Climate change impact on the geographic distribution of Nepeta glomerulosa, medicinal species endemic to southwestern and central Asia

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Abstract

Medicinal plants are valuable species, but their geographic distributions may be limited or exposed to extinction by climate change. Therefore, research on medicinal plants in the face of climate change is fundamental for developing conservation strategies. Distributional patterns for a semi-endemic medicinal plant species, *Nepeta glomerulosa*, distributed in southwestern and central Asia was determined based on a maximum–entropy algorithm. We evaluated potential geographic shifts in suitability patterns for this species under two scenarios (RCP 4.5 and RCP 8.5) of climate change for 2050. Our models indicate that the species occupies montane areas under current conditions; transfer of the model to future climate scenarios indicated that suitable areas for the species will decrease, and the species will likely shift towards higher elevations. But the types and degrees of these shifts differ among areas. Our findings can be used to inform conservation management programs for medicinal, endemic, and endangered species in southwestern and central Asia.

Introduction

Climate change is considered as one of the most important issues globally, with shifting conditions affecting geographic distributions of plant species[1–7]. Studies of various plant species indicate that climate change may reduce the climatically suitable areas for species or shift their geographic distributions[8–13]. Investigating climate change impacts and the response of wild plant species to these changes is important for effective species conservation and sustainable ecological development[3,11]. An important and long-standing challenge in ecology is understanding the factors limiting geographic distributions and molding abundance patterns[14–17], which are especially important in predicting consequences of environmental and climate change for plant species[17–19].

Numerous modeling approaches have been developed to explore and anticipate future species distributions under changing climates. Ecological niche models (ENMs) are a suite of techniques based on occurrence data and environmental variables that allow researchers to estimate relative suitability of habitats of the species. These approaches can elucidate the relative suitability of sites in areas not occupied by the species, allowing estimates of likely changes in ranges of species over time[20–22].

A semi-endemic medicinal plant species of the genus *Nepeta* L. (*Nepeta glomerulosa* Boiss.) was selected for investigating effects of climate change in southwestern and central Asia based on ecological niche models (Fig. 1). *Nepeta* is a large genera, with about 300 species, belonging to Lamiaceae family[23]. It is found across Eurasia, with southwestern Asia and the western Himalayas serving as diversification hotspots[24,25]. *Nepeta* species are used for their antispasmodic, expectorant, diuretic, and antiseptic properties; therefore, they are widely used by pharmaceutics, and since the species is considered semi-endemic and has taxonomic problems at the subspecies level, it makes them important among taxonomists and ecologists as well[23–26].

Nepeta glomerulosa is a semi-endemic species traditionally used to treat pneumonia, itching, and various skin and gastrointestinal disorders[27,28]. It occurs at elevations of 1500–4000 m in Iran's Zagros, Alborz, and Khorassan–Kopet Dagh mountains, as well as mountains in Afghanistan[28] (Fig. 1). The species grows on gravelly and rocky slopes, along with communities of *Artemisia*, *Astragalus*, *Pistacia*, and *Amygdalus*[29] and also in dry springs and rivers in the Irano–Turanian region (Fig. 2). Previous studies of this species have focused on analysis of their essential oils [28,30–36] and hypnotic effects[33]; however, no information has been assembled about the species' geographic distribution or environmental dimensions that shape these distributions. Since *N. glomerulosa* is a semi-endemic medicinal species that is widely used[37,38], underlying likely the effects of climate change on its populations could be useful for conservation planning[9].

In this study, we studied likely climate change impacts on the distribution of *N. glomerulosa* in southwestern and central Asia under current and modeled future climatic conditions. The aim of this study was to determine key environmental factors limiting the distribution of the species. We used this information to estimate the likely change in the distribution of *N. glomerulosa* coming decades, and assessed how conservation efforts can shift in response.

Materials And Methods

Study area

The Irano-Turanian (IT) region is one of the most important phytogeographic zones, covering a large swath of southwest and central Asia. IT is divided into four sub-regions (IT1, IT2, IT3, and IT4) (Fig. 1), with IT2 serving as the main center of speciation and endemism, with low annual precipitation (low in winter and high in summer, in some areas), low winter temperatures, and a high continentality index[39,40]. *Nepeta glomerulosa*,as a species of the IT region, is distributed in the Zagros and Alborz Mountain ranges, Khorassan-Kopet Dagh Floristic Province in Iran and the Paropamisus Mountains in Afghanistan (IT2). This species has also been seen as transitional between two regions the IT and the Sahara–Sindian in the southern and southwestern parts of the country (Fig.1)[26].

Occurrence data

We obtained occurrence data from the following herbaria: FUMH, HUI, SFAHAN, HSHU, MIR, Natural Resources of Khuzestan, Animal & Natural Resources Research Center of Hormozgan, and Natural Resources of Kohgiluyeh and Boyer–Ahmad (Table S1). We also used Global Biodiversity Information Facility (GBIF; http://www.gbif.org/).

Occurrence data were reviewed and filtered in two steps. First, sites where the species was expected to be present were checked, and locations outside of the known range for the species were evaluated; we also removed records for which coordinates had high associated uncertainty[41]. Second, to reduce autocorrelation in the occurrence data, one pair of records less than ~1 km apart was removed using the spThin package[42] in R (version4.1.1).

Climate data

For current and potential future situations, a set of bioclimatic variables was established. The 19 bioclimatic variables for current conditions were acquired from WorldClim version 1.4 (http://www.worldclim.org), at a spatial resolution of 30" (~1 km). Four of the layers (bio 8, bio 9, bio 18, and bio 19) were removed because they include known spatial artifacts[12,43,44]. To select the most important environmental factors across the calibration area, we used Pearson correlation coefficients[45] in R; from each pair of variables with a correlation ≥0.8 we removed one.

Bioclimatic variables under future climate scenarios were downloaded from the CCAFS website (http://www.ccafs–climate.org)[46] at a spatial resolution of 30". Nine general circulation models (GCMs) were selected under two RCP 4.5 and RCP 8.5 scenarios, including (1) BCC-CSM-1, (2) CCCMA-CANESM2, (3) CSIRO-ACCESS1, (4) GISS-E2–R, (5) IPSL-CM5A-IR, (6) LASG-FGOALS-G2, (7) MIROC-MIROC5, (8) MOHC-HADGEM2-CC, and (9) NCC-NORESM1-M. This variety of GCMs was used to illuminate the uncertainty in predictions of the distribution potential of the species in the future[45]. Finally, for assessing the model's performance, records split ten times (cross-validation) for calibrating the model and estimating the precision of model predictive[47].

Ecological niche modeling

Model selection was performed using the ENMeval package[38,48] in R.A set of 22 regularization parameter values (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1; 1.25, 1.5, 1.75, 2; 3, 4, 5, 6, 7, 8, 9, and 10) and 32 combinations of model response types (linear, quadratic, product, threshold, and hinge responses) were explored. Out of the 704 candidate models, the best model was chosen based onthe lowest value of the Akaike information criterion (AICc) to identify the model of suitable area and conditions consistent with the data[48].

The final model was created using maximum entropy algorithm (Maxent) (version 3.3), with 10 cross-validation replicates among occurrence data; it was transferred across southwestern and central Asia under the current conditions. We also transferred the final model to future conditions allowing extrapolation and clamping. Median values across the replicate versions of the final model were used to estimate suitability across the region for current conditions. The median of all of the medians for the 9 GCMs was calculated to interpret the future potential geographic distribution of *N. glomerulosa* under different climate change scenarios (i.e., the two RCPs). Based on the range of values across the 10 cross-validation replicates, we estimated uncertainty for current and future conditions. Suitability scores were converted to binary using maxSSS (maximizing the sum of sensitivity and specificity), one of the best threshold selection methods for presence and absence data and also large samples[46].

Results

We obtained a total of 384 occurrence records for *N. glomerulosa*. Of these records 202 were eliminated as they were repetitive or lacked adequate precision. To reduce autocorrelation among records, 11 additional records were also removed under the 1 km distance criterion. In the end, the model was calibrated and evaluated based on 171 records, representing the whole set of data available on the species' occurrence.

Using correlations among environmental variables, the variables bio 1, bio 4, bio 5, bio 6, bio 10, bio 11, bio 13, bio 14, and bio 16 were omitted. Analyses were performed with seven variables: mean diurnal range (bio 2), isothermality (bio 3), temperature annual range (bio 7), mean temperature of warmest quarter (bio 10), annual precipitation (bio 12), precipitation seasonality (bio 15) and precipitation of driest quarter (bio 17). Two variables (bio 2 and bio 12) explain > 94% of overall variance, and bio 12 was the most important variable in our study.

In total, 704 models were evaluated in the process of model calibration. The best model included only linear, quadratic, and product features and a quite low regularization parameter of 0.1. The model had a high AUC value (0.94), suggesting that it has good power to estimate potential distributions of *N. glomerulosa* under present-day condition and different future scenarios.

Models indicated suitable conditions with high confidence for present-day conditions for *N. glomerulosa* throughout the montane regions of Iran, Afghanistan, and Pakistan. Highest suitability in Iran was in the Zagros Mountains, which extend from west to south, as well as in the Paropamisus Mountains in Afghanistan, and a small part of southern Pakistan (Fig. 3).

With the transfer of the model to future climate scenarios, an overall distributional pattern similar to current distributions was identified. The future potential distribution under RCP 4.5 was concentrated in the Zagros Mountains, Kerman Massif, montane parts of eastern Iran (southern Khorassan and Sistan); the Paropamisus Mountains in Afghanistan, and the Bruhui Range in Pakistan (Fig. 4, Fig. S1a). In contrast, model predictions under RCP 8.5 focused in the Zagros Mountains, Paropamisus Mountains in Afghanistan, and southern Pakistan as highly suitable areas (Fig. 5, Fig. S1b). High uncertainty was observed in western Iran and small parts of southern Afghanistan under present-day conditions (Fig. 3). The southern parts of the Kavir Plain and montane areas in the eastern and southern parts of the central plateau of Iran and a small area southern Pakistan showed high uncertainty under RCP 4.5 (Fig. 4). High uncertainty areas under RCP 8.5 matched those under present-day conditions (Fig. 5). From current conditions to RCP 4.5 and RCP 8.5 conditions, the potential distribution of *N. glomerulosa* dropped by 1.49% and 1.19% respectively.

Discussion

Ecological niche models are frequently used to describe potential distributions of endangered, endemic, and medicinal species[9,13,37,49]. Here the potential distribution of *N. glomerulosa*, a semi-endemic medicinal plant species, was estimated across southwestern and central Asia under current and future climate conditions. Mean diurnal range, iso-thermality, temperature annual range, mean temperature of warmest quarter, annual precipitation, precipitation seasonality, and precipitation of driest quarter were the most important explanatory environmental variables in the models. The importance of environmental dimensions have been confirmed in previous studies in the IT phytogeographical region[9].

A deep link exists between plant distributions and climatic factors. The Mediterranean macrobioclimate is dominant in the IT biogeographic region[39,50]. Three Mediterranean bioclimatic classifications occur in areas where *N. glomerulosa* occurs: (1) Mediterranean pluviseasonal-continental (Mpc) with much annual precipitation during winter months in the Zagros mountains and parts of the Alborz, Kopet-Dagh and Allah Dagh-Binalud mountains[39,51]; (2) Mediterranean xeric-continental (Mxc) with summer drought and low total annual precipitation in western and southwestern Iran, most of the Kopet-Dagh Mountains, and parts of the Kerman Massif; and (3) Mediterranean xeric-oceanic (Mxo), with relatively long summer droughts, low annual precipitation, but relatively elevated average winter temperature minima on the southern flanks of the Kerman Massif in southeastern Iran[39] (Fig. 1). According to a recent study[9], the highlands of Afghanistan have low annual temperature ranges: the maximum average summer temperature does not exceed 15°C, and average winter minimum temperatures are below zero. In Afghanistan, rainfall is rare, with maximum amounts falling in the northern highlands in March and April[52]. Given the relative lack of accurate information on climatic conditions Afghanistan, we focus on bioclimatic regions manifested in IT2 in Iran.

Given the distribution and presence of the species in the elevational range of 1500–4000 m, both the effect of precipitation at low elevations and the effect of temperature at high elevations[53–55] are considered important factors in montane areas. Climate parameters, particularly temperature, were recently identified as crucial in limiting plant dispersal on local-to-regional scales in montane ecosystems[9]. One factor that can have a significant impact on distributions of species is dispersal[56]. Although no information is available on how seeds are dispersed in *N. glomerulosa*. However, based on our field observations, *N. glomerulosa* has a small population size because individuals are clumped and are well-separated from other populations. Based on previous studies, dispersal at limited distances (atelechory) may play an important role in Nepetoideae (Lamiaceae)[57]. Since the fruits are enclosed calyces in Lamiaceae, they can be dispersed by animals; anemochory (dispersal by wind) is also particularly common in Labiates in arid regions[57]. Therefore, dispersal by animals and wind may affect this species' distribution across landscapes, but information is scanty.

Responses of plants to biotic and abiotic factors are important in determining species' distributional potential. In term of species composition, distributional limits at warmer sites are more likely to be explained by biotic variables than at colder sites, and abiotic variables are more likely to be important at colder sites[58]. Since *N. glomerulosa* can occupy a wide range of elevations, (Fig. 1), it may be more affected by abiotic variables at higher elevations where it is colder, and biotic variables at lower elevations, although our models do not inform about these differences.

Climate change ranks among the most powerful elements influencing future distributions of suitable areas for species. Human activities also have significant impacts on distributions of plants[59]. Since *N. glomerulosa* considered as a medicinal species and has small population sizes, human activities (e.g., irregular harvesting, heavy grazing, urbanization and suburbanization) can reduce its distribution in the future. These factors, their interactions and other potential influences (e.g., invasive species) may affect the distribution of *N. glomerulosa* into the future.

Conclusions

We investigated the potential geographic distribution of *N. glomerulosa* under current and future climate conditions using ecological niche modeling methods. Regions with high suitability were concentrated in montane areas, and climate change may decrease the species' potential distributional area on regional scales. Since the species can occupy a wide range of elevations, with climate change, it may be able to occupy montane habitats at different elevations and also shift to higher elevations. However, factors such as excessive harvesting by humans, development, and overgrazing may reduce the habitable geographic areas of the species because it has small, isolated populations. We therefore suggest that conservation and management actions be taken for this species and other endemic medicinal plants in southwestern and central Asia. Future studies should assure detailed sampling of different populations under diverse conditions, assessment of the species, interactions with other plants, study of effects of ecological and edaphic factors on different populations in different areas, assessment of mechanisms of seed dispersal and evaluation of possible barriers that may cause genetic and geographic isolation of populations.

Declarations

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Authors' contributions

S.K, H.E, H.M, J.V designed the study. S.K collected the data, performed the analysis, and wrote the first version of draft. M.B contributed to performing the analysis. H.E, H.M, J.V, M.B and S.K helped to revise and edited the draft. All authors read and approved the final draft.

Conflict of interest

The authors declare that they have no conflict of interest.

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Data accessibility

The datasets used during the current study available from the corresponding author on reasonable request.

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Figures

Figure 1

The study area and distribution of *Nepeta glomerulosa* in southwestern and central Asia: (a) Topographic map of mountain areas across southwestern and central Asia, (b) Irano–Turanian region (from Behroozian *et al*. 2020).

Figure 2

Nepeta glomerulosa: (a–d) Habitats. (e–f) life form and morphology of flower specifically, photos show (a) dry river bed, (b) gravelly slopes, (c) *Amygdalus* community, (d) dry rocky slopes, (e) life form, and (f) morphology of flower.

Figure 3

Predicted currently suitable regions for *Nepeta glomerulosa* across the southwestern and central Asia: (a) median prediction (based on median values in the replicates of the final model for current conditions), (b) uncertainty map (range through 10 cross–validation replicates), and (c) binary map (based on suitability scores and maxSSS threshold).

Figure 4

Potential future distribution of *Nepeta glomerulosa* under Representative Concentration Pathway (RCP) 4.5 across the southwestern and central Asia: (a) median prediction, (b) uncertainty map

Figure 5

Potential future distribution of *Nepeta glomerulosa* under Representative Concentration Pathway (RCP) 8.5 across the southwestern and central Asia: (a) median prediction, (b) uncertainty map

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementaryinformation.docx