



RESEARCH ARTICLE

Diversity and ecological differentiation between endemic species of the order *Salvia*

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Abstract

This study assesses the ecological differentiation, potential distribution and conservation significance of two Central Asian endemic species, *Salvia submutica* Botsch. & Vved. and *Salvia tianschanica* Makhm. A total of more than 50 georeferenced occurrence records were compiled from field surveys, herbarium collections and online databases, including the global biodiversity information facility (GBIF) and Plantarium. Ecological niche modelling (ENM) was performed using the MaxEnt algorithm based on selected bioclimatic variables and elevation data. The results revealed clear ecological differences between the two species. *Salvia submutica* is characterised by a narrow ecological niche, with suitable habitats mainly restricted to semi-arid rocky foothills of the Nuratau range, indicating a high degree of habitat specialisation. In contrast, *S. tianschanica* exhibited broader climatic tolerance and a wider potential distribution across the western Tien Shan, reflecting higher ecological plasticity. Model performance was high for both species, with area under the receiver operating characteristic curve (AUC) values indicating strong predictive accuracy. Precipitation-related variables were identified as the main factors influencing species distribution, particularly for *S. tianschanica* which is associated with more humid and climatically stable environments. These results suggest distinct ecological strategies and adaptive responses to environmental gradients. These findings highlight the contrasting ecological strategies of the two taxa and emphasise the importance of ENM in understanding species distribution patterns and informing conservation priorities in Central Asia.

Keywords: eco modelling; maps; Maxent; Nuratau; phytogeography; *Salvia submutica*; *Salvia tianschanica*; Tien Shan

Introduction

The genus *Salvia* is one of the most species-rich and morphologically diverse groups of angiosperms, comprising more than 1000 species distributed across the Mediterranean, Central and East Asia and the Americas (1–3). As a major component of the tribe Mentheae, *Salvia* exhibits remarkable diversity in floral morphology and ecological adaptation and is widely recognised for its ethnobotanical importance as a medicinal, aromatic and ornamental plant (4, 5). Owing to these characteristics, the genus has become an important model for studies of evolutionary diversification, biogeography and systematics.

Central Asia represents a key part of the Irano–Turanian floristic region, which is considered one of the global centers of plant biodiversity and endemism (6, 7). The region is characterised by complex orographic structures and diverse climatic conditions that have contributed to the persistence of ancient lineages and the formation of narrow-range endemic species. Recent integrative studies have demonstrated that geographic isolation and environmental heterogeneity in mountain systems play a crucial role

in shaping species diversification and endemism patterns in this region (8).

In Uzbekistan, several narrowly distributed *Salvia* species occur in mountainous systems such as the Nuratau Range, western Hissar and western Tien Shan. These areas are characterised by pronounced climatic gradients and historical environmental fluctuations, which have promoted localised ecological specialisation (9, 10). Among these species, *Salvia submutica* Botsch. & Vved. is a rare endemic restricted to the semi-arid rocky foothills of the Nuratau range (11, 12), whereas *Salvia tianschanica* Makhm. is distributed more widely across the relatively humid foothill and montane regions of the western Tien Shan, extending into southern Kazakhstan and northern Tajikistan (13). These contrasting distribution patterns suggest that topographic barriers and climatic gradients are key drivers of ecological differentiation between the two species.

Despite their ecological and conservation importance, the patterns of ecological differentiation, habitat preferences and potential distribution of *S. submutica* and *S. tianschanica* remain

insufficiently studied. In particular, the lack of integrative analyses combining field data, herbarium records and spatial modelling limits the understanding of the processes underlying endemism and complicates conservation planning under increasing anthropogenic and climate pressures (14). Ecological niche modelling (ENM) has been widely applied as an effective tool for identifying distribution constraints, quantifying niche differentiation and assessing the influence of climatic variables on species distributions (15, 16).

In this context, the present study aims to assess the ecological differentiation and potential distribution patterns of *S. submutica* and *S. tianschanica* using an ENM approach. By integrating field observations, herbarium data (Herbarium of the Komarov Botanical Institute of the Russian Academy of Sciences (LE), Tashkent Herbarium (TASH) and Herbarium of Moscow State University (MW)) and georeferenced occurrence records from online databases such as global biodiversity information facility (GBIF) and Plantarium, this study provides new insights into the ecological mechanisms driving endemism and spatial differentiation in the mountain systems of Central Asia.

Materials and Methods

Study area

Field investigations were conducted between 2021 and 2023 across major mountain systems of Central Asia, including the Western Tien Shan, the Nuratau range and adjacent regions of Uzbekistan and Tajikistan (Fig. 1). In total, 23 populations of two endemic species (Table 1), *S. submutica* and *S. tianschanica*, were surveyed based on their known distribution ranges derived from

field observations and herbarium records (3, 10, 11). Populations of *S. submutica* were restricted to the Nuratau botanical-geographical district, encompassing Jizzakh, Navoiy and Samarkand regions of Uzbekistan. In contrast, *S. tianschanica* populations were recorded from the Chatkal, Ugom and Pskem ranges of the Western Tien Shan in the Tashkent region, as well as from southern Kazakhstan (Fig. 2). The selection of sampling sites was based on accessibility, representativeness of habitat conditions and confirmed occurrence records.

Approximately 100 specimens were examined, with two to eight individuals sampled per population. For each occurrence, geographic coordinates (latitude and longitude) and elevation (850–1550 m above mean sea level) were recorded using a Garmin GPSMAP 64s handheld global positioning system (GPS) device. Additional environmental variables, including slope aspect, substrate type, vegetation cover and degree of anthropogenic disturbance, were documented following standard floristic survey protocols (4, 5). Voucher specimens were deposited in the TASH.

Ecological niche modelling

Ecological niche modelling was performed to assess the potential distribution and ecological differentiation of *S. submutica* and *S. tianschanica* using the MaxEnt algorithm implemented in MaxEnt version 3.4.4 (6).

Species occurrence data were compiled from field-collected GPS records and supplemented with verified herbarium specimens from TASH, LE, MW, Herbarium of the Institute of Biology of the National Academy of Sciences of the Kyrgyz Republic (FRU) and Karachi University Herbarium (KUN). Duplicate and spatially autocorrelated records were removed to reduce sampling bias.

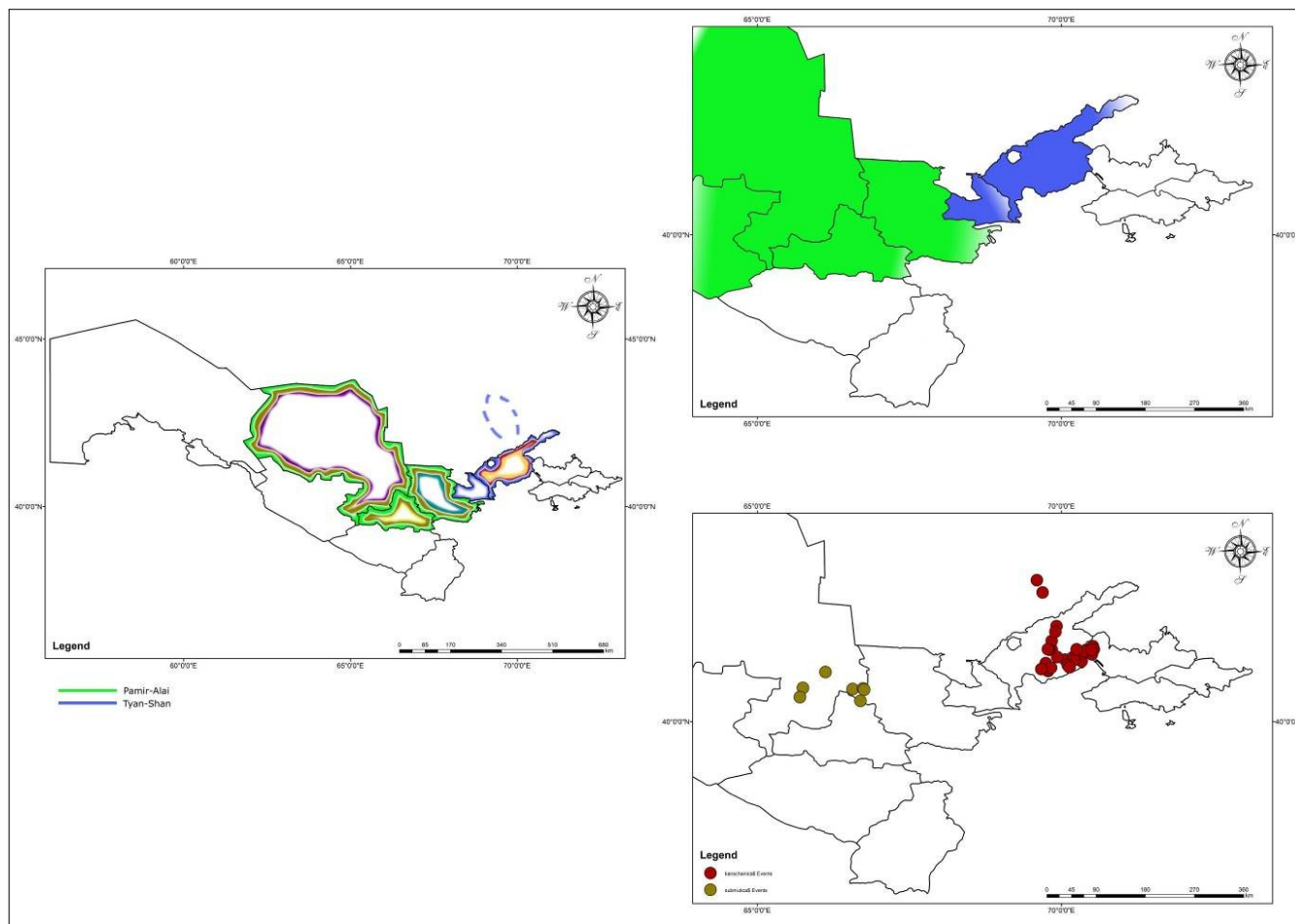


Fig. 1. Spatial distribution and diversity of endemic and related *Salvia* species in Uzbekistan.

Table 1. Details of sampling locations, number of individuals, geographic coordinates, elevation and population codes of *Salvia submutica* and *Salvia tianschanica*

Population code	Location	Species	Longitude	Latitude	Elevation (m)	Number of individuals
P1	Jizzakh region	<i>S. submutica</i>	65.7000	40.4000	1100	1
P2	Jizzakh region	<i>S. submutica</i>	65.7500	40.5500	1200	1
P3	Jizzakh region	<i>S. submutica</i>	66.1200	40.8100	1550	1
P4	Jizzakh region	<i>S. submutica</i>	66.566841	40.532674	850	1
P5	Jizzakh region	<i>S. submutica</i>	66.695416	40.338550	950	1
P6	Jizzakh region	<i>S. submutica</i>	66.737793	40.542213	920	2
P7	Jizzakh region	<i>S. submutica</i>	66.756591	40.521750	900	2
P9	Shymkent city	<i>S. tianschanica</i>	69.5958	42.3142	510	1
P10	Tashkent region	<i>S. tianschanica</i>	69.668543	40.858219	1100	1
P11	Turkistan region	<i>S. tianschanica</i>	69.6900	42.1133	1200	1
P12	Tashkent region	<i>S. tianschanica</i>	69.742439	40.956370	1250	4
P13	Tashkent region	<i>S. tianschanica</i>	69.773930	40.838587	803	1
P14	Tashkent region	<i>S. tianschanica</i>	69.776950	41.184870	1350	2
P15	Tashkent region	<i>S. tianschanica</i>	69.780302	40.828191	1100	1
P16	Tashkent region	<i>S. tianschanica</i>	69.798967	41.176646	1350	2
P17	Tashkent region	<i>S. tianschanica</i>	69.829662	40.881926	1150	2
P18	Tashkent region	<i>S. tianschanica</i>	69.8400	41.3200	1860	1
P19	Tashkent region	<i>S. tianschanica</i>	69.84028	41.17716	1200	2
P21	Tashkent region	<i>S. tianschanica</i>	69.9180	41.5610	1800	1
P22	Tashkent region	<i>S. tianschanica</i>	69.930383	41.055230	1400	1
P23	Tashkent region	<i>S. tianschanica</i>	70.05783	41.013684	1150	3
P24	Tashkent region	<i>S. tianschanica</i>	70.102535	40.923696	1300	3
P25	Tashkent region	<i>S. tianschanica</i>	70.132612	40.888480	1300	3
P26	Tashkent region	<i>S. tianschanica</i>	70.1833	41.0500	950	1
P27	Tashkent region	<i>S. tianschanica</i>	70.2067	41.0083	1120	1
P28	Tashkent region	<i>S. tianschanica</i>	70.2500	41.1833	1580	1
P29	Tashkent region	<i>S. tianschanica</i>	70.3000	41.0833	1750	1
P30	Tashkent region	<i>S. tianschanica</i>	70.3328	40.9883	1275	1
P31	Tashkent region	<i>S. tianschanica</i>	70.3417	41.1167	1620	1
P32	Tashkent region	<i>S. tianschanica</i>	70.3683	41.1480	1720	1
P33	Tashkent region	<i>S. tianschanica</i>	70.4083	41.1725	1900	1
P34	Tashkent region	<i>S. tianschanica</i>	70.4900	41.1700	1550	1
P35	Tashkent region	<i>S. tianschanica</i>	70.5000	41.1000	1650	1
P36	Tashkent region	<i>S. tianschanica</i>	70.5169	41.2336	2150	1
P37	Tashkent region	<i>S. tianschanica</i>	70.5333	41.1833	1750	1
P38	Andijan region	<i>S. tianschanica</i>	72.3667	41.0333	1100	1

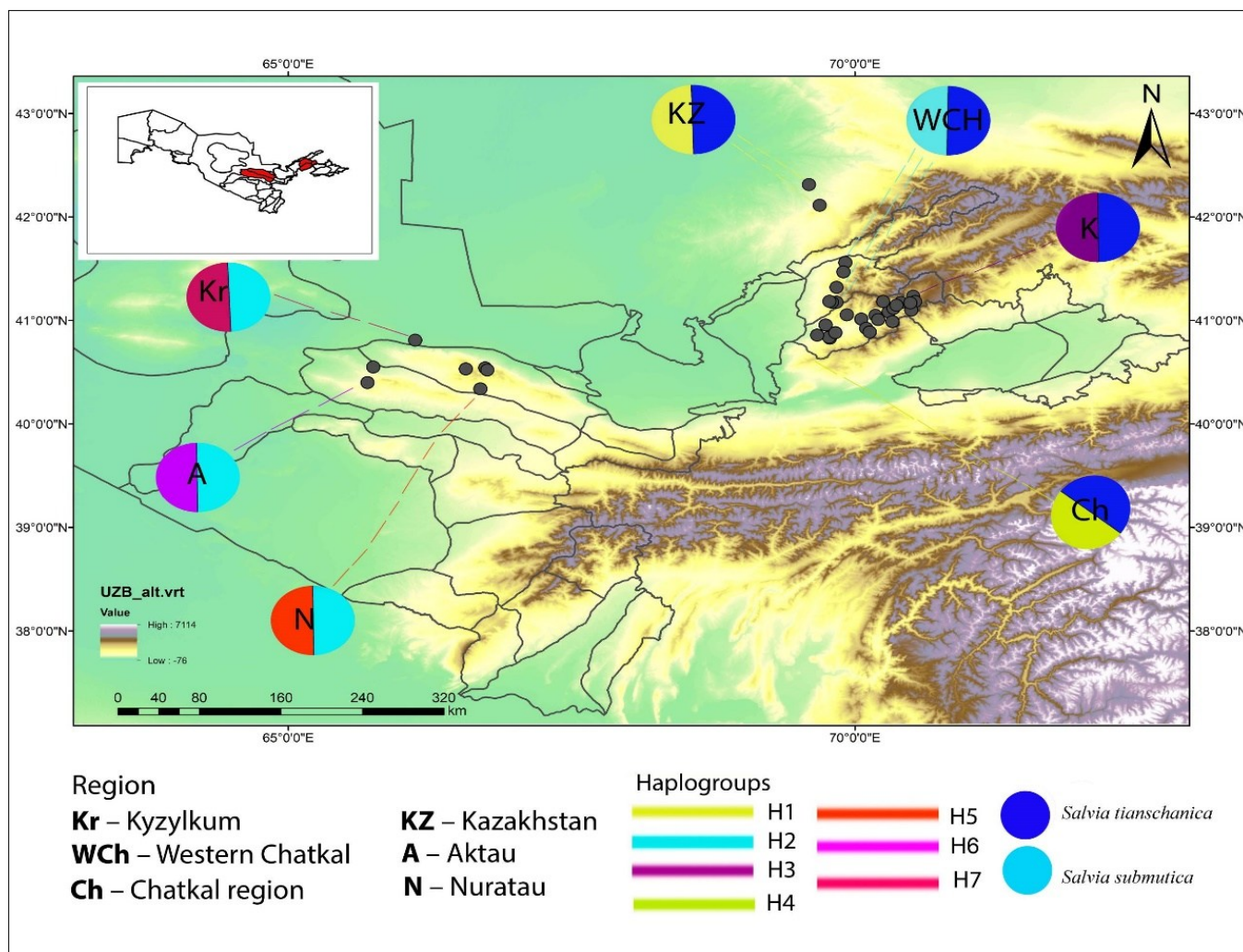


Fig. 2. Geographical distribution and haplogroup composition of *Salvia submutica* and *Salvia tianschanica* populations in Uzbekistan and neighbouring regions.

A set of 19 bioclimatic variables and elevation data were obtained from the WorldClim v2.1 database (7) at a spatial resolution of 2.5 arc-min. To minimise multicollinearity among predictor variables, Pearson correlation analysis ($r < 0.8$) was applied and only ecologically relevant and weakly correlated variables were retained. The final model included temperature seasonality (bio4), minimum temperature of the coldest month (bio6), precipitation seasonality (bio15) and precipitation of the coldest quarter (bio19).

MaxEnt models were run using default feature classes (linear, quadratic, hinge) and a regularisation multiplier of 1. Background points (10000 random points) were generated across the study region to characterise environmental conditions. For each species, 75 % of occurrence records were used for training and 25 % for testing. Models were replicated ten times using a subsampling approach and mean outputs were used for further analysis.

Model performance was evaluated using the area under the receiver operating characteristic curve (AUC). Variable importance was assessed using the jackknife test (6). Although AUC values were high, potential model overfitting was considered in the interpretation of results.

Habitat suitability maps were generated using logistic output and visualised in ArcGIS Pro 3.2. Suitability values were classified into four categories: low (< 0.3), moderate ($0.3-0.6$), high ($0.6-0.8$) and very high (> 0.8), following standard ENM classification approaches.

Results and Discussion

Phylogeographic patterns and ecological differentiation

Ecological niche modelling revealed pronounced differences between *S. submutica* and *S. tianschanica* in terms of habitat suitability, ecological amplitude and spatial distribution. The predicted distribution of *S. submutica* is highly restricted, being largely confined to rocky, semi-arid foothill environments of the Nuratau range. This pattern reflects a high degree of ecological specialisation and narrow climatic tolerance (1, 2). Areas of high habitat suitability are spatially limited and fragmented, indicating the strong influence of topographic isolation and localised environmental conditions on the distribution of this species.

In contrast, *S. tianschanica* exhibited a substantially broader potential distribution across the Western Tien Shan (3, 4). Suitable habitats extend across multiple mountain systems characterised by more mesic conditions, suggesting greater ecological flexibility. This broader ecological amplitude indicates a higher capacity to tolerate environmental variability and to occupy heterogeneous landscapes.

For both species, model performance was high, with AUC values exceeding 0.97, indicating strong predictive reliability (Fig. 3). However, such high values may also reflect potential model overfitting, particularly given the relatively limited number of occurrence records. Therefore, model outputs were interpreted cautiously, with emphasis on ecological plausibility rather than solely on statistical metrics.

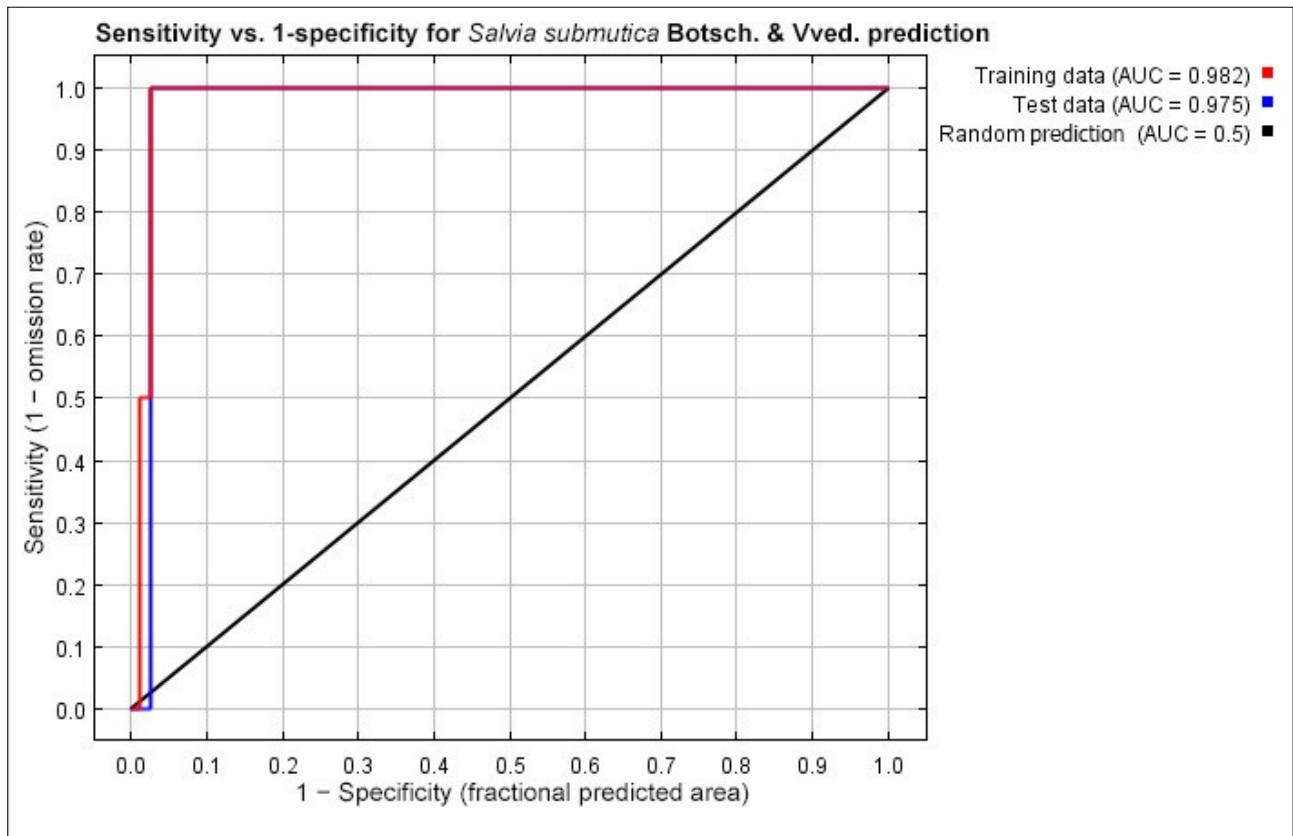


Fig. 3. A potential habitat suitability map of *Salvia submutica* was generated using the MaxEnt model under the current (1970–2000) climatic scenario. Dark red to green indicate high and low habitat suitability values respectively. Area under the receiver operating characteristic curve (AUC) = 0.975 for test data; most influential variables: bio4, bio19, bio6 and bio15.

Analysis of variable contributions demonstrated that temperature seasonality (bio4) and precipitation-related variables (bio15 and bio19) are the primary determinants of habitat suitability

(Fig. 4). These results highlight the key role of climatic gradients in structuring plant distributions in mountainous regions of Central Asia (5, 6).

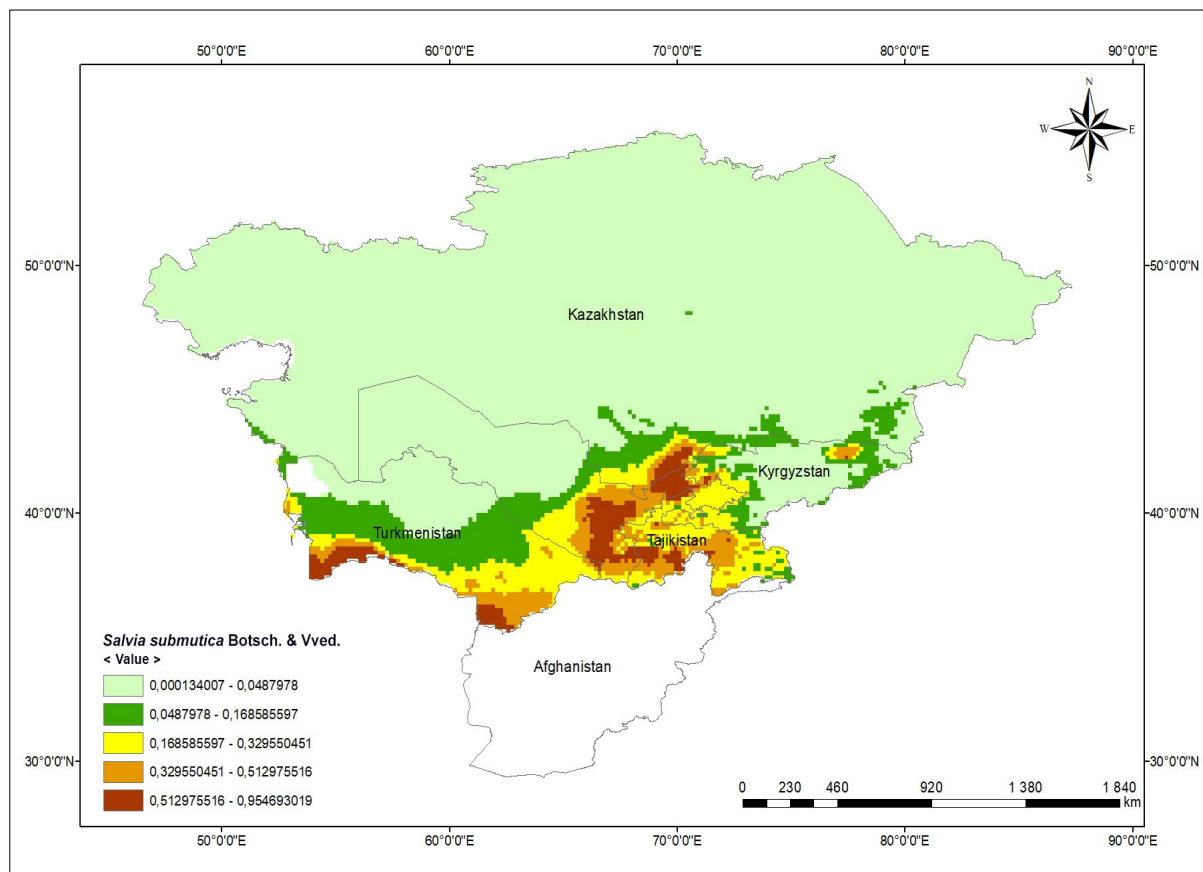


Fig. 4. MaxEnt-based habitat suitability map of *Salvia submutica* under present climatic conditions (1970–2000). High suitability values (red–orange) correspond to the southern slopes of the Nuratau ridge and adjacent mountain foothills in Uzbekistan.

The observed ecological divergence between the two species supports a scenario of niche differentiation driven by topographic complexity and climatic heterogeneity. The Nuratau range appears to function as a refugial system promoting narrow endemism, whereas the more extensive and interconnected mountain systems of the Western Tien Shan facilitate wider ecological tolerance and range expansion (1–7). Similar patterns have been reported for other endemic plant taxa in Central Asia (2–8), where isolated mountain systems harbour narrowly distributed species, while larger orogenic systems support broader distributions.

From a conservation perspective, the restricted distribution and narrow ecological niche of *S. submutica* suggest a high sensitivity to environmental changes, including climate change and anthropogenic disturbance. In contrast, the broader ecological amplitude of *S. tianschanica* may confer greater resilience under changing environmental conditions.

Ecological niche modelling and climatic suitability

The MaxEnt models provided detailed insights into the climatic constraints shaping species distributions. For *S. submutica*, the model demonstrated high predictive accuracy, with AUC values of 0.982 (training) and 0.975 (test). The most influential predictors were temperature seasonality (bio4) and precipitation of the coldest quarter (bio19), followed by precipitation seasonality (bio15) and minimum temperature of the coldest month (bio6) (Fig. 5).

Suitability maps indicated that highly suitable habitats are concentrated in the southern slopes of the Nuratau range and adjacent foothill areas, whereas arid lowlands and high-elevation zones were predicted as unsuitable. Response curves further indicated that *S. submutica* is associated with moderate temperature variability, relatively mild winter conditions and intermediate winter precipitation, confirming its narrow climatic niche.

For *S. tianschanica*, the model exhibited even higher predictive performance, with average AUC values of 0.996 (training) and 0.994 (test). Precipitation-related variables, particularly precipitation of the coldest quarter, were identified as dominant predictors. This reflects the species' adaptation to more humid and climatically stable foothill and montane environments.

Highly suitable areas for *S. tianschanica* were identified in the Chatkal, Ugom and Pskem ranges, with additional suitable zones extending into adjacent regions of the Western Tien Shan. This spatial pattern corresponds well with known distribution data and supports the ecological interpretation of broader niche tolerance (5, 6).

Ecological niche modelling for *Salvia tianschanica*

Ecological niche modelling results for *S. tianschanica* (Fig. 6–8) demonstrated very high predictive performance, with average training and test AUC values of 0.996 and 0.994 respectively (Fig. 6). While these high values indicate strong model accuracy, they may also reflect potential overfitting due to the relatively limited number of occurrence records.

Among the environmental predictors, precipitation-related variables, particularly precipitation of the coldest quarter (bio19), showed the highest contribution, indicating that *S. tianschanica* is strongly associated with more humid winter conditions. Response curves further revealed that the species reaches optimal suitability at moderate to high precipitation levels during the coldest quarter, suggesting adaptation to relatively stable and mesic climatic regimes.

Temperature-related variables, especially the minimum temperature of the coldest month (bio6), also influenced species distribution, indicating tolerance to moderate winter temperatures rather than extreme cold conditions. In contrast, high temperature seasonality (bio4) was associated with a decline in suitability, reflecting the species' preference for more climatically stable environments (Fig. 7, 8).

Spatial projections identified core areas of high habitat suitability within the Chatkal, Ugam and Pskem mountain ranges, corresponding to well-developed montane ecosystems. Secondary suitable areas extend into adjacent regions of the Western Tien Shan, indicating a broader ecological amplitude compared to *S. submutica*.

Overall, the ecological niche of *S. tianschanica* can be characterised as relatively wide (euryecious), with a strong dependence on precipitation stability and moderate thermal conditions, supporting its wider geographic distribution across mountain systems of Central Asia.

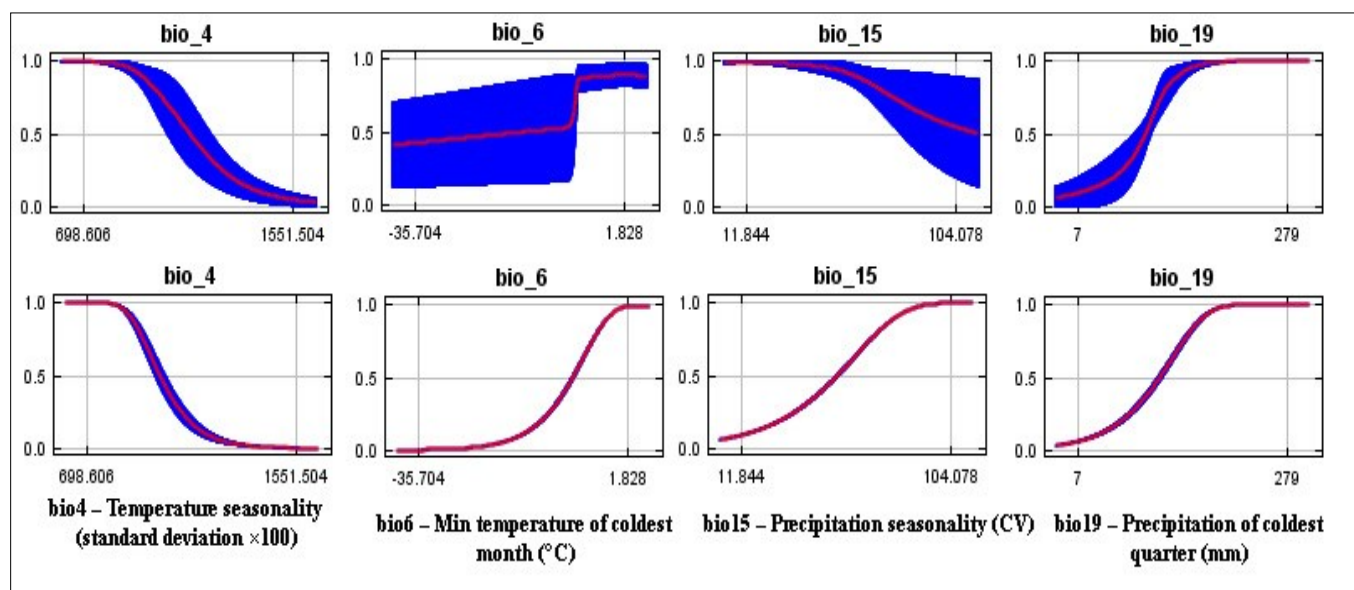


Fig. 5. Response curves showing the influence of the main bioclimatic variables (bio4, bio6, bio15 and bio19) on the predicted probability of *Salvia submutica* occurrence.

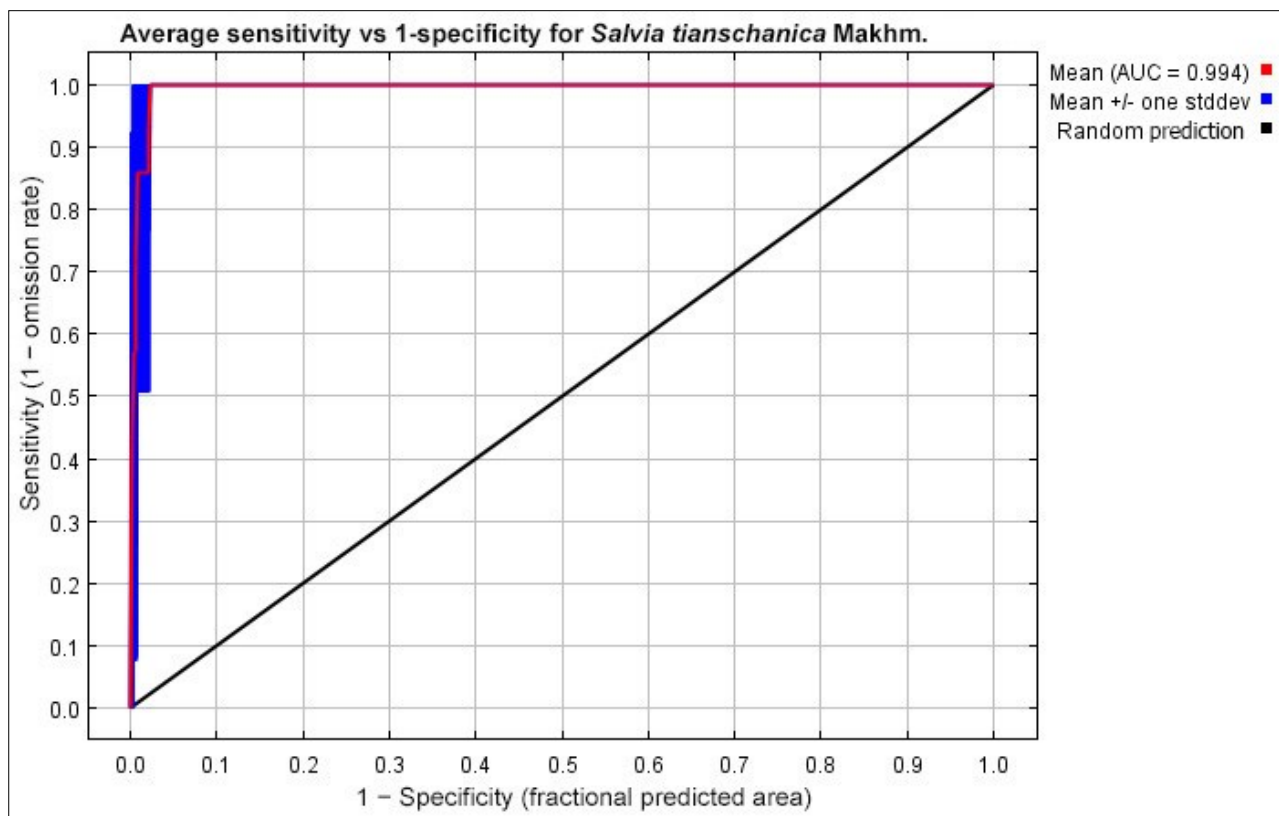


Fig. 6. A potential habitat suitability map of *Salvia tianschanica* was generated using the MaxEnt model under the current (1970–2000) climatic scenario. Dark red to green indicate high and low habitat suitability values respectively. Area under the receiver operating characteristic curve (AUC) = 0.994 for test data; most influential variables: bio4, bio19, bio6 and bio15.

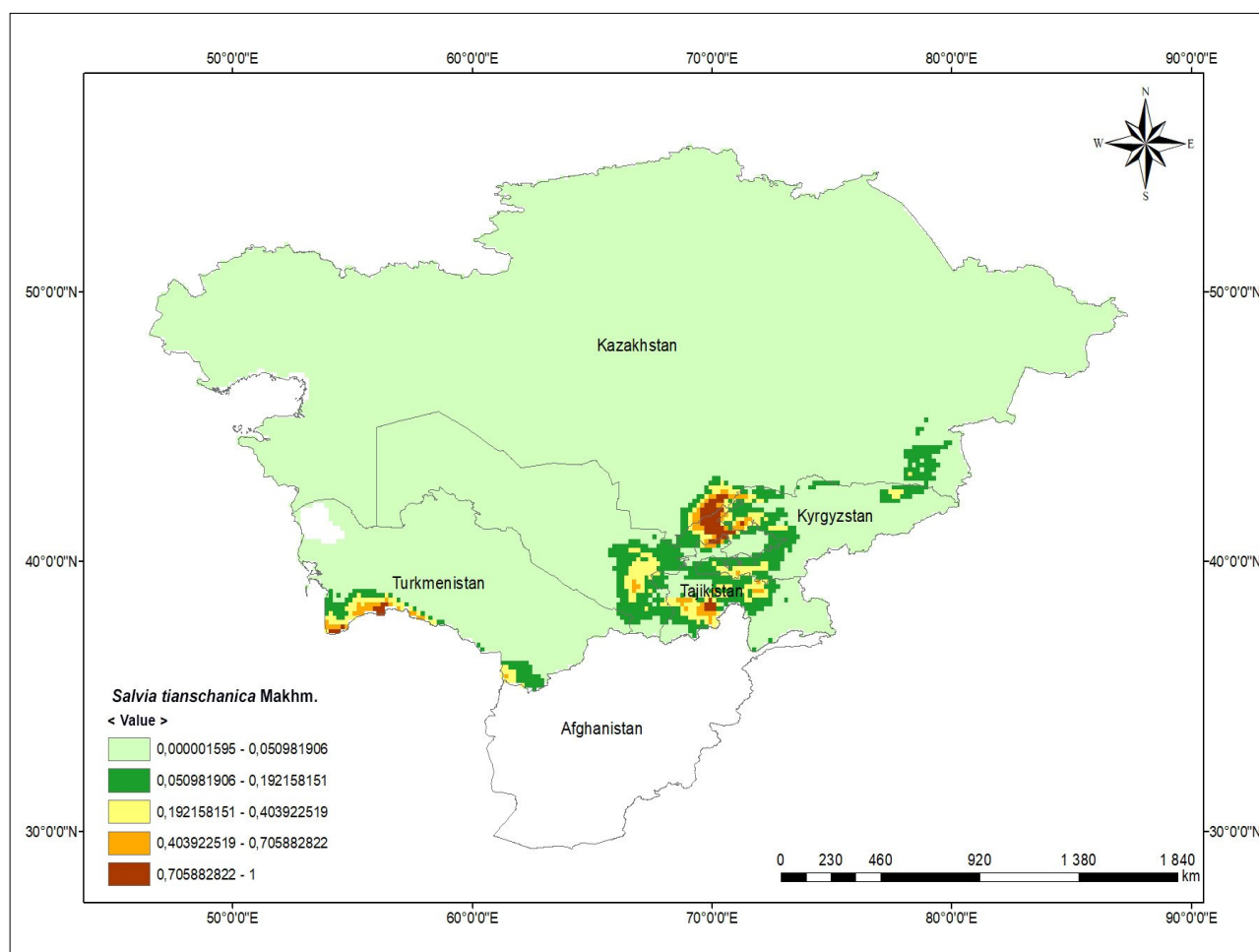


Fig. 7. MaxEnt-based habitat suitability map of *Salvia tianschanica* Makhm. Current climatic conditions: 1970–2000. Highly suitable areas (red-orange) are concentrated in the western Tien Shan foothills of Uzbekistan, Kazakhstan and Kyrgyzstan area under the receiver operating characteristic curve (AUC = 0.994).

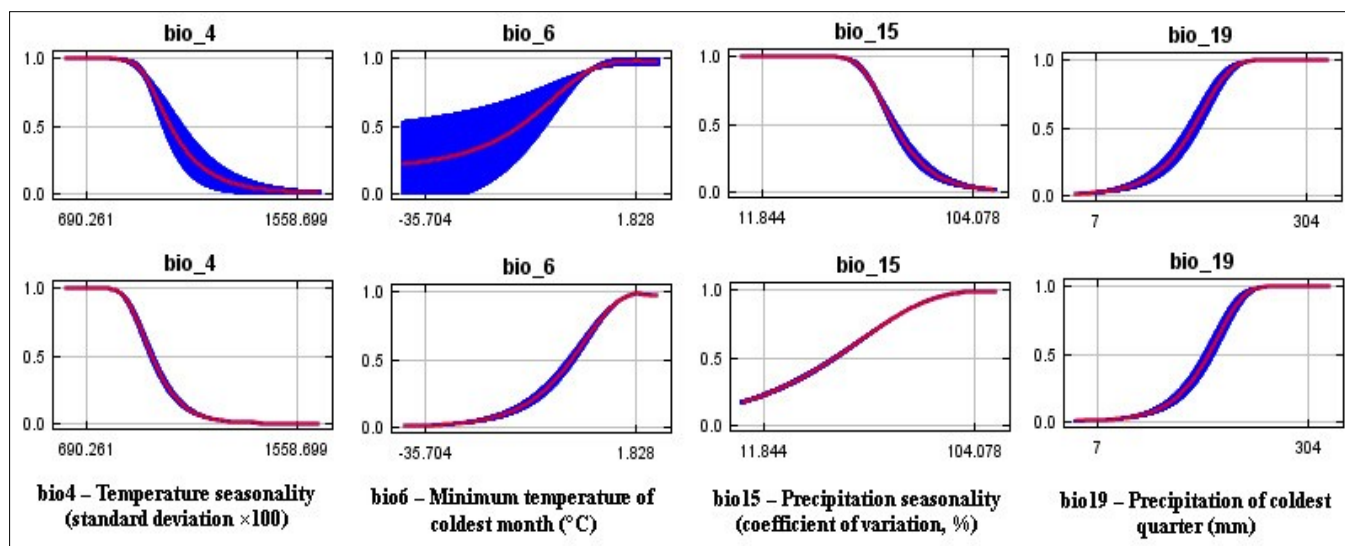


Fig. 8. Response curves showing the influence of the main bioclimatic variables (bio4, bio6, bio15 and bio19) on the predicted probability of *Salvia tianschanica* occurrence.

Comparative analysis and conservation significance

Comparative analysis revealed clear differences in ecological strategies between the two species. *Salvia submutica* exhibits a stenoecic (narrow ecological) niche, confined to semi-arid and topographically isolated habitats, whereas *S. tianschanica* displays a euryoecic (broad ecological) strategy, occupying a wider range of climatic and environmental conditions across multiple mountain systems.

These contrasting niche characteristics underscore the importance of topographic complexity and climatic heterogeneity in driving ecological differentiation and endemism in Central Asian mountain floras (1, 7, 8). The Nuratau range represents a key center of narrow endemism, supporting species with restricted distributions and high conservation value.

The limited ecological tolerance and fragmented distribution of *S. submutica* highlight the need for targeted conservation measures, particularly under increasing anthropogenic pressure and climate change. In contrast, the broader ecological amplitude of *S. tianschanica* suggests greater potential for persistence under environmental fluctuations.

Overall, this study demonstrates that ENM is an effective tool for identifying distribution constraints, understanding niche differentiation and assessing extinction risk in endemic plant species. Such integrative approaches are essential for biodiversity conservation in regions characterised by complex terrain and strong environmental gradients, such as Central Asia.

Conclusion

This study provides an integrative assessment of ecological niche differentiation and distribution patterns in two Central Asian endemic species, *Salvia submutica* and *Salvia tianschanica*. The results demonstrate clear differences in habitat suitability, climatic tolerance and potential distribution, reflecting contrasting ecological strategies shaped by geographic isolation and environmental heterogeneity. *Salvia submutica* is characterised by a restricted distribution and a narrow ecological niche, largely confined to semi-arid rocky foothills of the Nuratau range. Its high degree of habitat specialisation and limited climatic tolerance indicate long-term persistence in isolated mountain systems but also suggest increased vulnerability to climate change and anthropogenic disturbance. These findings emphasise

the importance of targeted *in situ* conservation measures for narrowly distributed endemic species. In contrast, *S. tianschanica* exhibits a broader ecological amplitude and wider potential distribution across the Western Tien Shan and adjacent regions. Its ability to occupy more mesic foothill and montane environments reflects higher ecological plasticity and greater resilience to environmental variability. Overall, the contrasting ecological profiles of these species highlight the dual role of Central Asian mountain systems as both centers of narrow endemism and zones of ecological diversification. The study confirms that ecological niche modelling (ENM) is a powerful tool for identifying environmental constraints, evaluating extinction risk and informing conservation priorities in biodiversity-rich regions such as the Irano-Turanian floristic region. These findings provide a valuable framework for future taxonomic, biogeographic and conservation-oriented studies within the genus *Salvia*.

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Authors' contributions

GTK conceived and designed the study, conducted field sampling, performed ecological niche modelling, analysed the data and wrote the first draft of the manuscript. DNJ contributed to fieldwork and data collection. OAT assisted in data interpretation and contributed to manuscript revision. NAR participated in ecological analysis and visualisation of results. RAU contributed to data processing and figure preparation. RXE contributed to data collection, data interpretation and revision of the manuscript. ZOY provided critical revision of the manuscript and scientific guidance. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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