them. Given the potential threats to species distribution and habitats, it is crucial to make informed management decisions.

This requires a deeper understanding of how global climate change affects species distribution. These decisions are essential to minimize the destructive consequences of future climate change on species habitats (Ardestani and Ghahfarrokhi, 2021; Pressey et al., 2007). Species distribution models (SDMs) have become a robust instrument for investigating the geographic distribution of diverse life forms, including plants and animals. They have proven helpful in assessing the conservation implications of distribution patterns and predicting future climate change impacts. SDMs offer novel perspectives for evaluating species range shifts under different climatic conditions between present and future periods (Chhetri et al., 2021; Ardestani and Ghahfarrokhi, 2021). These models utilize quantitative equations that incorporate environmental variables, species presence data, and, in some cases, absence to forecast species distribution (Crego et al., 2022).

Rhododendron arboreum, commonly known as the Rhododendron or *Laligurans* in Nepal, is a species of flowering plant that holds immense cultural and ecological significance in the country. It is Nepal's national flower and deeply embedded in local traditions and festivities. It is one of the most stately and impressive Rhododendron species (Srivastava, 2012). The species can be observed in various regions of Nepal, including the western, central, and eastern areas, specifically in hilly open areas at altitudes ranging from 1300 to 3200 meters. Its distribution also extends beyond Nepal to other parts of the Himalayas, spanning from Kashmir to Arunachal Pradesh (Shrestha, 2016; Srivastava, 2012). It is an evergreen tree that exhibits a dense branching pattern, reaching a height of up to 14 meters with a circumference of 2.4 meters. It flowers from March to April or June to September, displaying vibrant flowers ranging from deep red or crimson to pale pink.

Reports indicate that the bright red forms of *Rhododendron arboreum* are commonly observed at lower elevations (Orwa et al., 2009). This plant thrives in light (sandy) to medium (loamy) soil and requires a moderately moist and acidic soil environment (Srivastava, 2012). The wood grain of *Rhododendron arboreum* is utilized in the production of handles for the traditional Nepalese knife called *'khukuri'*, packsaddles, gift boxes, gunstocks, and posts. Its durable and versatile wood is prized for its suitability in crafting these items (Paul et al., 2005). This species stands out as a favored and extensively harvested species within the rhododendron genus, primarily due to its exceptional qualities as fuelwood as it boasts a remarkable combination of high calorific value and an elevated fuelwood index value (Ranjitkar et al., 2014). In hilly regions, the flowers of *Rhododendron arboreum*, known for their sweet and sour taste, are utilized in making squash, jams, jellies, and local brew. Its flowers are a popular and delightful beverage, consumed daily as a refreshing appetizer and for their potential to prevent high altitude sickness (Pant et al., 2009; Prakash et al., 2007; Singh and Chatterjee, 2022; Solanki et al., 2013).

Despite the well-established impact of climate change on various plant species, understanding its effects on *Rhododendron arboreum* in Nepal remains limited. This knowledge gap can be attributed to several factors. Previous research on climate change impacts has often focused on more widespread or economically significant plant species, giving relatively less attention to *Rhododendron arboreum*. Additionally, the species distribution range, which includes diverse geographical and altitudinal gradients within Nepal, presents challenges for comprehensive studies. Moreover, the cultural and ecological significance of *Rhododendron arboreum* in Nepal adds a unique dimension to its analysis, warranting specific research to assess the potential implications of climate change in its distribution and conservation.

Given these reasons, there is a pressing need to fill this knowledge gap and generate insights into the effects of climate change on *Rhododendron arboreum* in Nepal. Predicting species distribution changes and their responses to climate change can offer valuable insights for ecological monitoring, species conservation, and effective management strategies (Bahadur et al., 2023; Moradi et al., 2019). The main objective of this research article is to investigate the distribution patterns of *Rhododendron arboreum* in Nepal under current and future climate change scenarios. By assessing the potential impact of climate change on the distribution of this species, our study aims to provide valuable insights into the possible range shifts and conservation implications for *Rhododendron arboreum* in Nepal's changing climate

2. MATERIALS AND METHODS

Study Area

Situated in South Asia, Nepal is a mountainous nation spanning an area of 147,516 km2 and positioned between the latitudes and longitudes of 26°22′–30°27′ N and 80°04′–88°12′ E respectively (Figure 1) (Dhami et al., 2023). Nepal boasts a rich biodiversity that flourishes across its steep altitudinal gradient, ranging from 60 to 8,848 meters above sea level, owing to its diverse climate and topography (Bhattacharjee et al., 2017). This variation in elevation creates distinct habitats across five primary physiographic regions: the High Himalaya, High Mountain, Middle Mountain, Siwalik, and Terai (Uddin et al., 2015). The area experiences a mild climate characterized by dry winters and rainy summers (Karki et al., 2016). The region receives an average annual precipitation of 1768 mm, accompanied by mean annual temperatures of 18 °C (Shrestha et al., 2000).

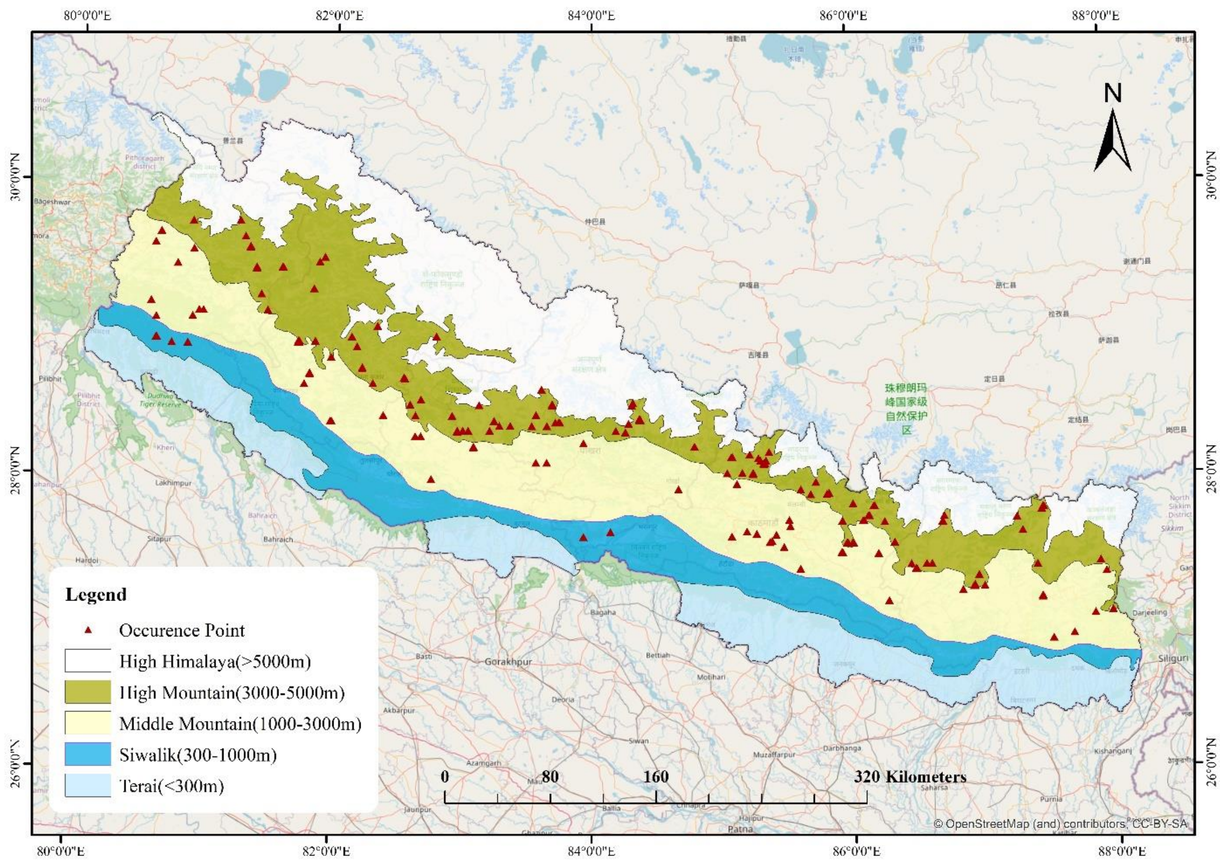

Figure 1 Study area (Nepal) with occurrence points of *Rhododendron arboretum*

Data Collection

Species Occurrence Data

The acquisition of species occurrence data (n=232) relied on detecting and surveying established permanent sample plots during regular inventories conducted by the Forest Research and Training Centre (FRTC) under the Ministry of Forest and Environment in Nepal. This approach ensured the reliability and representativeness of the dataset for subsequent analyses and research on species distributions, thanks to the use of standardized protocols, taxonomic expertise, and repeated surveys over time. Additionally, we augmented the dataset with 71 occurrence records obtained from the Global Biodiversity Information Facilities (GBIF, 2023).

Thus, a total of 303 occurrences of *Rhododendron arboreum* were collected. We manually eliminated occurrences that coincided with buildings and water bodies to refine the dataset. Additionally, to address spatial autocorrelation, we employed the 'fuzzySim' package in R Barbosa, (2015), to randomly select one occurrence per pixel of the predictor variables. As a result, our dataset consisted of 160 occurrence point that exclusively represented the presence of the species.

Current Environmental Parameter

For the assessment of the current distribution of *Rhododendron arboreum*, a total of 23 environmental parameters were selected. These parameters comprised 19 bioclimatic variables and three topographic variables (elevation, slope, and aspect). The bioclimatic variables and the Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) were retrieved from WorldClim (http://www.worldclim.org/) at a resolution of 30 seconds, which approximately corresponds to 1 km2. To derive the slope and aspect, the DEM data was processed within the R programming language (R Core Team, 2022). This comprehensive set of environmental parameters was chosen to capture the diverse range of factors that potentially influence the distribution of *Rhododendron arboreum*.

Likewise, to address the issue of multicollinearity among the predictors, a Pearson correlation test was performed using the 'usdm' package in R (Naimi, 2015). Variables with a correlation coefficient exceeding 0.7 and variation inflation factors (VIFs) greater than ten were identified and subsequently excluded from the analysis. Finally, 9 out of 23 variables were used to build the model: Mean Diurnal Range (BIO2), Temperature Seasonality (BIO4), Min Temperature of Coldest Month (BIO6), Annual Precipitation (BIO12), Precipitation of Driest Month (BIO14), Precipitation Seasonality (BIO15), Precipitation of Coldest Quarter (BIO19), Slope and Aspect (Table 1).

Table 1 A complete list of predictor variables compiled for this study. Predictor variables used for the study are highlighted in bold text.

Source	Category	Variable	Unit
Worldclim	Bioclimatic	BIO1 = Annual Mean Temperature	℃
		BIO2 = Mean Diurnal Range (Mean of monthly (max temp–min temp))	℃
		BIO3 = Isothermality (BIO2/BIO7) (×100)	%
		BIO4 = Temperature Seasonality (standard deviation × 100)	℃
		BIO5 = Max Temperature of Warmest Month	℃
		BIO6 = Min Temperature of Coldest Month	℃
		BIO7 = Temperature Annual Range (BIO5-BIO6)	℃
		BIO8 = Mean Temperature of Wettest Quarter	℃
		BIO9 = Mean Temperature of Driest Quarter	℃
		BIO10 = Mean Temperature of Warmest Quarter	℃
		BIO11 = Mean Temperature of Coldest Quarter	℃
		BIO12 = Annual Precipitation	mm
		BIO13 = Precipitation of Wettest Month	mm
		BIO14 = Precipitation of Driest Month	mm
		BIO15 = Precipitation Seasonality (Coefficient of Variation)	%
		BIO16 = Precipitation of Wettest Quarter	mm
		BIO17 = Precipitation of Driest Quarter	mm
		BIO18 = Precipitation of Warmest Quarter	mm
		BIO19 = Precipitation of Coldest Quarter	mm
		Aspect	Degree
SRTM	Topographic	Slope	Degree
		Elevation	km

Future Environmental Parameter

To assess the response of *Rhododendron arboreum* to future climate conditions, we utilized the sixth version of the Model for Interdisciplinary Research on Climate (MIROC), also known as MIROC6. MIROC6 is a global circulation model (GCM) submitted for the Coupled Model Inter-comparison Project Phase 6 (CMIP6). MIROC's circulation has been demonstrated to effectively capture rainfall and temperature variability across South Asia, as highlighted by (Mishra et al., 2014). This characteristic makes MIROC particularly suitable for investigating the climate dynamics and patterns in the region under consideration.

It is advisable to select multiple distinct future climate patterns to mitigate potential uncertainties and errors associated with future climate projections (Ncube et al., 2020). Hence, we chose bioclimatic variables representing two Green House Gas (GHG) concentration paths based on Shared Socioeconomic Pathways (SSP): SSP2-4.5, which is based on an intermediate emission scenario, and SSP5-8.5, which is based on a very high emission scenario. By incorporating these different pathways, we aimed to account for a range of potential future climate scenarios and improve the reliability of our analysis.

Species distribution modeling

Species distribution modeling aims to predict spatial and temporal distribution of a species by analyzing the correlation between its occurrence or abundance and environmental conditions (Elith and Leathwick, 2009). Different tools, including statistical regression, machine learning, and geographic extrapolation, are used for this purpose (Shrestha and Shrestha, 2019). However, it is essential to note that the performance of these algorithms can vary significantly (Elith et al., 2010). Ensemble modeling, which involves simulating multiple sets of initial conditions, model classes, parameters, and boundary conditions, improves the reliability and accuracy of species distribution predictions (Araújo and New, 2007; Sagi and Rokach, 2018). Combining multiple approaches and accounting for algorithm uncertainties, ensemble modeling provides a consensus approach that outperforms individual models (Aguirre-Gutiérrez et al., 2017). In this research, we employed ensemble modeling to enhance the reliability and accuracy of species distribution predictions (Araújo and New, 2007; Thuiller et al., 2009).

To conduct ensemble modeling, we utilized the 'biomod2' package within the R program (R Core Team, 2022). We selected ten algorithms: Multiple analysis regression splines (MARS), maximum entropy (MaxEnt), random forest (RF), boosted regression tree (BRT), generalized linear model (GLM), gradient boosting machine (GBM), classification tree analysis (CTA), artificial neural network (ANN), flexible discriminant analysis (FDA), surface range envelope (SRE) and generalized additive model (GAM) for creating the ensemble model. As actual absence data were unavailable, we randomly selected 10000 pseudo-absences for model training and evaluation. The models were calibrated using 80% of the occurrence points (presence and pseudo-absence) as training data, while the remaining 20% served as testing data to evaluate model performance. We performed seven evaluation repetitions using the ten selected model algorithms, resulting in 70 individual model runs.

To evaluate predictive performance, we employed two widely accepted metrics: The area under the curve (AUC) of the receiver operating characteristic (ROC) plot and the true skill statistic (TSS) (Naimi et al., 2022). The AUC is a threshold-independent metric ranging from 0 to 1, categorizing models as excellent (AUC > 0.9), good (0.8 to 0.9), fair (0.7 to 0.8), or poor (0.6 to 0.7) (Ben-Rais-Lasram et al., 2010). The TSS, calculated as "sensitivity + specificity - 1", ranges from -1 to +1, with values below 0.4 indicating poor model discrimination (Allouche et al., 2006; Beaumont et al., 2016; Shrestha and Shrestha, 2019). Eight models (GLM, GBM, GAM, ANN, FDA, MARS, RF, MAXENT) with AUC values greater than 0.8 were selected for further analysis.

The ensemble model was constructed using a committee averaging approach to combine predictions from those 8 individual models, aiming to enhance overall accuracy and reliability. We also determined the relative importance of each predictor variable used in the models. To determine the presence and absence based on the predicted probabilities, we employed the "Maximum Sensitivity plus Specificity" threshold, as described by (Liu et al., 2005; Naimi and Araújo, 2016). This threshold allowed us to convert the predicted probabilities into binary predictions. Subsequently, we calculated the areas of the expected current distribution of the species and the changes in these habitats between the current and future prediction scenarios.

3. RESULTS

Model performance

The models showcased commendable performance based on their evaluation scores. The TSS value displayed some variation across the models, ranging from 0.63 for the FDA model to 0.80 for the GBM model. Similarly, the AUC value showed a range of scores, with the ANN model scoring 0.83 and the GBM model achieving an impressive score of 0.94. The final ensemble model, which incorporated eight carefully selected algorithms, outperformed the rest with an outstanding AUC value of 0.97 and a TSS value of 0.77 (Table 2). These results genuinely highlight the strong performance of the ensemble model and its potential in predictive modeling.

Table 2 Evaluation metrices of algorithms used in the study.

Model	ANN	FDA	GAM	GBM	GLM	MARS	MAXENT	RF	Ensemble
AUC	0.83	0.88	0.91	0.94	0.89	0.90	0.93	1.00	0.97
TSS	0.64	0.63	0.76	0.80	0.70	0.70	0.74	1.00	0.77

Variables contribution

Two variables stood out as the most influential: the minimum temperature of the coldest month (BIO6) and the annual precipitation (BIO12), as shown in (Table 3). These two variables contributed significantly, accounting for 69.52% and 13.20% of the model's importance, respectively. Another important variable was the temperature seasonality (BIO4), which had a contribution of 9.55%. Interestingly, the bioclimatic variables played a more crucial role in determining the potential distribution of *Rhododendron arboreum* compared to the topographic variables. The cumulative contribution of the bioclimatic variables was remarkably high at 99.17%.

Table 3 Importance and percentage contribution of predictor variables.

Variable codes	Mean Variable Importance	Percentage
BIO2	0.0178	1.67
BIO4	0.1025	9.55
BIO6	0.7465	69.52
BIO12	0.1417	13.20
BIO14	0.0069	0.64
BIO15	0.0186	1.73
BIO19	0.0308	2.87
Sope	0.0054	0.51
Aspect	0.0034	0.32

Current and Future Potential Distribution

By analyzing various environmental variables and species occurrence data, we were able to generate a comprehensive understanding of the current distribution of Rhododendron within the country. The findings revealed substantial variations in suitability across Nepal, with a total of 115,317.1 km2 (78.17%) identified as unsuitable for the species, while 32,198.89 km2 (21.83%) were classified as suitable habitats, as shown in (Figure 2). The province-wise analysis of the current habitat distribution for *Rhododendron arboreum* revealed interesting patterns across Nepal. Province No. 1 exhibited a substantial suitable habitat area of 6503.48 km2, accounting for 24.62% of its total area. This indicates a significant presence of favorable conditions for the species within this province. On the other hand, Province No. 2 did not exhibit any suitable habitat for *Rhododendron arboreum*, suggesting limited or unfavorable environmental conditions for the species in this region. Moving to Bagmati Province, we found a suitable habitat area of 6585.56 km2, representing approximately 32.11% of its total area.

This province demonstrates a relatively high potential for supporting the growth and distribution of *Rhododendron arboreum*. Similarly, Gandaki Province showcased a suitable habitat area of 5064.26 km2, accounting for 22.88% of its total area. This suggests that the species can thrive in various parts of this province. Lumbini Province exhibited a suitable habitat area of 3663.27 km2, representing 18.89% of the province's total area. Although relatively more minor than other provinces, it still provides a significant suitable habitat for *Rhododendron arboreum*. Karnali Province showcased a suitable habitat area of 5044.67 km2, comprising 16.36% of its total area. Despite the lower percentage, the province harbors substantial areas where the species can flourish. Sudurpaschim Province demonstrated a notable suitable habitat area of 5337.66 km2, representing 26.45% of its total area. This indicates a relatively high potential for supporting *Rhododendron arboreum* within this province.

The study examined the current distribution of Rhododendron in Nepal and made projections for its future suitable habitat under two different climate scenarios: SSP2-4.5 and SSP5-8.5. The analysis revealed that the species faces substantial changes in habitat suitability by the years 2050 and 2070, as shown in (Figure 3).

Considering the current distribution patterns, which indicate that 115,317.1 km2 are unsuitable and 32,198.89 km2 are suitable for Rhododendron, we observed significant shifts in suitable and unsuitable areas. For the year 2050, under the SSP2-4.5 scenario, the models projected an increase in unsuitable areas, covering approximately 121,234.7 km2, and a decrease in suitable habitat, with 26,281.3 km2 remaining. Conversely, under the SSP5-8.5 scenario for the same year, the unsuitable areas were projected to expand further, encompassing 123,858.3 km2, while the suitable habitat decreased to 23,657.7 km2. Looking ahead to 2070, under the SSP2-4.5 scenario, the models predicted a further decline in suitable habitat, with only 23,260.4 km2 remaining, and an increase in unsuitable areas, which expanded to 124,255.6 km2.

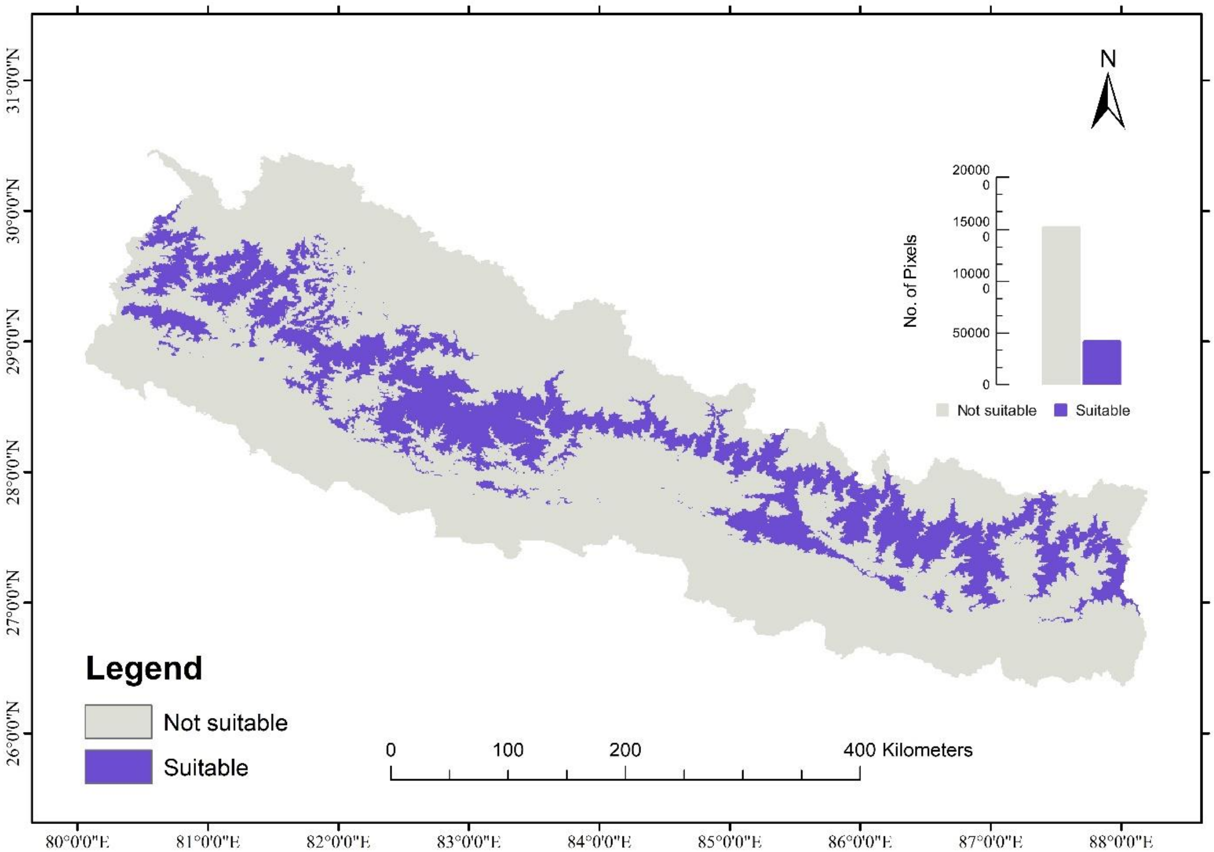

Figure 2 Predicted current distribution of *Rhododendron arboreum* in Nepal

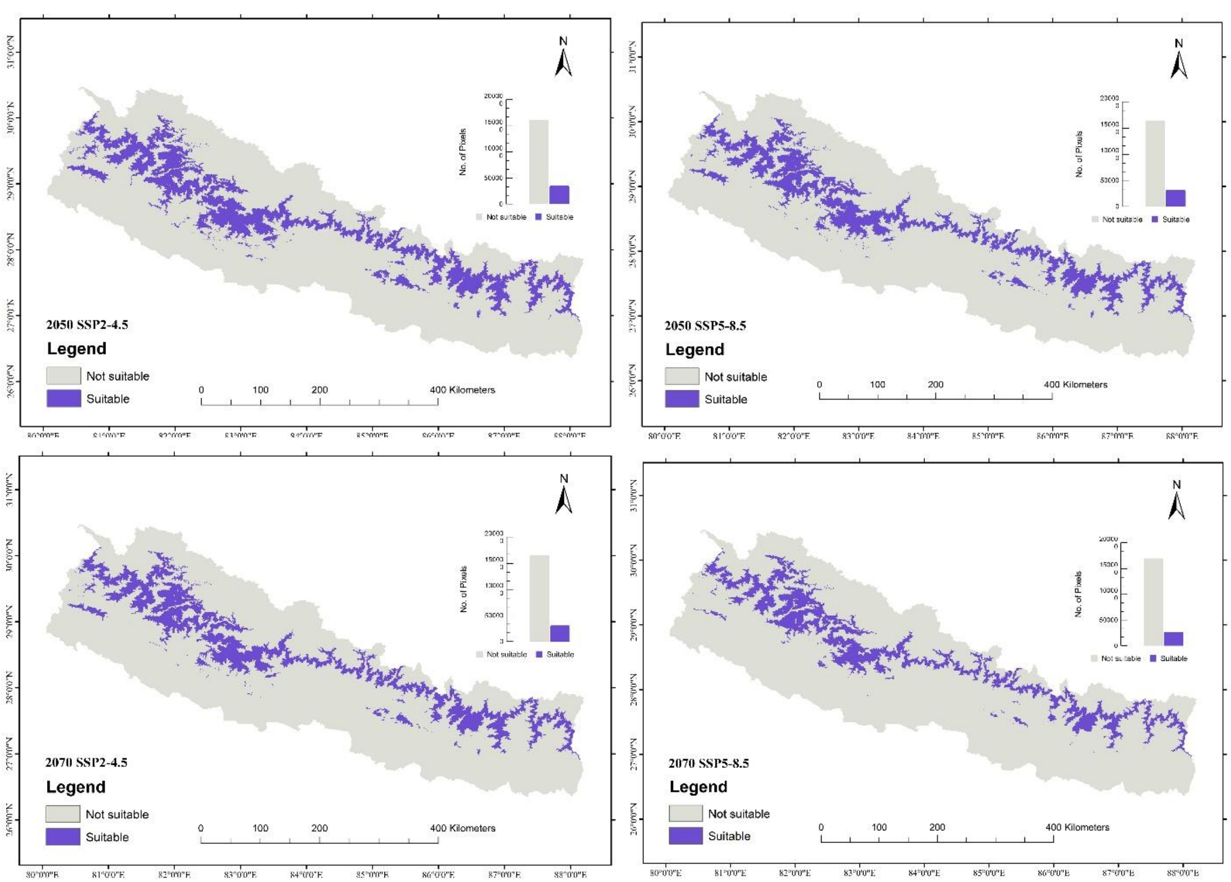

Figure 3 Predicted future distribution of *Rhododendron arboreum* in Nepal.

Similarly, under the SSP5-8.5 scenario, the projections indicated a significant reduction in suitable habitat to 19,913.73 km2, while the unsuitable areas expanded to cover 127,602.3 km2. These findings suggest a concerning trend of declining suitable habitats for Rhododendron in the future, with both climate scenarios pointing towards a potential decrease in suitable areas and an expansion of unsuitable regions. The projections indicate that the species may face increasing challenges to its survival and persistence, particularly under the SSP5-8.5 scenario.

Habitat Gain and Loss

We observed losses and gains in suitable habitats by comparing the current distribution patterns with the projected scenarios for the years 2050 and 2070 under the SSP2-4.5 and SSP5-8.5 climate scenarios (Figure 4). For the year 2050 under the SSP2-4.5 scenario, the models predicted a loss of approximately 10,710.39 km2 and a gain of 4,792.78 km2 in suitable habitats. Moreover, an area of 21,488.5 km2 was projected to remain stable. In contrast, under the SSP5-8.5 scenario for the same year, the projections indicated the more extensive loss of 14,237.64 km2 and a smaller gain of 5,696.41 km2. Additionally, an area of 17,961.26 km2 was expected to remain stable.

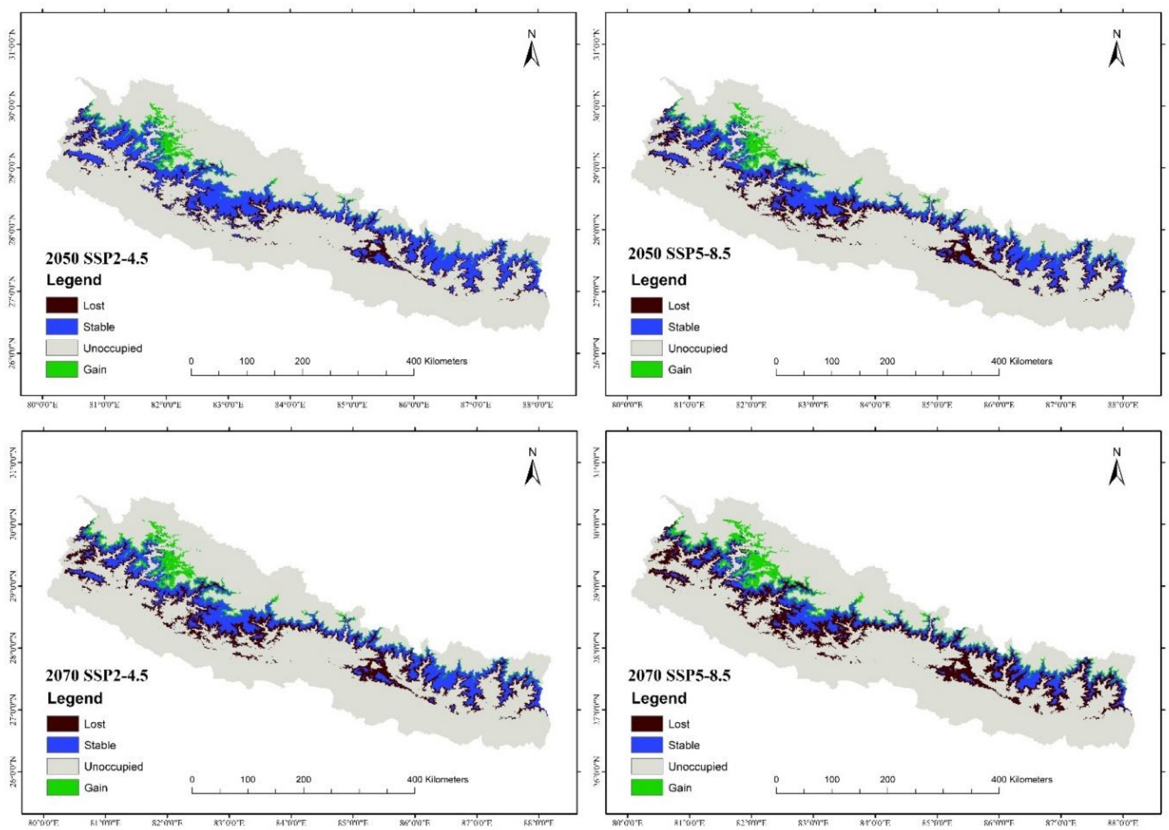

Figure 4 Habitat gain and loss of *Rhododendron arboreum* under different climate change scenarios for the future.

Looking ahead to 2070, under the SSP2-4.5 scenario, the models predicted a further loss of 14,985.52 km2 and a gain of 6,047.03 km2 in suitable habitat. Meanwhile, an area of 17,213.37 km2 was projected to remain stable. Similarly, under the SSP5-8.5 scenario, the projections indicated a more significant loss of 19,790.34 km2 and a more considerable gain of 7,505.18 km2. Additionally, an area of 12,408.56 km2 was expected to remain stable.

Elevation range shift

Our findings indicate that *Rhododendron arboreum* predominantly occupies hilly areas in Nepal within an elevation range of 1080 to 3730 meters during the current period. Our projections for the year 2050, specifically under the SSP2-4.5 scenario, present a noteworthy upward shift in elevation for *Rhododendron arboreum*. The projected suitable habitat elevation range expands from 1373 to 4029 meters, implying a potential movement of the species toward higher altitudes, likely in response to anticipated climate variations. The widening of the suitable habitat elevation range signifies the species' remarkable adaptability to evolving environmental conditions.

Similarly, under the SSP5-8.5 scenario for the year 2050, the suitable habitat elevation range extends even further, ranging from 1525 to 4203 meters. This indicates a more pronounced upward shift compared to the SSP2-4.5 scenario, emphasizing the heightened impact of climate change on the species distribution patterns. These findings underscore the importance of considering various climate scenarios to comprehend the full spectrum of potential influences *on Rhododendron arboreum*. Looking ahead to 2070, our projections under the SSP2-4.5 scenario indicate a continuation of the upward trend in elevation shifts. The estimated suitable habitat elevation range extends from 1525 to 4208 meters, suggesting a continuous movement of the species toward higher altitudes. The projected expansion of the suitable habitat range further emphasizes the need for long-term conservation strategies that account for the anticipated changes in the species distribution patterns.

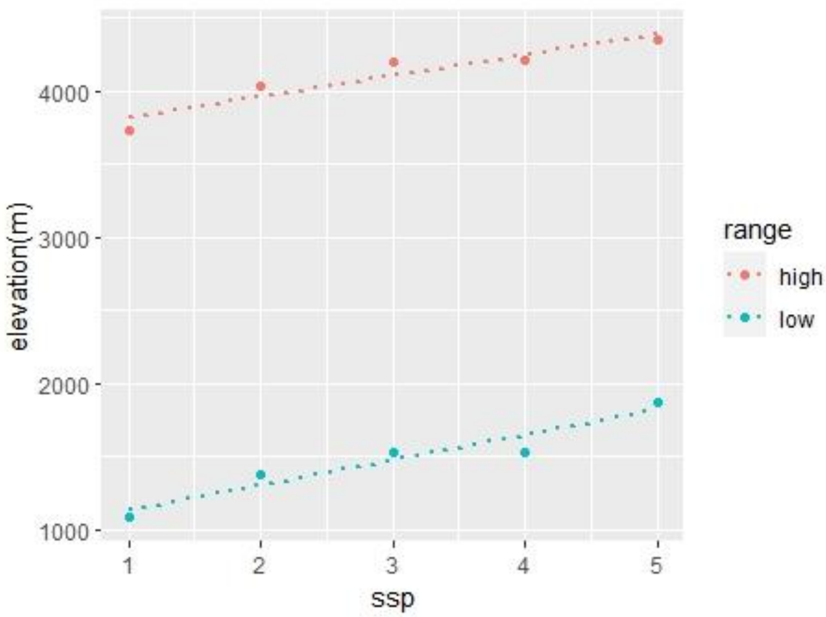

Figure 5 Elevation range of suitable habitat for *Rhododendron arboreum* for current and future period. In the x-axis, 1 represents the current range, 2 represents the range for 2050 ssp2-4.5, 3 represents the range for 2050 ssp5-8.5, 4 represents the range for 2070 ssp2-4.5 and 5 represents the range for 2070 ssp5-8.5

Under the SSP5-8.5 scenario for the year 2070, the suitable habitat elevation range undergoes a significant expansion, ranging from 1864 to 4355 meters. This substantial upward shift, as shown in Figure 5, highlights the considerable displacement of *Rhododendron arboreum* towards higher elevations in response to changing climatic conditions.

4. DISCUSSION

To develop effective species recovery plans within their natural habitats, an important step involves modeling the present habitats and predicting the future range of species (Kumari et al., 2022). To ensure the conservation and sustainability of species habitats in the future, it is crucial to employ habitat distribution modeling, which enables us to assess dispersal range and the impact of climate change on future habitat suitability (Mushtaq et al., 2021; Zhong et al., 2021). This approach helps us understand the intricate relationship between species distribution range, extinction, and the critical determinants of geographical range area (Cardillo et al., 2008; Purvis et al., 2000). In this context, the present study takes a pioneering approach by mapping the existing habitats of *Rhododendron arboreum* in Nepal and forecasting how climate change will influence the suitability of these habitats in the future using an ensemble approach.

In our study, we employed the 'biomod2' package to model the potential distribution of *Rhododendron arboreum* in Nepal. The 'biomod2' package offers a unique advantage by integrating multiple modeling algorithms and demonstrating high predictive accuracy. Notably, prior research by Wani et al., (2022) utilized 'biomod2' for predicting the habitat suitability of *Dactylorhiza hatagiera* in the Himalayan region under projected climate change. Their study achieved impressive evaluation metrics, with an AUC value of 0.93 and a TSS value of 0.82. Similarly, other studies by Farashi and Erfani, (2018), Kumari et al., (2022), Shrestha and Shrestha, (2019) have successfully employed 'biomod2' for ensemble distribution modeling of various flora and fauna, yielding notable predictive accuracy. In our investigation, we evaluated the performance of our models using commonly accepted evaluation metrics. We obtained an AUC value of 0.97 and a TSS value of 0.77, considered acceptable and consistent with the aforementioned studies. These results highlight our modeling approach's robustness and reinforce our findings' reliability.

The predicted current distribution of *Rhododendron arboreum* aligns remarkably well with the known occurrence records, providing a reliable baseline for understanding the species' habitat preferences. This species favors hilly regions at moderate elevations Anand et al., (2021), which is consistent with its established ecological characteristics. In our study, we have meticulously compiled a comprehensive dataset comprising 160 occurrence records encompassing a wide range of elevations, from 1241 to 3281 meters. Notably, an exceptionally high number of occurrences are observed within the elevation range of 1500 to 3000 meters, as depicted in (Figure 6).

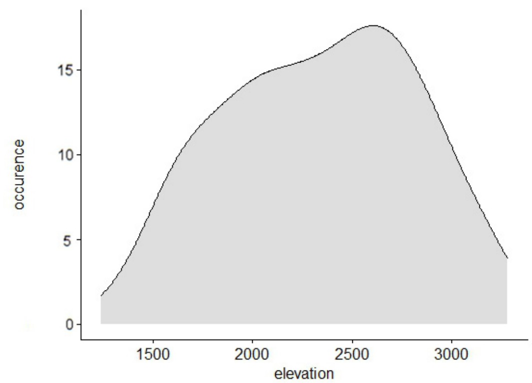

Figure 6 Histogram of occurrence points with respect to elevation.

Our models confirm that the species thrives within an elevation range of 1080 to 3730 meters, which corresponds closely with the findings of Veera et al., (2019) in the western Himalayas of India. Their research suggests that the distribution of *Rhododendron arboreum* typically occurs between 1500 and 3500 meters above sea level. Similarly, our study revealed that, based on the current climate conditions, the potentially suitable areas are primarily concentrated in the eastern and western parts, while the central region exhibits relatively fewer suitable areas. The province-wise analysis of the current habitat distribution for *Rhododendron arboreum* in Nepal provides valuable insights into the species' ecological preferences and distribution patterns. The findings reveal notable variations in suitable habitat availability across different provinces, emphasizing the importance of considering regional factors in conservation planning.

Province No. 1 emerges as a significant hotspot for *Rhododendron arboreum*, covering nearly a quarter of the province's total area. This highlights the province's favorable environmental conditions, such as suitable elevation, climate, and vegetation, that support the growth and proliferation of the species. Identifying such a sizable habitat area in Province No. 1 underscores the need for targeted conservation efforts to preserve and protect this vital stronghold of *Rhododendron arboreum*. In contrast, Province No. 2 lacks a suitable habitat for the species. The absence of favorable conditions in this region might be attributed to various factors, including unsuitable elevation ranges, land-use patterns, or climatic conditions, as described by (Sharma et al., 2020). Understanding the limitations or constraints that prevent the establishment of suitable habitats in Province No. 2 is crucial for informing conservation strategies in areas where *Rhododendron arboreum* currently faces challenges. Bagmati Province and Gandaki Province exhibit considerable suitable habitat areas, with 6585.56 km2 (32.11% of total area) and 5064.26 km2 (22.88% of total area), respectively.

These findings indicate that these provinces provide favorable conditions for *Rhododendron arboreum*, potentially contributing to the species' ecological resilience and conservation. The presence of significant suitable habitat areas in these regions highlights their importance as key conservation areas and calls for targeted conservation initiatives to preserve the existing populations and promote their long-term viability. Lumbini Province, Karnali Province, and Sudurpaschim Province also demonstrate varying degrees of suitable habitat availability for *Rhododendron arboreum*, comprising 18.89%, 16.36%, and 26.45% of their total areas. Despite variations in the percentage of suitable habitat, these provinces play crucial roles in supporting the species distribution and maintaining its ecological balance within Nepal's diverse landscapes.

Furthermore, when considering future climate scenarios, we found that the potentially suitable areas are expected to decrease overall, indicating a higher probability of habitat loss than habitat gain, as shown in (Table 4). Our findings indicated that across all projected future climate scenarios, there was a notable increase in suitable habitats in the higher latitude areas, especially in Karnali and Sudurpaschim province, as highlighted in the study (Shifting Habitats, 2020). However, habitat loss was consistent throughout the entire country. These projected losses in the habitat of *Rhododendron arboreum* highlight the need for proactive conservation measures to ensure the preservation and protection of suitable habitats.

Table 4 Area of suitable habitat of *Rhododendron arboreum* for current and future period as well as area gained and lost in future.

	Current		2050		2070	
Area in sq. km.			ssp2-4.5	ssp5-8.5	ssp2-4.5	ssp5-8.5
	Not suitable	115317.11	121234.72	123858.33	124255.60	127602.27
	Suitable	32198.89	26281.28	23657.67	23260.40	19913.73
	Gain	-	4792.78	5696.41	6047.03	7505.17
	Loss	-	10710.39	14237.64	14985.52	19790.34

The two most influential variables were the minimum temperature of the coldest month (BIO6) and the annual precipitation (BIO12). The prominence of these two variables suggests that they play a crucial role in shaping suitable habitats for *Rhododendron arboreum*. The minimum temperature of the coldest month likely affects the plant's ability to tolerate low temperatures, while annual precipitation is a vital factor in determining the availability of water resources. Together, these variables appear to influence the potential distribution of Rhododendron arboreum strongly. Additionally, we found that the temperature seasonality (BIO4) had a notable contribution of 9.55%. This suggests that the variation in temperature throughout the year, rather than just extreme cold temperatures, also significantly determines the suitable habitats for *Rhododendron arboreum*.

These findings highlight the importance of considering bioclimatic variables when studying the potential distribution of *Rhododendron arboreum*. By focusing on these factors, we can better understand the environmental conditions required for the plant's survival and identify suitable habitats for conservation and management efforts. It is worth noting that our study focused on a specific species in a particular region. Future research could explore the influence of these variables on other species or in different geographical contexts to gain a more comprehensive understanding of the factors influencing species distributions. Furthermore, incorporating additional variables, such as soil characteristics or land use patterns, may provide further insights into the ecological requirements and potential threats to *Rhododendron arboreum*.

5. CONCLUSION

In conclusion, this research provides valuable insights into the distribution patterns of *Rhododendron arboreum* in Nepal, highlighting its cultural and ecological significance. Through applying species distribution modeling techniques and utilizing an ensemble approach, we have gained a comprehensive understanding of the current distribution and projected future changes in suitable habitats for this iconic species. Our findings indicate that a significant portion of Nepal's land area is unsuitable for *Rhododendron arboreum*, emphasizing the need for conservation efforts to protect the remaining suitable habitat. The future projections under different climate scenarios reveal potential gains and losses in suitable habitats, pointing to the dynamic nature of the species distribution and the impact of climate change. The implications of this research call for proactive conservation measures to safeguard *Rhododendron arboreum* in the face of climate change.

By understanding the potential challenges and predicting future habitat changes, we can develop informed conservation strategies to preserve the species and its cultural and ecological importance. The study contributes to the broader field of species distribution modeling by showcasing the effectiveness of ensemble approaches in generating reliable predictions. It is a foundation for further research and conservation efforts focused on *the region's Rhododendron arboreum and other vulnerable plant species*. By protecting and managing suitable habitats, we can ensure the long-term survival of *Rhododendron arboreum*, preserving its beauty, cultural significance, and the intricate ecological balance it contributes to Nepal's diverse landscapes.

Acknowledgment

We would like to express our sincere gratitude to the Forest Research and Training Centre (FRTC) for their invaluable contribution to this research article. Their generous provision of species occurrence data has greatly enriched our study and enhanced the accuracy of our findings. Additionally, we extend our appreciation for their technical assistance, which played a crucial role in the successful execution of this research. Without their support and collaboration, this project would not have been possible. We are truly thankful for their dedication and commitment to advancing scientific knowledge in the field of forest research.

Authors Contributions

Samit Kafle: Conceptualization, Methodology, Software, Formal analysis, original draft preparation
Divya Thapa: Writing – Review & Editing, Validation
Keshav Ghimire: Resources, Writing – Review & Editing, Supervision
Jeetendra Gautam: Writing – Review & Editing

Ethical approval

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interest.

Funding

The study has not received any external funding.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCES AND NOTES

1. Aguirre-Gutiérrez J, van Treuren R, Hoekstra R, van Hintum TJL. Crop wild relatives range shifts and conservation in Europe under climate change. Divers Distrib 2017; 23:739–50. doi: 10.1111/ddi.12573
2. Allouche O, Tsoar A, Kadmon R. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J Appl Ecol 2006; 43:1223–32. doi: 10.1111/j.1365-2664.2006.01214.x
3. Anand A, Pandey MK, Srivastava PK, Gupta A, Khan ML. Integrating Multi-Sensors Data for Species Distribution Mapping Using Deep Learning and Envelope Models. Remote Sens 2021; 13. doi: 10.3390/rs13163284
4. Araújo MB, New M. Ensemble forecasting of species distributions. Trends Ecol Evol 2007; 22:42–7. doi: 10.1016/j.tree.2006.09.010
5. Bahadur H, Prasad H, Rokka P, Prasad K, Prasad B, Koirala S, Chhetri S, Yadav S, Sah G, Sagar H, Prasad L, Wang L, Quan R. The effects of climate and land use change on the potential distribution and nesting habitat of the Lesser Adjutant in Nepal. Avian Res 2023; 14:100105. doi: 10.1016/j.avrs.2023.100105
6. Barbosa AM. FuzzySim: applying fuzzy logic to binary similarity indices in ecology. Methods Ecol Evol 2015; 6:853–8. doi: 10.1111/2041-210X.12372
7. Beaumont LJ, Graham E, Duursma DE, Wilson PD, Cabrelli A, Baumgartner JB, Hallgren W, Esperón-Rodríguez M, Nipperess DA, Warren DL, Laffan SW, VanDerWal J. Which species distribution models are more (or less) likely to project broad-scale, climate-induced shifts in species ranges? Ecol Modell 2016; 342:135–46. doi: 10.1016/j.ecolmodel.2016.10.004
8. Ben-Rais-Lasram F, Guilhaumon F, Albouy C, Somot S, Thuiller W, Mouillot D. The Mediterranean Sea as a 'cul-de-sac' for endemic fishes facing climate change. Glob Chang Biol 2010; 16:3233–45. doi: 10.1111/j.1365-2486.2010.02224.x
9. Bhattacharjee A, Anadón JD, Lohman DJ, Doleck T, Lakhankar T, Shrestha BB, Thapa P, Devkota D, Tiwari S, Jha A. The impact of climate change on biodiversity in Nepal: Current knowledge, lacunae, and opportunities. Clim 2017; 5: 80.
10. Cardillo M, Mace GM, Gittleman JL, Jones KE, Bielby J, Purvis A. The predictability of extinction: biological and external correlates of decline in mammals. Proc Biol Sci 2008; 275 (1641):1441-8. doi: 10.1098/rspb.2008.0179
11. Chhetri B, Badola HK, Barat S. Modelling climate change impacts on distribution of Himalayan pheasants. Ecol Indic 2021; 123:107368. doi: 10.1016/j.ecolind.2021.107368
12. Crego RD, Stabach JA, Connette G. Implementation of species distribution models in Google Earth Engine. Divers Distrib 2022; 28:904–16. doi: 10.1111/ddi.13491
13. Dhami B, Bhusal A, Adhikari B, Miya MS, Maharjan SK, Neupane D, Adhikari H. Habitat Suitability and Conflict Zone Mapping for the Blue Bull (Boselaphus tragocamelus) across Nepal. Anim 2023; 13(5). doi: 10.3390/ani13050937
14. Elith J, Kearney M, Phillips S. The art of modelling range-shifting species. Methods Ecol Evol 2010; 1:330–42. doi: 10.1111/j.2041-210X.2010.00036.x
15. Elith J, Leathwick JR. Species Distribution Models: Ecological Explanation and Prediction Across Space and Time. Annu Rev Ecol Evol Syst 2009; 40:677–97. doi: 10.1146/annurev.ecolsys.110308.120159

16. Farashi A, Erfani M. Modeling of habitat suitability of Asiatic black bear (Ursus thibetanus gedrosianus) in Iran in future. Acta Ecol Sin 2018; 38:9–14.
17. GBIF. Occurrence Download 2023. doi: 10.15468/DL.D6Z4TY
18. Ardestani EG, Ghahfarrokhi ZH. Ensembpecies distribution modeling of Salvia hydrangea under future climate change scenarios in Central Zagros Mountains, Iran. Glob Ecol Conserv 2021; 26:e01488. doi: 10.1016/j.gecco.2021.e01488
19. Karki R, Talchabhadel R, Aalto J, Baidya SK. New climatic classification of Nepal. Theor Appl Climatol 2016; 125:799–80 8.
20. Kumari P, Wani IA, Khan S, Verma S, Mushtaq S, Gulnaz A, Paray BA. Modeling of Valeriana wallichii Habitat Suitability and Niche Dynamics in the Himalayan Region under Anticipated Climate Change. Biology (Basel) 2022; 11(4):498. doi: 10.3390/biology11040498
21. Liu C, Berry PM, Dawson TP, Pearson RG. Selecting thresholds of occurrence in the prediction of species distributions. Ecography (Cop) 2005; 28:385–93. doi: 10.1111/j. 0906-7590.2005.03957.x
22. Mishra V, Kumar D, Ganguly AR, Sanjay J, Mujumdar M, Krishnan R, Shah RD. Reliability of regional and global climate models to simulate precipitation extremes over India. J Geophys Res Atmos 2014; 119:9301–9323.
23. Moradi S, Ilanloo SS, Kafash A, Yousefi M. Identifying high-priority conservation areas for avian biodiversity using species distribution modeling. Ecol Indic 2019; 97:159–64.
24. Mushtaq S, Reshi ZA, Shah MA, Charles B. Modelled distribution of an invasive alien plant species differs at different spatiotemporal scales under changing climate: a case study of Parthenium hysterophorus L. Trop Ecol 2021; 62:398–417.
25. Naimi B, Araújo MB. Sdm: A reproducible and extensible R platform for species distribution modelling. Ecography 2016; 3 9(4):368-375. doi: 10.1111/ecog.01881
26. Naimi B, Capinha C, Ribeiro J, Rahbek C, Strubbe D, Reino L, Araújo MB. Potential for invasion of traded birds under climate and land-cover change. Glob Chang Biol 2022; 28:5654 –66. doi: 10.1111/gcb.16310
27. Naimi B. Usdm: Uncertainty Analysis for Species Distribution Models. R package version 1.1-15, 2015.
28. Ncube B, Shekede MD, Gwitira I, Dube T. Spatial modelling the effects of climate change on the distribution of Lantana camara in Southern Zimbabwe. Appl Geogr 2020; 117:102172.
29. Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A. Agroforestry Database: A Tree Reference and Selection Guide Version 4.0. World Agroforestry Centre, Kenya, 2009.
30. Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Ipcc, Geneva, Switzerland, 2014; 151.
31. Pant S, Samant SS, Arya SC. Diversity and indigenous household remedies of the inhabitants surrounding Mornaula reserve forest in West Himalaya. Indian J Tradit Knowl 2009; 8:606–610.
32. Paul A, Khan ML, Arunachalam A, Arunachalam K. Biodiversity and conservation of rhododendrons in Arunachal Pradesh in the Indo-Burma biodiversity hotspot. Curr Sci 2005; 89:623–634.
33. Prakash D, Upadhyay G, Singh BN, Dhakarey R, Kumar S, Singh KK. Free-radical scavenging activities of Himalayan rhododendrons. Curr Sci India 2007; 92:526–32.
34. Pressey RL, Cabeza M, Watts ME, Cowling RM, Wilson KA. Conservation planning in a changing world. Trends Ecol Evol 2007; 22(11):583–92. doi: 10.1016/j.tree.2007.10.001
35. Purvis A, Gittleman JL, Cowlishaw G, Mace GM. Predicting extinction risk in declining species. Proc Biol Sci 2000; 267 (1456):1947-52. doi: 10.1098/rspb.2000.1234
36. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria 2022.
37. Ranjitkar S, Sujakhu NM, Jati R, Xu J, Schmidt-Vogt D. Yield and household consumption of Rhododendron arboreum as a fuelwood species in Eastern Nepal. Biomass and Bioenergy 2014; 61:245–53. doi: 10.1016/j.biombioe.2013.12.016
38. Sagi O, Rokach L. Ensemble learning: A survey. Wiley Interdiscip Rev Data Min Knowl Discov 2018; 8(4):e1249. doi: 10.1002/WIDM.1249
39. Sharma S, Khadka N, Hamal K, Baniya B, Luintel N, Joshi BB. Spatial and Temporal Analysis of Precipitation and Its Extremities in Seven Provinces of Nepal (2001-2016). Appl Ecol Environ Sci 2020; 8:64–73. doi: 10.12691/aees-8-2-4
40. Shifting habitats. Nat Clim Chang 2020; 10:377. doi: 10.1038/s 41558-020-0789-x
41. Shrestha AB, Wake CP, Dibb JE, Mayewski PA. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large-scale climatological parameters. Int J Climatol 2000; 20(3):317–327.
42. Shrestha I. Study on Distribution of Rhododendron Arboreum Sm. In Langtang National Park Using Geographic Information System and Remote Sensing. Tribhuvan Univ J 2016; 29:79–84. doi: 10.3126/tuj.v29i1.25672
43. Shrestha UB, Shrestha BB. Climate change amplifies plant invasion hotspots in Nepal. Divers Distrib 2019; 25:1599–612. doi: 10.1111/ddi.12963
44. Singh S, Chatterjee S. Value chain analysis of Rhododendron arboreum squash 'buransh' as a non-timber forest product (NTFP) in Western Himalayas: Case study of Chamoli district,

Uttarakhand in India. Trees For People 2022; 7:100200. doi: 10.1016/j.tfp.2022.100200

45. Solanki SN, Huria AK, Chopra CS. Physico-chemical characteristics of buransh (Rhododendron arboreum)-a nutritious and edible flower. J Hill Agric 2013; 4(1):50–52.
46. Srivastava P. Rhododendron arboreum: An overview. J Appl Pharm Sci 2012; 2(1):158–162.
47. Thuiller W, Lafourcade B, Engler R, Araújo MB. BIOMOD – a platform for ensemble forecasting of species distributions. Ecography (Cop) 2009; 32:369–73. doi: 10.1111/j.1600-0587.2008.05742.x
48. Uddin K, Shrestha HL, Murthy MSR, Bajracharya B, Shrestha B, Gilani H, Pradhan S, Dangol B. Development of 2010 national land cover database for the Nepal. J Environ Manage 2015; 148:82–90. doi: 10.1016/j.jenvman.2014.07.047
49. Veera SNS, Panda RM, Behera MD, Goel S, Roy PS, Barik SK. Prediction of upslope movement of Rhododendron arboreum in Western Himalaya. Trop Ecol 2019; 60:518–24. doi: 10.1007/s42965-020-00057-x
50. Wani IA, Khan S, Verma S, Al-Misned FA, Shafik HM, El-Serehy HA. Predicting habitat suitability and niche dynamics of Dactylorhiza hatagirea and Rheum webbianum in the Himalaya under projected climate change. Sci Rep 2022; 12:13205. doi: 10.1038/s41598-022-16837-5
51. Zhao G, Cui X, Sun J, Li T, Wang Q, Ye X, Fan B. Analysis of the distribution pattern of Chinese Ziziphus jujuba under climate change based on optimized biomod2 and MaxEnt models. Ecol Indic 2021; 132:108256. doi: 10.1016/j.ecolind.2021.108256
52. Zhong Y, Xue Z, Jiang M, Liu B, Wang G. The application of species distribution modeling in wetland restoration: A case study in the Songnen Plain, Northeast China. Ecol Indic 2021; 121:107137.