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Distribution of important medicinal plant species in Nepal under past, present, and future climatic conditions

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ABSTRACT

Climate change is causing shifts in the habitat, distribution, ecology, and phenology of Himalayan plants. These changes are predicted to continue, jeopardizing the survival of medicinal plant species and local livelihoods that rely on them. We analyzed the present and future diversity and distribution of medicinal plant species influenced by different climate change scenarios, and calculated the climatic niche of the species using ensemble species distribution modeling (eSDM). We compiled 1041 (N) geospatial data of seven high-value medicinal plant species of Nepal: *Aconitum spicatum* (n = 100), *Allium wallichii* (n = 151), *Bergenia ciliata* (n = 48), *Nardostachys jatamansi* (n = 121), *Neopicrorhiza scrophulariiflora* (n = 94), *Paris polyphylla* (n = 310) and *Valeriana jatamansi* (n = 217) including over 85 % from field surveys and the rest from literature and online database. We used bioclimatic variables from Models for Interdisciplinary Research on Climate (MIROC) of version MIROC6, and selected Shared Socioeconomic Pathways (SSP)2-4.5 and SSP5-8.5 for the year of 2050 and 2070 for modeling. We found elevation, mean diurnal and annual temperature ranges (BIO2 and BIO7), and precipitation of warmest and coldest quarters (BIO18 and BIO19) to be the most high weight cofactors for projecting the future potential distribution of high-value medicinal plants in Nepal. Results showed that the suitable range of distribution for high-value medicinal plants would increase and concentrate in mountainous areas of central Nepal, but decline in (sub)tropical and temperate areas, suggesting both *in-situ* and *ex-situ* conservation practices, respectively.

1. Introduction

Climate change already affects and is expected to continue affecting earth's weather systems in many ways, including seasonal patterns (Hajek and Knapp, 2022), extreme weather occurrences (Jentsch et al., 2007), temperature changes and precipitation fluctuations (Vincze et al., 2017). The frequency and severity of these changes are predicted to result in an increase in the future due to continued burning of fossil fuels and ecosystem degradation. As temperature rises and erratic rainfall persists, irreversible changes to ecosystems, biodiversity, species, habitats, and distribution ranges are likely to occur (Tse-Ring et al., 2010; Muluneh, 2021; Shrestha et al., 2021). Rates of species' distributional shifts, habitat loss and fragmentation, and extinction of species are expected to increase in time (Colwell et al., 2008). Forecasting these abrupt changes and the way that will affect biodiversity and people's lives is challenging and includes much uncertainty (Hallegatte et al., 2018).

Mountainous ecosystems and biodiversity are expected to be

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constantly impacted by climate change (IPCC, 2014; Dolezal et al., 2016; Bhattacharjee et al., 2017; Shrestha et al., 2018a,b, 2022). Mountainous plant species including alpine medicinal plants are well adapted to relatively narrow ranges of temperature and precipitation (Schickhoff et al., 2016). Available evidence shows that plants' habitat, distribution, ecology, and phenology are changing due to changes in temperature and precipitation (Kunwar et al., 2010; Aryal, 2015; Das et al., 2016; Rana et al., 2020). For example, mean temperature of warmest quarter (Kunwar et al., 2020; Charmakar et al., 2021; Kunwar et al., 2021), mean temperature of wettest quarter (Rana et al., 2017, 2020), and precipitation seasonality (Shrestha et al., 2021) are major bioclimatic indicators influencing the distribution of medicinal plants in Nepal. The change in distribution of medicinal plants is predicted to have major impacts on biodiversity and local livelihood (Ranjitkar et al., 2014; Kunwar et al., 2020; Charmakar et al., 2021; Shrestha et al., 2022). The range shifts in response to climate change could also threaten the survival of medicinal plants and sustenance of local livelihood across the mountains (Kunwar et al., 2014; Aryal, 2015; Rana et al., 2020). Assessment of distributional change of medicinal plants at the level of bioclimatic variables can provide more information on which variable largely affects the distribution of medicinal plants (Hadipour et al., 2019).

Nepal has a large medicinal plant economy (Pyakurel et al., 2019; Rana et al., 2020; Charmakar et al., 2021)) and is highly vulnerable to climate change (Aryal, 2015; Subedi et al., 2015), but no long-term estimates have been made as to the long-term impacts of climate change on the country's medicinal plant supply (Harish et al., 2012). One of the strategies for the sustainable supply of medicinal plants in the Himalaya is to map the current and potential habitats along the gradients of culture, climate, time and geography (Ranjitkar et al., 2014; Kunwar et al., 2016). Population modeling considering the demographic, ecological and socioeconomic aspects of the species' distribution changes can facilitate sustainable management of medicinal plants, and their potential for sustainable harvesting (Paul et al., 2015). Species distribution modeling is useful in explaining basic ecological phenomena behind species distribution patterns, exploration of the yet uncovered areas, and assessment of impacts of environmental changes on species distribution and conservation planning (Guisan and Thuiller, 2005; Coetzee et al., 2009; Kunwar et al., 2021a). Distribution modeling and climate change impact studies have been used to aid in identification of species and sites appropriate for *in situ* and *ex situ* conservation (Vincent et al., 2019; Gaisberger et al., 2020).

MaxEnt has become one of the most popular tools for modeling species distribution, while its results are criticized because it depends on small sample size (Morales et al., 2017; Qin et al., 2017; Kunwar et al., 2021). Currently, ensemble species distribution modeling (eSDM) is widely used for determining the species climatic space aiding the conservation of medicinal plants (Elith and Leathwick, 2009). It is important to evaluate the prospective influence of climate change on distribution of medicinal plants specifically as they are important to support economic livelihoods and cultural tradition, yet their detail impacts have not yet been assessed (Ranjitkar et al., 2014; Kunwar et al., 2014; Das et al., 2016; Shrestha et al., 2018a,b; Rana et al., 2017, 2020; Kunwar et al., 2020; Charmakar et al., 2021; Shrestha et al., 2018a,b, 2022). Thus, we investigated how climate change affects the diversity and distribution of medicinal plants in the present and future contexts. To be precise, we aimed at (i) documenting the present and potential geographic distribution of selected medicinal plant species, (ii) analyzing the impact of climate change on medicinal plants at diversity and distribution level, and (iii) finding out the suitable climatic spaces of medicinal plants for future distribution. In general, we tried to identify the key factors determining the current and future distributions and consolidate the knowledge of spatial patterns and distribution of the selected medicinal plant species to help devise long-term plant conservation strategies in Nepal. As climate change causes plants to move upslope to stay in a similar biome over time, we hypothesized that the range of tropical and temperate plant species gets upshifted and expanded at the expense of alpine species range.

2. Materials and methods

2.1. Study area and species

Nepal has five disparate physiographic regions (Fig. 1) ranging from i) High Himalaya (above 5,000 m, nival bioclimate), ii) High Mountains (3,000–5,000 m, alpine bioclimate), iii) Middle Mountains (1,000–3,000 m, subtropical and temperate bioclimate), iv) Siwalik (500–1,000 m, tropical bioclimate), and v) Lowland Tarai (<500 m, tropical bioclimate) from north to south (MoSTE, 2014). Politically the country is divided into seven provinces, 77 districts, and 753 local bodies (Chaudhary, 2020). Longitudinally, the country has three distinct regions, Western Nepal (from 80° E to 83° E), Central Nepal (from 83° E to 86° 30′ E), and Eastern Nepal (from 86° 30′ E to 88° 12′) (Stearn, 1960; Subedi et al., 2015). Owing to diverse geography and bioclimates, the country has over 13,000 species of plants (Chaudhary et al., 2020), including about 7,000 species of flowering plants (Shrestha et al., 2018a, b) and 2,500 medicinal and aromatic plants (Pyakurel et al., 2019; Kunwar et al., 2021b). Medicinal plant species richness in Nepal peaks at the elevational range 1,000–2,500 m above sea level (asl) (Bhattarai and Ghimire, 2006).

We selected seven medicinal plant species of Nepal that range between 1,000 m and 4,800 m asl (Kanel et al., 2017) representing lower Siwalik to high mountain physiography (Table 1). These seven species were selected because they (i) have a wide range of distribution, (ii) represent annual and herbal growth forms and life histories for assessment of impacts of climate change, (iii) are being widely collected, used and traded in Nepalese villages and markets, (iv) and are being threatened. These seven species are considered as high-value medicinal plants of Nepal as the species are frequently collected and traded in high volume in Nepal (Pyakurel et al., 2019; Rana et al., 2020; Shrestha et al., 2022), with an average of 53 tons per annum with maximum 687 tons of *Nardostachys jatamansi* in 2004 and minimum 446 kg of *Allium wallichii* in 2002 (GoN, 2015; Rana et al., 2020).

Among these species, *V. jatamansi* (Sugandhwal) is native to subtropical and temperate zones of the Himalayas and is regionally distributed in China, Bhutan, Nepal, India, Pakistan, Afghanistan, and Myanmar (Mabberley and Noltie, 2014). *N. jatamansi* (Jatamansi) is listed under Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II (https://checklist.cites.org), and is also globally regarded as critically endangered under IUCN Red List (Ved et al., 2015). *P. polyphylla* (Satuwa) is found at subtropical to temperate region and native to China, Taiwan, Nepal and the Indian Subcontinent (KBG, 2020; Ji et al., 2006). *A. spicatum* (Bikhma), *A. wallichii* (Ban lasun), *B. ciliata* (Pakhanved), *N. scrophulariiflora* (Kutki) are also under the vulnerable list of Conservation Assessment and Management Planning (CAMP) (Bhattarai et al., 2002). The species *N. jatamansi, V. jatamansi, N. scrophulariiflora* are banned by the government of Nepal for collection, transportation and trade, and export without processing, identification and certification (MoFSC, 2014).

2.2. Data acquisition

For identifying the current and future ecological distribution of the selected medicinal plants through modeling, we used species occurrence points collected from field surveys, literature, herbaria and online databases. Most of the occurrence points (900) were collected from Kanel et al. (2017) and fieldworks of the authors RMK, GJT, KSU, NJ and STM. The fieldworks were conducted to locate the presence of species. Additional presence locations were collected from a review of literature, voucher specimens deposited at National Herbarium and Plant Laboratories (KATH) https://plantdatabase.kath.gov.np/plants/search and Tribhuvan University Central Herbarium (TUCH), and search from the

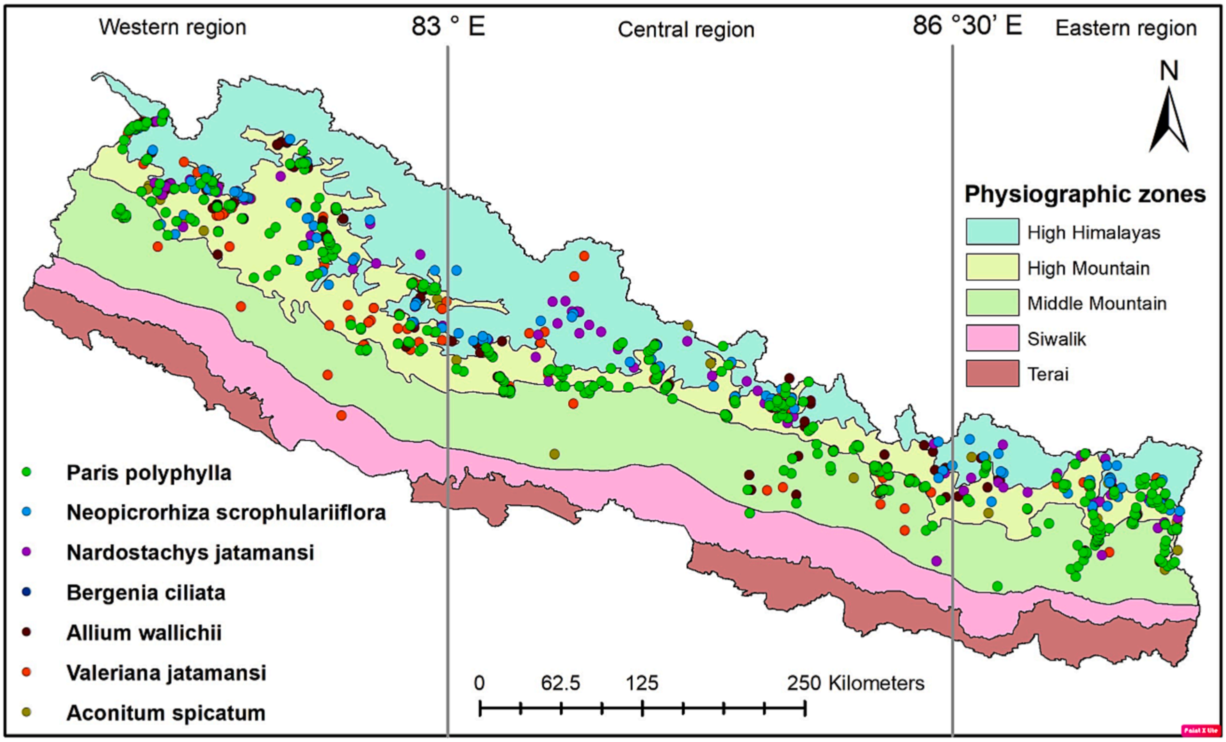

Fig. 1. Study area map showing physiographic regions of Nepal and distribution of occurrence points of sample species.

Table 1
Study species, their elevational range and habitats.

Study species	Elevation range	Habitat
Bergenia ciliata (Haw.) Sternb. (Saxifragaceae)	1000 m–3600 m	(Sub)tropical to temperate, open moist rocky areas
Valeriana jatamansi Jones (Caprifoliaceae)	1500 m–3600 m	Sub-tropical to temperate, open moist areas
Paris polyphylla Sm. (Melanthiaceae)	1800 m–3500 m	Sub-tropical to temperate, oak laurel rhododendron forest
Aconitum spicatum Stapf (Ranunculaceae)	1800 m–4300 m	Temperate to alpine, open grassy meadows, forests
Allium wallichii Kunth. (Amaryllidaceae)	2300 m–4800 m	Temperate to alpine, open grassy meadows, forests
Neopicrorhiza scrophulariiflora (Pennell) D.Y. Hong (Plantaginaceae)	3500 m–4800 m	Alpine, dry open rocky forests and scrubs, north slopes
Nardostachys jatamansi (D.Don) DC (Caprifoliaceae)	3600 m–4500 m	Alpine, dry open rocky forests and scrubs, north slopes

databases including Flora of Nepal (https://www.floraofnepal.org), iNaturalist (https://www.inaturalist.org/observations/71121639), the Global Biodiversity Information Facility (https://www.gbif.org/), the Royal Botanical Garden at Edinburgh, United Kingdom (RBGE; https://data.rbge. org.uk/search/herbarium/), and the Herbarium at the University of Tokyo, Japan (TI; https://umdb.um.u-tokyo.ac.jp/DShokubu/). The occurrence points and presence locations were verified through consultations with divisional forest officers, local communities, local harvesters and medicinal plant traders.

A total of 1,041 (N) geospatial occurrence points of seven species: *A. spicatum* (n = 100), *A. wallichii* (n = 151), *B. ciliata* (n = 48), *N. jatamansi* (n = 121), *N. scrophulariiflora* (n = 94), *P. polyphylla* (n = 310) and *V. jatamansi* (n = 217) were compiled and analyzed for simulating the species' distribution (Fig. 1). Before the analysis, the data was rarified for one km^2 using SDM toolbox 2.3. Therefore, we had no more than one presence data at each grid cell (1 km × 1 km) to reduce spatial autocorrelation and avoid inflated measures of accuracy. This method reduced sample bias and improved predictive performance of the models (Boria et al., 2014).

2.3. Modeling

We used combination of 19 bioclimatic variables and one topographical variable (elevation) for the prediction of suitable area for medicinal plant species in Nepal following the protocol established by Rana et al. (2020). The bioclimatic and elevation variables with a spatial resolution of 30 s (approximately 1 km^2) were downloaded from WorldClim database (https://worldclim.org/) (Fick and Hijmans, 2017). Future climate projections were based on the bioclimatic variables from Models for Interdisciplinary Research on Climate (MIROC) of version MIROC6. We choose MIROC because this global circulation model (GCM) has consistent for rainfall projection in the Indian subcontinent and can simulate future projection better than other GCM's model for South Asian region (Babar et al., 2015). Out of five Shared Socioeconomic Pathways (SPPs), we selected SSP2-4.5 and SSP5-8.5 for the year of 2050 and 2070. We selected these two SSP scenarios because it covers full range of predicted climate scenarios of low to hardest hit and makes overall presentation and discussion simpler in the manuscript. To eliminate highly correlated variables among the 20 climatic and topographical variables, a correlation matrix was created. From the matrix, least correlated variables were selected removing highly correlated variables (correlation coefficient $r > 0.7$ (Kunwar et al., 2021; Shrestha et al., 2022 (Supplementary file 1). Those variables selected for the model were mean diurnal range - BIO2, temperature annual range - BIO7, precipitation of warmest quarter - BIO18, precipitation of coldest quarter - BIO19 and elevation. With these five bioclimatic and topographical variables final eSDM on medicinal plants was conducted.

All the data processing for modeling process for medicinal plants were conducted using R 4.2 package "biomod2" in R environment (R development Core Team, 2022) except rarifying the presence points of medicinal plants by 1 km × 1 km which was conducted in ArcMapp 10.8.2 (ESRI, 2021). After selecting subset of predictor variables (Supplementary file 2), we used default 10 algorithms within an ensemble framework to create consensus bioclimatic niche models of each species using Biomod2 R package (Thuiller et al., 2019). The consensus model for each species included a general additive model (GAM), general linear model (GLM), generalized boosting model (GBM), Random forest (RF), artificial neural network (ANN), classification tree analysis (CTA), flexible discriminant analysis (FDA), multiple adaptive regression splines (MARS), surface range envelope (SRE), and maximum entropy (MAXENT). In the model we used 5,000 pseudo points that were generated within the predicted area of the polygon, following Rana et al., (2020). The accuracy of the model was assessed from the data generated by a split-sample where 80 % of data were used for model development and 20 % for predictive power of each model with 3-fold cross-validation. We used area under curve (AUC) and values of receiver operator characteristic (ROC) curve and true skill statistics (TSS) to assess the model performance. Models with the TSS value < 0.70 was considered poor, 0.7–0.9 considered moderate, and > 0.9 considered a good model (Hajian-Tilaki, 2013). We selected only those models having TSS values > 0.70 for building the ensemble model using a weighted mean approach.

Ensemble model output (probability of species occurrence) was converted to a binary model (presence/absence) by applying thresholds that were estimated to allow a maximum of 50 % probability of future suitable habitat based on present distribution. In order to avoid over-estimating, the modeling result was masked by applying the buffer of 250 m to the given distribution range of each species following Kunwar et al. (2020).

The potential changes in the distribution were assessed by comparing the suitability map produced by eSDM under current and future climate scenarios for each species.

2.4. Species loss, gain and turnover

Similar to investigations made by Ramirez-Villegas et al. (2014) and Phillips et al. (2017), the impact of climate change on selected species was evaluated by assessing the species richness, species loss and species gain. We obtained the single species richness raster layer by aggregating suitable area raster for all species, and calculated average values using the "raster' package extract function. We considered each district as a unit to track the species' loss and gain over time. For the end result comparison, the turnover rate (T) was calculated for SSP5 8.5 for year 2050 and 2070 with the formula:

$$T = 100 \times (L\ or\ G)/(SR + L\ or\ G)$$

where SR represents current species richness, L is the loss of species per district, and G is the gain of species per district (adapted from Phillips et al., 2017; Ramirez-Villegas et al., 2014). The turnover rate possesses negative value when species are lost, and positive value when species are gained and value zero when no species are gained or lost.

In addition, we collected biogeographic information (elevation of collection site) and time of the collection of specimens from both field surveys and herbaria vouchers as a proxy to assess changes in distribution. We used biogeographic information of specimens collected between 1950 and 2022 July and evaluated the distribution change in the future using Lang et al. (2019). Also, we compiled each species' voucher record, latitude, longitude, and elevation as well as the month and year it was collected. The elevation of each species was regressed against the period of collection to determine if the collection sites were becoming more elevated over time.

3. Results

3.1. Model performance and key environmental variables

Overall, the predictive performance of the ensemble model was good with the average TSS values among species ranged between 0.71 and 0.80. The average TSS values for *A. spicatum, A. wallichii, B. cilliata, N. jatamansi, N. scrophulariiflora, P. polyphylla,* and *V. jatamansi* were 0.71, 0.78, 0.71, 0.75, 0.73, 0.79, and 0.75, respectively. In general, regression models such as general additive model (GAM), general boosting model (GBM) and generalized linear model (GLM) had stronger performances in models (TSS values > 0.80). However, artificial neural model (ANN) and surface range envelope (SRE) had lower performance in comparison to others (Table 2).

Among the selected five predictive bioclimatic variables, elevation contributed the highest (31–51 %) in models for all species (Table 3). Among the temperature related predictive variables (BIO1 - BIO11) BIO7 (Temperature Annual Range (BIO5-BIO6) contributed 21–38 % and BIO2 (Mean Diurnal Range (Mean of monthly max. temp-min. temp) contributed 6–11 %. Within the precipitation related variables (BIO12-BIO19), BIO18 (Precipitation of Warmest Quarter) and BIO19 (Precipitation of Coldest Quarter) showed the contributions 7–17 % and 2–7 %, respectively. Thus, elevation was found as a major determinant with its contribution mean 42.07 % followed by BIO7 31.67 %, BIO18 12.12 %, BIO2 8.7 % and BIO19 5.42 %. However, their role varied greatly at species level. Elevation contributed the most (51.6 %) to the distribution of *V. jatamansi.* It also contributed higher for *A. spicatum, A. wallichii, N. jatamansi,* and *P. polyphylla*, 43.85 %, 42.54 %, 42.77 %, 48.15 %, respectively. BIO7 was the most determinant to the distribution of *N. scrophulariiflora* and *B. ciliata.* Temperature related predictive variables BIO2 and BIO7 combined contributed the most (43–49 %) to the distribution of *N. scrophulariiflora*, *N. jatamansi* and *B. ciliata*. Precipitation related variables BIO18 and BIO19 combined contributed the most to *B. ciliata, A. spicatum* and *V. jatamansi* by 23.25 %, 21.66 %, and 19.57 %, respectively (Table 3).

3.2. Medicinal plant species richness at present and future scenarios

We observed that the model expects species to be present in 62 districts but absent in 15 Tarai lowland districts. Among 15 species absent districts, eight districts (Bara, Parsa, Rautahat, Sarlahi, Mahottari, Dhanusa, Siraha and Saptari) represent Madhesh province, four districts (Banke, Kapilbastu, Rupandehi and Nawalparasi) represent Lumbini province, Sunsari and Jhapa are from province One, and Kanchanpur in Sudurpaschim province. The least number of study species were reported from Bardiya, Kailali, Morang, Tanahun, Dang, Nawalpur, Chitwan and Udayapur districts (average species number < 1). All districts of Gandaki and Bagmati provinces possessed at least one species with the average ∼ 2 species (Fig. 2). Among the 62 districts the species recorded, Jumla and Kalikot districts of Karnali province, Rukum-E of Lumbini and Baglung of Gandaki possessed the most species (average species number > 4) followed by Myagdi of Gandaki, Bajura of Sudurpaschim, Jajarkot and Rukum-W of Karnali and Rasuwa and Dolakha of Bagmati (average species number > 3) out of seven (Supplementary file 3).

As 15 districts were null in the distribution of sample species (represented by white in Fig. 2), they were not considered for further analysis. Amongst the 62 districts, only two districts Bardiya and Kailali had no change in species number yet they were accounted for loss in suitable areas for medicinal plants in the future. Districts - Chitwan, Surkhet, Dang and Dailekh - had significant loss in species (>-0.2) while the districts Manang, Mustang, Ilam and Darchula has significant gain (>0.2). The districts with the highest diversity of medicinal plant species represent middle mountainous terrain (around 3,000 m asl) while the species gain was concentrated in northern mountainous districts (Fig. 2). There were 35 districts with species turnover (species loss) while the 25 districts had species gain. Jumla and Kalikot districts of Karnali province would lose species in the future (Fig. 2).

3.3. Species potential distribution

Our results revealed that the average suitable area for each species

Table 2
Predictive performance of various algorithms used in eSDM for prediction of distribution of medicinal plants found in Nepal.

		ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF	SRE
Aconitum spicatum (As)	AUC	0.697	0.877	0.926	0.894	0.933	0.944	0.944	0.946	0.897	0.818
	TSS	0.395	0.738	0.775	0.709	0.775	0.807	0.788	0.807	0.745	0.636
Allium wallichii (Aw)	AUC	0.762	0.899	0.936	0.942	0.950	0.952	0.954	0.955	0.946	0.858
	TSS	0.520	0.771	0.824	0.822	0.842	0.848	0.840	0.844	0.839	0.715
Bergenia cilliata (Bc)	AUC	0.782	0.843	0.929	0.865	0.906	0.930	0.887	0.950	0.894	0.755
	TSS	0.549	0.686	0.796	0.707	0.763	0.800	0.723	0.849	0.743	0.510
Nardostachys jatamansi (Nj)	AUC	0.836	0.871	0.914	0.903	0.938	0.933	0.911	0.947	0.925	0.829
	TSS	0.676	0.713	0.769	0.749	0.806	0.805	0.754	0.840	0.782	0.658
Neopicrorhiza scrophulariiflora (Ns)	AUC	0.720	0.871	0.941	0.917	0.940	0.937	0.929	0.946	0.926	0.783
	TSS	0.439	0.735	0.820	0.786	0.805	0.830	0.798	0.836	0.770	0.566
Paris polyphylla (Pp)	AUC	0.838	0.917	0.948	0.950	0.957	0.955	0.957	0.956	0.956	0.836
	TSS	0.658	0.795	0.818	0.826	0.843	0.829	0.839	0.840	0.813	0.671
Valeriana jatamansi (Vj)	AUC	0.702	0.887	0.935	0.927	0.940	0.942	0.935	0.948	0.938	0.843
	TSS	0.403	0.783	0.804	0.795	0.824	0.816	0.804	0.824	0.771	0.688

Table 3
Average importance of variables, and rank score in parenthesis.

Species (abbreviation)	Occurrence points sampled	TSS	BIO2 (%)	BIO7 (%)	BIO18 (%)	BIO19 (%)	Elevation (%)
A. spicatum (As)	100	0.82	8.21(2)	26.28 (4)	15.91 (3)	5.75 (1)	43.85 (5)
A. wallichii (Aw)	151	0.78	9.71(3)	31.72 (4)	9.18 (2)	6.85 (1)	42.54 (5)
B. ciliata (Bc)	48	0.84	8.91 (2)	36.44 (5)	17.10 (3)	6.15 (1)	31.40 (4)
N. jatamansi (Nj)	121	0.75	8.21 (3)	35.39 (4)	7.91 (2)	5.72 (1)	42.77 (5)
N. scrophulariiflora (Ns)	94	0.78	10.98 (3)	38.70 (5)	8.71 (2)	7.46 (1)	34.15 (4)
P. polyphylla (Pp)	310	0.77	8.03 (2)	31.30 (4)	9.87 (3)	2.66 (1)	48.15 (5)
V. jatamansi (Vj)	217	0.76	6.88 (2)	21.89 (4)	16.21 (3)	3.36 (1)	51.65 (5)
Average		*0.78*	*8.70 (2)*	*31.67 (4)*	*12.12 (3)*	*5.42 (1)*	*42.07 (5)*

BIO2 = Temperature mean diurnal range, BIO7 = Temperature Annual range, BIO18 = Precipitation of warmest quarter, BIO19 = Precipitation of coldest quarter.

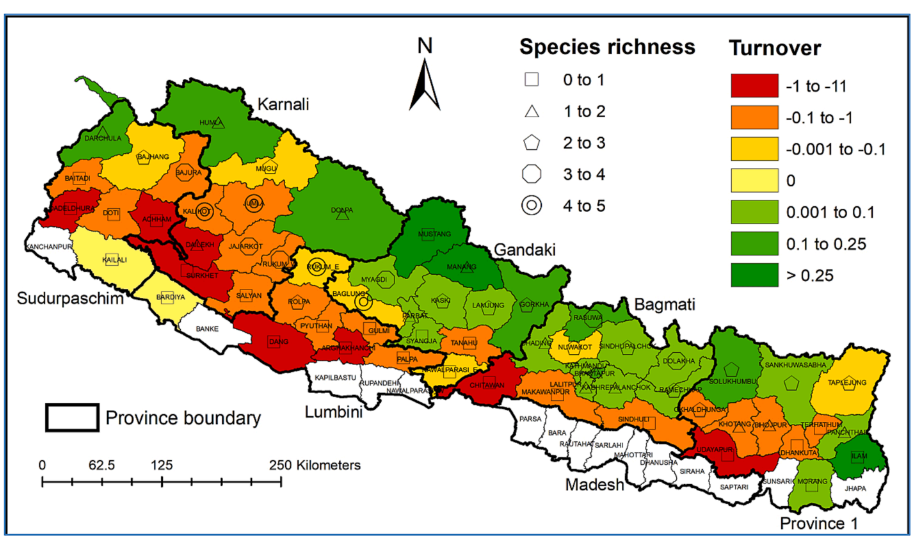

Fig. 2. Species richness and turnover of medicinal plants at present and year 2070 (SSP5).

for the whole country at current (2022) is 30,500 km^2 and decreased to 28,600 km^2 in 2070 (SSP5 8.5). The average current suitable area for each species for each province is 4,365 km^2, and will be 4,310 km^2 and 4,094 km^2 in 2050 and 2070, respectively under SSP5 8.5 scenario (Fig. 3). The total suitable area for seven medicinal plant species gets contracted by 1.25 % in 2050 and by 6.20 % in 2070 under the climate change under the SSP5 8.5 scenario. However, the projection varied at species level. The predicted suitable distribution area of alpine species *N. jatamansi* and *N. scrophulariiflora* was found to be increased by 12.45 % and 26.65 %, respectively and that of *A. wallichii* was 0.87 %. All three

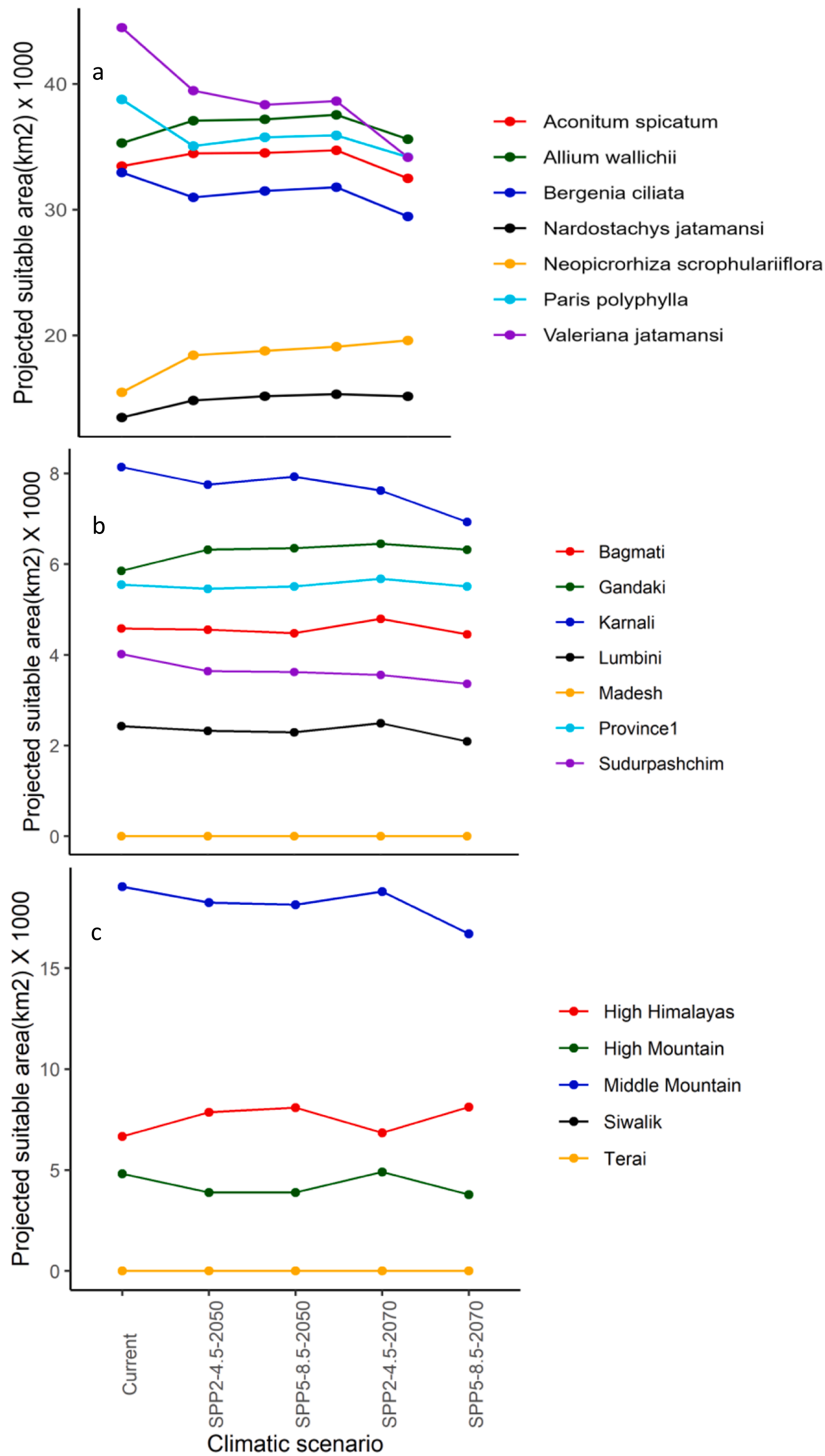

Fig. 3. Projected suitable areas for sample species (a), average area of each species in each province (b) and, average area of each species in each physiography (c) under different climatic scenarios.

species were predicted to be increased in all six provinces except a loss for *A. wallichii* (9.75 %) at Karnali province. However, for the other four species, their distribution area was expected to be decreased by 12.94 % in 2070 (SSP5 8.5). Among four species, the distribution of sub-tropical and temperate species (*B. ciliata, P. polyphylla*, and *V. jatamansi*) growing in middle mountains and high mountains was constrained in a greater extent by 10.61 %, 11.83 % and 23.18 %, respectively (Fig. 3a).

At province level, *B. ciliata* is expected to be greatly changed in distribution and it is likely that around 34 % of its habitats will be lost in Karnali and Sudurpaschim provinces between 2022 and 2070 (SSP5 8.5) while its habitat would be slightly increased in Gandaki province, by an insignificant value (0.44 %). In Karnali and Sudurpaschim provinces, the habitat of *P. polyphylla* is projected to be lost by 27–28 % and that of *V. jatamansi* by 44–49 % between 2020 and 2070 (SSP5 8.5). However, the suitable areas for alpine species *N. scrophulariiflora* and *N. jatamansi* are likely to be increased by 4.7–44.7 % in these provinces. In overall, it is anticipated that by 2070, habitats for high-value medicinal plant species will decline in Karnali and Sudurpaschim provinces by 14.8 % and 16.2 %, followed by Lumbini (−13.2 %), Bagmati (−2.8 %), Province One (−0.6 %) (Fig. 3b) (Supplementary file 4).

Conversely, the habitats will be increased at Gandaki province by 8.02 %. Gandaki is only the province that is expected to have the increased suitable areas of all seven species in future with 24.7 %, 23.2 %, 15.1 %, 11.1 %, 1.5 %, 0.44 %, and 0.42 % increment of *N. jatamansi, N. scrophulariiflora, A. wallichii, A. spicatum, P. polyphylla, B. ciliata* and *V. jatamansi*, respectively. The suitable areas for *P. polyphylla* is expected to be declined in all four provinces except Gandaki and Bagmati, and that of *V. jatamansi* is to be slightly increased only in Gandaki by 0.42 %. Suitable area for *P. polyphylla* and *V. jatamansi* is expected to be increased in mountains of Gandaki province despite they get lost by 11.8 % and 23.1 %, respectively at national level. The suitable areas for *N. jatamansi, N. scrophulariiflora* and *B. ciliata* expanded from west to central mountainous districts (Fig. 4) (Supplementary file 5). However, about 29 % current habitats of medicinal plants is confined at Karnali province and projected to be a home of 28 % in 2050 and 24 % in 2070 (SSP5 8.5).

At district level, Jumla had the largest distribution area of five study species (*A. spicatum, A. wallichii, P. polyphylla, N. scrophulariiflora, V. jatamansi*) while the Bajhang had four (*A. spicatum, A. wallichii, P. polyphylla, V. jatamansi*). Dolpa had the largest distribution area of *N. jatamansi* and *N. scrophulariiflora* while the Humla had the second largest distribution of *N. jatamansi*. Sankhuwasabha district was second in possessing the largest distribution area of *P. polyphylla*. The largest distribution area of *B. ciliata* at present and by 2070 is accounted from

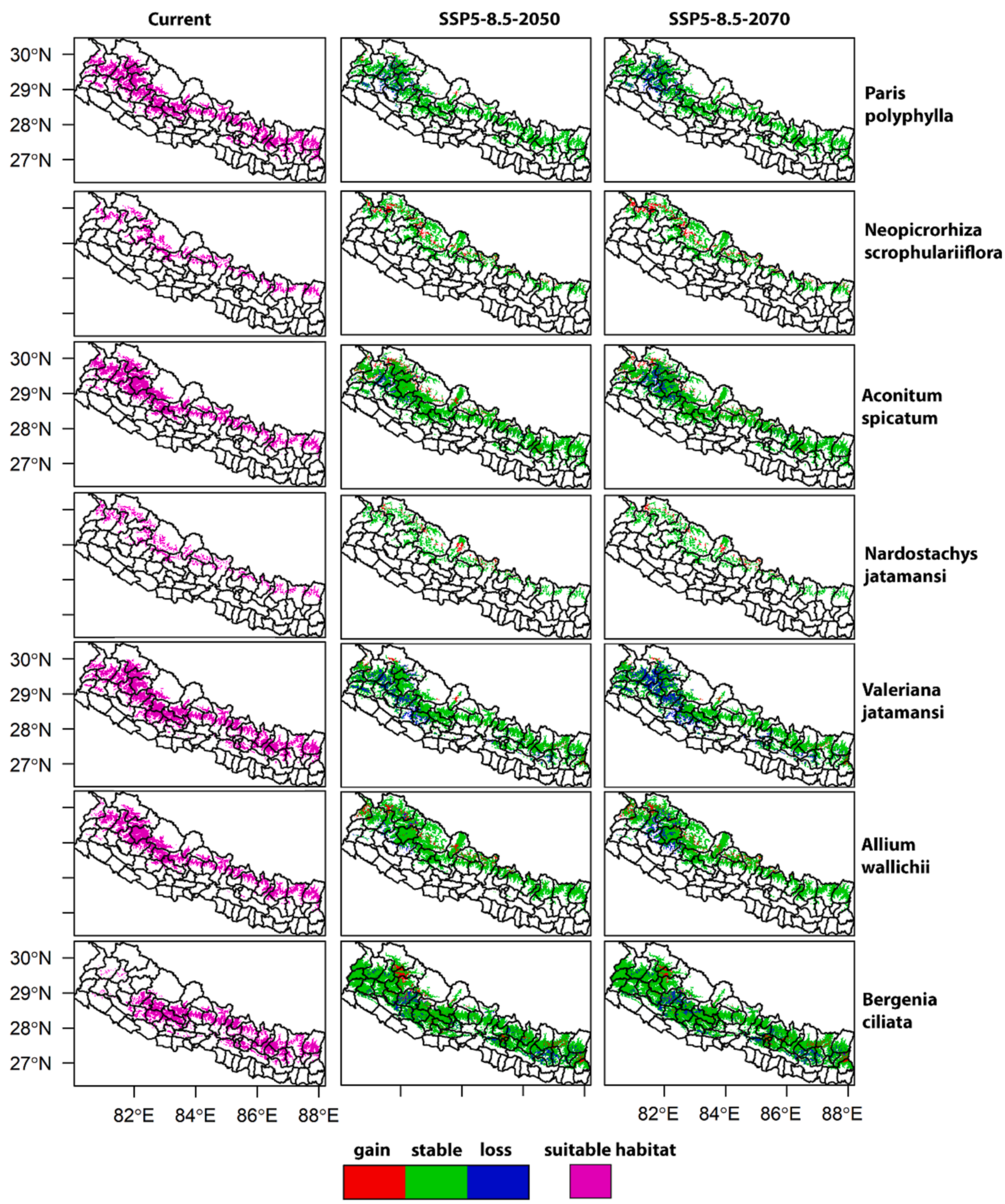

Fig. 4. Potential distribution of medicinal plants under current and future (2050, 2070, SSP5 8.5) bioclimatic conditions categorizing their habitat suitability level.

Baglung and Taplejung districts revealing that there would not be any change in *B. ciliata* distribution in the future. While, the distribution area of *V. jatamansi* was mostly changed and it will largely be found in Baglung and Taplejung districts. Jumla will not possess the largest distribution area of all five species in 2070 and it lessened to be a good habitat for only two species *A. spicatum, A. wallichii*. By 2070 (SSP5 8.5), Dolpa was found to be the largest distribution area of *N. jatamansi*, *N. scrophulariiflora* and *A. wallichii* at present and under future scenarios (Supplementary file 6).

3.4. Distribution change overtime

Despite the species-specific significance, the overall analysis of distribution change exhibited a weak relation (Fig. 5). As collection records of *A. spicatum* and *A. wallichii* were from lower elevation areas in early days and the later records from higher elevation areas supported the upslope migration ($p = 0.31$ and 0.03 respectively). Out of seven species, the collection records of subtropical and temperate species *P. polyphylla* ($p = 0.013$), *B. ciliata* ($p = 0.32$) and *V. jatamansi* ($p = 0.75$) species were found insignificantly descending while that of *N. jatamansi* and *N. scrophulariiflora* were significantly descended ($p = 0.003, 0.0003$ respectively) overtime.

4. Discussion

4.1. Key variables and medicinal plant species

Current and future climatic scenarios were modeled for the potential distribution of high-value medicinal plant species in Nepal. Elevation contributed the most (31–51 %) to the prediction scores, followed by temperature. Other predictive variables mean diurnal and annual temperature ranges (BIO2 and BIO7) contributed up to 38 % and precipitation related variables (precipitation of warmest and coldest quarters) shared up to 17 %. Temperature related variables were more responsive in determining the suitable area of the seven studied species. Rana et al., (2020) also recorded temperature as a major variable for predicting the suitable areas for high-value medicinal plants, and Rawat et al., (2021) observed annual range of temperature as an important factor determining the distribution of *N. scrophulariiflora*.

Elevation, as a non-climatic environmental variable, had a significant impact on species distribution, consistent to the findings of Cahyaningsih et al. (2021). However, the result refutes to the findings of Pearson and Dawson (2003) and Blach-Overgaard et al. (2010). Elevation was also found important in predicting the future distribution of *B. ciliata* in India (Kaliyathan et al., 2016). Matched to the findings of Chhetri et al., (2018), we observed the greatest amount of variance in the distribution of alpine species in Nepal by temperature-related climatic variables and elevation. At species level, we recorded temperature annual range as a major contributor to *N. jatamansi, P. polyphylla* and *V. jatamansi*, while Rana et al., (2020) found precipitation as a determinant for them. Temperature related variables contributed the most to the distribution of *N. scrophulariiflora*, *N. jatamansi* and *B. ciliata* as higher temperature helps recede glaciers and allows plants to grow (Anderson et al., 2020). We observed precipitation of the warmest quarter (BIO18) was the most influential for determining the distribution of *B. ciliata* because it may need a large amount of rainfall during the wettest month to survive, grow, and reproduce (Kunwar, 2021). Similarly, precipitation related variables (BIO18 and BIO19) contributed the most to *A. spicatum* (21.66 %) and *V. jatamansi* (19.57 %).

4.2. Species richness and turn over

Many medicinal plant species were recorded at central middle mountainous with average elevation 3,000 m asl. All districts of Gandaki and Bagmati provinces possessed at least one species with average 2.75 species present in these districts. Whereas in the lowland Tarai districts with elevation range (100–1,500 m asl), few (0–0.104) medicinal plant species were recorded. The outcome demonstrated an increased biodiversity in mountainous areas and a loss in subtropical-temperate regions. Plant species may shift to areas outside their usual favorable bioclimatic conditions to adapt to the changing climatic conditions (Phillips et al., 2017) leading to change in distribution and species.

The average turnover rate for both SSPs was greater for 2050 than in 2070. The overall average species turnover rates for high-value medicinal plant species in Nepal was negative which indicates that the medicinal plants diversity is expected to be higher than the gain. Districts - Chitwan, Surkhet, Dang and Dailekh (Siwalik to Middle mountains physiography with average elevation range 390–1,546 m asl) - had high-value medicinal plants loss while the districts Manang, Mustang, Ilam and Darchula (middle to high mountains with average elevation range

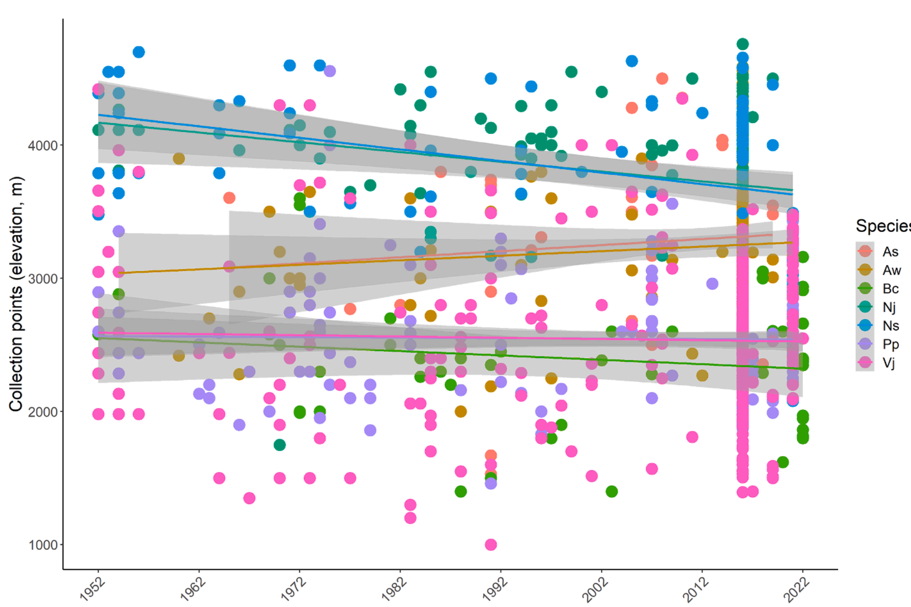

Fig. 5. Distribution of collection points of each sample species between 1950 and 2022. *Note: As = Aconitum spicatum, Aw = Allium wallichii, Bc = Bergenia ciliata, Ng = Nardostachys jatamansi, Ns = Neopicrorhiza scrophulariiflora, Pp = Paris polyphylla, Vw = Valeriana jatamansi.*

1,100–4,800 m asl) had gain in species number and suitable areas (Fig. 3c). Areas with positive turnover may have more appropriate habitat available for the species in the future (Sanchez et al., 2011; Asase and Peterson, 2019; Vincent et al., 2019; Gaisberger et al., 2020). Topographically, the mid-elevational range from *ca.* 1,800–4,200 m asl was found to be more suitable for medicinal plant species (Rana et al., 2020). Furthermore, United Nations Biodiversity Lab showed high species richness in the middle mountains of Nepal (MoFE, 2018; Shrestha et al., 2022). Higher mountain areas around the elevation 3,500–4,200 m asl possesses high species endemicity (Tiwari et al., 2018) and the middle mountain possesses high medicinal plant species diversity (Rokaya et al., 2012; Kutal et al., 2021; Kunwar et al., 2022). High elevation areas enrich with higher diversity and endemicity than lowland areas (Noroozi et al., 2018; Rahbek et al., 2019).

4.3. Distribution and suitable habitats

The total suitable area for seven high-value medicinal plant species gets contracted in 2050 and in 2070 under SSP2 4.5 and yielded a huge lost under SSP5 8.5 (extreme climate change) scenarios. This indicates that suitable area of high-value medicinal plants is expected to be increasingly contracted overtime in Nepal, as predicted earlier (Wani et al., 2022), which is concerning. The result varied at the level of species, province and physiography. The Karnali province and low-lying areas were projected to be a region of huge loss of medicinal plants under future climate change. Medicinal plants of tropical region are highly impacted by climate change (Cahyaningsih et al., 2021). The predicted suitable distribution area of (sub)alpine species *N. jatamansi* and *N. scrophulariiflora* increased in all provinces and, *A. wallichii* increased in all but not in Karnali province. The upper habitat limit of these three species is ~4,500 m asl whereas that of other four species is 2,500 m asl (Kanel et al., 2017). Rana et al. (2020) observed increasing habitat of alpine species (*N. jatamansi, N. scrophulariiflora*) under the future climate scenarios. Increasing suitable areas for alpine species *N. jatamansi* in future climate change scenarios (RCP2.6, 2050, 2070) was also observed in China (Li et al., 2019). However, the suitable area for A. *wallichii, P. polyphylla* was found to be increased and that for *N. jatamansi, N. scrophulariiflora* decreased shown by Shrestha et al., (2022). They predicted the declining suitable areas for *A. spicatum, B. ciliata* and *Valeriana* species in 2050 under RCP 6.0 scenario.

The distribution of sub-tropical and temperate species particularly of *B. ciliata, P. polyphylla*, and *V. jatamansi* growing in middle mountains (1,000–3,000 m asl) was constrained in a greater extent. Tropical and subtropical species are, on average, shifting their distributions faster than temperate species (Freeman and Class, 2014). A study showed that about 55 % of tropical and subtropical species experiencing more climate change impact, whereas the figure was lower, at 39 %, for alpine-temperate species (Wiens and Barnosky, 2016). In Nepal, the vulnerability of (sub)tropical plant species may be further compounded by anthropogenic pressure such as over-grazing and overexploitation of forests for fodder, fuelwood and medicinal plants coupled with increasing biological invasion (Shrestha et al., 2021). Over 50 % of the population lives in hills and mountains (Cosic et al., 2017) that exerts several anthropogenic pressures to the nearby plants. Moreover, the (sub)tropical and temperate areas are increasingly and aggressively abraded by southern invasive species (Baral et al., 2017), limiting the niches for useful medicinal plant species (Bhattarai et al., 2014; Shrestha et al., 2018a,b; Acharya et al., 2022). Unlike in the more tropical areas, more mountainous areas will offer habitat to these species, accepted the null hypothesis. There are some reports accounting the increasing suitable areas of high-value medicinal plants in the northern part of Nepal under future climate change (Kunwar et al., 2020; Charmakar et al., 2021). Northern and higher elevation areas of Nepal were also found suitable for alpine tree species (Chhetri et al., 2018).

The area of expected high suitability for *N. jatamansi, N. scrophulariiflora* and *B. ciliata* expanded from west to central mountainous areas. This indicates that the suitability areas for medicinal plants concentrate in central mountains of Gandaki and Bagmati provinces. As the precipitation at warmest and coldest quarters influenced the distribution of medicinal plants, the high precipitation records (>3,000 mm) at central mountains supported the present and future distribution of plants (Regmi and Bookhagen, 2022). This region is also highly suitable for *P. polyphylla* and considered as a hotspot for the medicinal plants (Rana et al., 2020). Gandaki province, and Bagmati province were also found as hotspots of medicinal plants by Shrestha et al., (2022).

The highest species turnover gain was in the Mustang and Manang districts (Gandaki province, Central trans-Himalayan region) with an estimated 10.69 % increase in expected suitable area. Mountainous districts such as Mustang, Manang and Gorkha of Gandaki province, and Darchula, Humla and Ilam of other provinces are likely to have increased suitable areas for medicinal plant species in the future. The highest diversity of medicinal plant species and the outstanding gain was recorded in the middle mountainous physiography (around 3,000 m asl) and northern region of central Nepal and its surroundings. Whereas, the low elevation areas such as Chitwan, Surkhet, Dang, Udayapur, etc., is projected to suffer the loss of suitable area by 60–90 % of the present distribution area. A modeling (SSP1, SSP5) carried out in tropical region of Nepal including Chitwan district revealed that there would be a loss of over one third of the current wildlife habitats by 2070 (Pant et al., 2021).

The data from the earlier collection records of alpine plants *N. jatamansi* and *N. scrophulariiflora* from the higher elevation and the recent collection records from the successive lower elevation areas provided the evidence of downslope shift and refuted the hypothesis. It also opened up the concerns that plants not only exhibit upslope movement but they do also reveal the downslope movement as the resource partitioning is competitive at newer and higher elevation areas (Lenoir et al., 2010). Some plant species migrate downhill due to mean temperature of coldest quarter and hazards (Crimmins et al., 2011; Lenoir et al., 2010; Zu et al. 2021). However, glaciers receding due to climate change allows wider spaces for expanding alpine species (Schickhoff et al., 2016; Anderson et al., 2020) and migrating to the favorable areas. The other factors contributing to species downhill movement may be changes in precipitation patterns as well (Elsen and Tingley, 2015).

4.4. Implications for conservation

Our modeling approach predicted that suitable areas for subtropical and temperate medicinal plant species would be constrained under the scenarios of climate change. Whereas, the suitable areas for overall medicinal plant species are expected to expand in the mountainous areas. The highest diversity of medicinal plant species was accounted in middle mountains (around 3,000 m asl) of Central Nepal, supported by the species gain concentrated in the central and northern mountains. Areas with the least positive turnover may require *in situ* conservation with sustainable utilization (Asase and Peterson, 2019). In contrast, the region with a loss of species (negative turnover) and suitable areas may have hostile habitat for expansion of medicinal plants in the future, which thus demands strict preservation measure to protect them from the verge of extinction.

Climate change and its associated consequences are expected worsen in the near future (Colwell et al., 2008), yet the true extent to which it damages can not be precisely anticipated due to many uncertainties. In these constraints, climate change may become a more pressing issue for the medicinal plants as it directly changes their habitat distribution. Extreme weather has been known to influence harvesters' and cultivators' ability to grow and/or harvest medicinal plant species, and similar issues have been witnessed in recent years (Das et al., 2016, Kutal et al., 2021). Increasing human populations in the mountainous areas of Nepal that rely on local medicinal plants for primary healthcare and livelihood (Rokaya et al., 2012, Pyakurel et al., 2019; Kunwar et al., 2022) also are expected to pose additional pressures on local habitats and niches, making medicinal plants more vulnerable. Our results serve conservation policy support that helps better manage the species and habitats, which are crucial for biodiversity and livelihood in the present and future.

4.5. Limitations

The microclimatic heterogeneity on different periods may alter the spatial distribution of species, but we did not consider this as a subject variable, and we selected only one physiographic variable (elevation) and 19 bioclimatic variables for simple discussion in this presentation. We did not consider applying slope and aspect in modeling, however many studies use slope, aspect, geographical barriers and human disturbances (e.g. modification of habitats) as variables for habitat modeling. Thus, it is possible that the impact of these factors could lead to greater or lesser habitat change than presented here. The predictions from our model might not be perfectly accurate because the SSP modeling is based on assumptions and projections about future conditions rather than on direct observations. It is, however, noted that even with some limitations, this study contributes to a growing body of literature that argues for application of species distribution modeling for assessing the impact of climate change effect on future distribution of species.

5. Conclusions

In addition to elevation, mean diurnal and annual temperature range (BIO2 and BIO7), and precipitation of warmest and coldest quarter (BIO18 and BIO19) contributed all explained variation in medicinal plant distribution in Nepal. The highest diversity of medicinal plant species and their positive turnover in the future estimated to be found in the central and northern mountains. Modeling results showed that with 2050 and 2070 expectations of climate change, suitable distribution area of (sub)alpine species (*A. wallichii, N. jatamansi, N. scrophulariiflora*) increased in all six provinces except a loss of *A. wallichii* in the Karnali province. Three sub-tropical and temperate species (*B. ciliata, P. polyphylla*, and *V. jatamansi*) showed a decrease of suitable area by up to 24 %. This indicates that the central mountainous physiography and precipitation are important indicators in determining the future distribution of medicinal plant species.

Because of the expected changes in future suitable areas for medicinal plants growth, the distribution of medicinal plants is expected to change in 60 districts, with gain in 25 districts and loss in 35. The overall average turnover rate for medicinal plant species in Nepal in this study was negative indicating that the loss of species number in areas is projected to outnumber the gain. The anticipated loss of habitats and species strongly necessitates the need for performing *ex-situ* and *in-situ* conservation. The results of modeling predicting changes in distribution and populations need to be considered while planning sustainable management of medicinal plants and climate change adaptation.

6. Data archiving statement

All relevant data are within the manuscript and its supporting iinformation files.

7. Ethics statement

Prior to field visit, informed consent was obtained from all stakeholders that include, Divisional Forest Office at each district, divisional forest officers, local communities, local harvesters and medicinal plant traders.

CRediT authorship contribution statement

Ripu M. Kunwar: Conceptualization, Investigation, Methodology, Validation, Formal analysis, Writing – review & editing, Funding acquisition. **Khum B. Thapa-Magar:** Methodology, Formal analysis, Writing – review & editing. **Suresh C. Subedi:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Durga H. Kutal:** Methodology, Formal analysis, Writing – review & editing. **Bikash Baral:** Data curation, Validation, Writing – review & editing. **Nabin R. Joshi:** Investigation, Data curation, Validation, Writing – review & editing. **Binaya Adhikari:** Methodology, Formal analysis, Writing – review & editing. **Kul S. Upadhyaya:** Data curation, Validation, Writing – review & editing. **Santosh Thapa-Magar:** Investigation, Data curation, Validation, Writing – review & editing. **Abdul S. Ansari:** Methodology, Resources, Writing – review & editing. **Gokarna J. Thapa:** Methodology, Validation, Resources, Writing – review & editing. **Ananta R. Bhandari:** Methodology, Resources, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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