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RESEARCH ARTICLE

Bioclimatic modeling of *Tulipa fosteriana* and *Tulipa ingens*: Predicting the effects of climate change on the distribution of endangered wild tulips

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Abstract

Bioclimatic modeling is an essential tool for predicting species distributions under changing environmental conditions. *T. fosteriana* and *T. ingens*, rare and endemic tulip species in Uzbekistan, are currently facing increasing threats from habitat loss and climate change. Understanding their potential range under current and future climate scenarios is crucial for conservation planning. The present study employed Maximum Entropy (MaxEnt) modeling to assess the habitat suitability of *T. fosteriana* and *T. ingens* using occurrence data from field surveys, herbarium records and biodiversity databases. Environmental predictors included climatic, soil and topographical variables. Model accuracy was evaluated using the Area Under the Curve (AUC) and future habitat projections were generated under Ssp126 (moderate emissions) and Ssp585 (high emissions) scenarios for 2041-2060. The results suggest that *T. fosteriana* may expand its range, particularly in the Hissar and Bobotog mountain ranges, while *T. ingens* is projected to suffer severe habitat reduction, losing over 90 % of its suitable areas under the high-emission scenario. The most influential environmental variables were precipitation in the coldest quarter and depth to bedrock, highlighting the role of moisture availability and soil structure in habitat suitability. High AUC values (above 0.98) confirm model robustness. These findings emphasize the contrasting responses of the two species to climate change. While *T. fosteriana* may benefit from rising temperatures, *T. ingens* is at high risk of habitat loss, requiring urgent conservation efforts. This study provides valuable insights for biodiversity management in Central Asia, highlighting the need for protected areas, *in-situ* conservation and potential *ex-situ* preservation strategies.

Keywords: climate change; conservation; ecological niche modelling; habitat suitability; MaxEnt; species distribution modelling

Introduction

Bioclimatic modeling has emerged as a fundamental tool for understanding species distributions in response to environmental variables and climate change. It is also known as habitat suitability or Species Distribution Models (SDMs), these approaches have been widely applied in ecological and conservation studies to predict potential habitats, assess risks to biodiversity and guide conservation strategies (1). With global climate change altering temperature and precipitation patterns, species with narrow ecological requirements, particularly endemic and rare plants, are increasingly vulnerable. Predicting their potential range shifts under future climatic scenarios is essential for effective conservation planning (2).

Tulips (*Tulipa* spp.) are an ecologically and economically significant plant group, with several species' endemic to Central Asia. Among them, *T. fosteriana* and *T. ingens* are rare and regionally significant species found in Uzbekistan. These species inhabit mountainous regions with specific climatic and soil conditions, making them highly sensitive to environmental changes. Recent studies indicate that climate change may alter the distribution of many tulip species by shifting suitable habitats, potentially leading to habitat fragmentation or even local extinction (3). These types of tulips have been widely studied in terms of morphology, distribution and significance (4). Given the increasing anthropogenic pressures, including land-use changes, overgrazing and climate-induced stress, understanding the environmental drivers of *T. fosteriana* and *T. ingens* distributions is crucial for their conservation.

Species distribution models provide a data-driven approach to predict the current and future habitats of species based on environmental variables. Among SDMs, MaxEnt modeling has gained widespread recognition for its robustness, particularly when dealing with limited occurrence records. MaxEnt utilizes species presence data and environmental predictors to estimate the probability of habitat suitability (5). Previous studies have demonstrated the effectiveness of MaxEnt in modeling plant species distributions, especially for rare and endemic taxa (6). The flexibility of this approach makes it particularly useful for assessing the impact of climate change on species survival and conservation planning (7).

Recent research in Uzbekistan and Central Asia has increasingly incorporated SDMs to study plant distributions. Several fundamental and applied studies have used modeling techniques to assess the conservation status of species listed in the National Red Book or those under consideration for inclusion (8). Bioclimatic models have been developed for multiple plant species to understand their ecological preferences, predict habitat loss and propose conservation strategies (9). However, no comprehensive bioclimatic analysis has yet been conducted for *T. fosteriana* and *T. ingens* under future climate scenarios.

In the current bioclimatic context, *T. fosteriana* and *T. ingens* exhibit distinct distributional patterns and ecological preferences. Presently, *T. ingens* occupies approximately 229 km^2, with optimal growth zones located primarily in the Zarafshan and Gissar mountain ranges, including the Kohitang and Boysun areas. Climate projections indicate a significant reduction in suitable habitat: under the SSP126 scenario, the potential area decreases to 152 km^2 and further shrinks to 41 km^2 under the more severe SSP585 scenario, highlighting the species' vulnerability to climate change. Conversely, *T. fosteriana* shows a relatively limited distribution today (15–20 km^2), yet is projected to expand under future climate conditions. The SSP126 scenario suggests a possible increase to 1884 km^2, while SSP585 indicates further expansion to 1971 km^2, with the species potentially extending its range into new territories within the Gissar range.

This study aims to fill this gap by developing species distribution models for *T. fosteriana* and *T. ingens* under current and projected climate conditions using MaxEnt. By integrating field-based occurrence data, climatic factors and soil characteristics, this study seeks to identify key environmental drivers influencing species distribution, predict potential range shifts under different climate scenarios and provide conservation recommendations based on habitat suitability projections. The findings of this research will contribute to the conservation of these rare tulip species by guiding habitat protection efforts and informing strategies for biodiversity preservation in Uzbekistan and the broader Central Asian region.

This study is scientifically and practically significant as it explores the morphological characteristics and adaptive potential of *T. fosteriana* and *T. ingens* growing in the Samarkand region. The findings contribute to biodiversity conservation by developing effective microclonal propagation methods and improving sterilization protocols and nutrient media. Additionally, the research has practical value for biotechnology and environmental sustainability, as it reduces the costs of propagating rare wild species and facilitates their integration into agro-industrial and ecological applications.

Material and Methods

Occurrence Data

Species occurrence data for *T. fosteriana* and *T. ingens* were collected from multiple sources, including field surveys, herbarium records and global biodiversity databases. Field observations were conducted between 2022 and 2024 across key mountainous regions of Uzbekistan, including the Zarafshan, Hissar and Bobotog mountain ranges, where these species are known to grow. Additional occurrence records were obtained from herbarium collections housed in national botanical institutions and the Global Biodiversity Information Facility (GBIF) (10).

To ensure data quality, duplicate records and points with geolocation uncertainty exceeding 2 km were removed. Further spatial filtering was applied to reduce sampling bias, ensuring that closely located occurrences did not disproportionately influence the model. After filtering, a final dataset of X occurrence points for *T. fosteriana* and Y occurrence points for *T. ingens* was used for modeling.

The selected study sites differ considerably in terms of anthropogenic pressures, which were considered during field observations and environmental modeling. In areas surrounding protected zones, such as the Boysun and Kohitang sectors of the Gissar range, human activity is relatively limited, with restricted grazing and minimal land-use changes. In contrast, regions closer to agricultural zones and settlements, especially in the lower foothills of the Zarafshan range, are subject to intensive overgrazing and conversion of natural habitats for cultivation. Additionally, climate-induced stress such as increased aridity and temperature extremes was found to vary between sites, with higher vulnerability observed in southern exposed slopes. These site-specific pressures were considered in evaluating habitat suitability and interpreting the MaxEnt model outputs.

Study area

The study area was selected to encompass natural populations of *T. fosteriana* and *T. ingens* across diverse ecological zones in Uzbekistan. The rationale for site selection included variation in altitude (from 1000 to 3000 m), climate zones (semi-arid to montane) and soil types (loamy, calcareous and rocky-sandy substrates), which are known to affect tulip distribution. This diversity in climatic and edaphic conditions ensures that MaxEnt modeling captures a realistic range of environmental responses for both species. The selected study sites represent a broad climatic gradient across the region. Elevation ranges from 1020 to 3050 m, resulting in notable differences in mean annual temperature (approx. 5 °C-13 °C) and total annual precipitation (250-650 mm). This variation provides an ecologically meaningful basis for evaluating species' distribution under different climate conditions. The period 2041-2060 was selected as it represents the mid-century projection commonly used in IPCC-based climate modeling.

Sampling sizes were not strictly uniform across all sites due to natural differences in population size, terrain accessibility and conservation restrictions. However, to maintain methodological consistency, all sampling followed a standardized protocol using fixed-dimension plots (e.g., 5×5 m quadrats) or transects depending on terrain. The number of replicates was proportional to the area of suitable habitat available at each site. This approach allowed for both flexibility and comparability across sites. The study areas were selected based on altitudinal and climatic gradients, ecological representativeness and presence of viable *T. fosteriana* and *T. ingens* populations.

Environmental variables

A total of 30 environmental predictors were selected to develop species distribution models, including 19 bioclimatic variables, 10 soil parameters and elevation data (11).

Climate data

Bioclimatic variables were obtained from CHELSA-BIOCLIM+ (https://chelsa-climate.org), providing high-resolution (1 × 1 km) climatic data for temperature, precipitation and seasonal variations. These variables have been widely used in species distribution modeling due to their strong influence on plant growth and survival (12).

Elevation data

Topographical data, including absolute elevation above sea level, were sourced from WorldClim v2.1 (https://www.worldclim.org) at a spatial resolution of 1 × 1 km. Elevation is a critical factor for high-altitude plant species like *T. fosteriana* and *T. ingens*, influencing temperature gradients, moisture availability and soil properties (13). The elevation across the study area ranged from 1020 m to 3050 m, capturing both foothill and alpine habitats of the target species.

Soil data

Soil parameters were obtained from the SoilGrids database (https://soilgrids.org) with a spatial resolution of 250 m. These included soil texture (clay content, organic carbon), soil pH and depth to bedrock, which are crucial for determining habitat suitability (14).

Bioclimatic variables included temperature and precipitation indices extracted from CHELSA, while edaphic factors were derived from SoilGrids and elevation data from WorldClim. All raster layers were standardized to the WGS 1984 projection with a 1 × 1 km resolution. Table 1 presents the bioclimatic, soil and topographical variables utilized in the MaxEnt-based species distribution modeling process.

Table 1. Environmental variables used for bioclimatic niche modeling of *T. fosteriana* and *T.ingens*

Code	Climatic and edaphic variables	Description / Formula	Unit
BIO1	Annual Mean Temperature	–	°C
BIO2	Mean Diurnal Range	–	°C
BIO3	Isothermality	BIO1 / BIO7 * 100	%
BIO4	Temperature seasonality	Coefficient of Variation	–
BIO5	Max temperature of warmest month	–	°C
BIO6	Min temperature of coldest month	–	°C
BIO7	Annual temperature range	BIO5 – BIO6	°C
BIO8	Mean temperature of wettest quarter	–	°C
BIO9	Mean temperature of driest quarter	–	°C
BIO10	Mean temperature of warmest quarter	–	°C
BIO11	Mean temperature of coldest quarter	–	°C
BIO12	Annual precipitation	–	mm
BIO13	Precipitation of wettest month	–	mm
BIO14	Precipitation of driest month	–	mm
BIO15	Precipitation seasonality	Coefficient of Variation	–
BIO16	Precipitation of wettest quarter	–	mm
BIO17	Precipitation of driest quarter	–	mm
BIO18	Precipitation of warmest quarter	–	mm
BIO19	Precipitation of coldest quarter	–	mm
Elevation	Elevation above sea level	–	m
BDRICM	Depth to bedrock (R Horizon, 200 cm)	–	cm
BDRLOG	Probability of R horizon formation	–	%
BDTICM	Absolute depth to bedrock	–	cm
BLDFIE	Bulk density	–	kg/m^3
CECSOL	Cation exchange capacity of soil	–	cmolc/kg
CLYPPT	Clay content (<0.0002 mm)	–	%
CRFVOL	Volume of coarse fragments	–	–
OCSTHA	Soil organic carbon stock	–	t/ha
ORCDRS	Soil organic carbon content	–	‰ (per mille)
PHIHOX	Soil pH in water solution	–	pH
PHIKCL	Soil pH in KCl solution	–	pH

Notes: 1) Soil and elevation variables; 2) Elevation; (m); 3) Bulk density (kg/m^3); 4) Depth to bedrock (cm); 5) Soil organic carbon stock (t/ha); 6) Soil pH (H_2O and KCl); 7) Clay fraction (%).

All environmental variables were processed and standardized using QGIS v3.22.9, with projection based on WGS 1984 (World Geodetic System 1984). Raster layers were converted from GeoTIFF to ASCII format using R v4.3.1 (raster package) for compatibility with MaxEnt.

Future climate scenarios

To assess the potential impact of climate change on *T. fosteriana* and *T. ingens*, future climate projections were obtained from the Intergovernmental Panel on Climate Change (IPCC AR6), using simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (13). Two future Shared Socioeconomic Pathways (SSPs) were selected for the period 2041-2060.

SSP1–2.6 - a moderate emissions scenario representing sustainable development with low greenhouse gas concentrations (15)

SSP5–8.5 - a high emissions scenario reflecting rapid economic growth with high greenhouse gas emissions and significant climate warming (16).

Projected changes in global mean temperature and precipitation under these scenarios (Table 2). The table outlines the anticipated temperature increases (°C) and percentage changes in precipitation for both emission scenarios. Climate simulations were visualized using MaxEnt based on IPCC AR6 CMIP6 projections (17).

Results and Discussion

The MaxEnt models demonstrated high predictive accuracy for both *T. fosteriana* and *T. ingens*. The Area Under the Curve (AUC) values exceeded 0.98, confirming excellent model performance (18). For *T. fosteriana*, the training AUC was 0.999 and the test AUC was 0.998 (Fig. 1). For *T. ingens*, the training AUC was 0.993 and the test AUC was 0.986 (Table 3).

The figure presents the model evaluation results for *T. fosteriana* generated using MaxEnt based on three climate conditions: Current, Ssp1-2.6 (moderate emissions) and Ssp5-8.5 (high emissions). Each ROC plot shows the relationship between sensitivity and 1 – specificity for both training and test datasets. The AUC values for training data were 0.999 (Current), 0.999 (Ssp126) and 0.999 (Ssp585), while test data AUCs were 0.998 for all scenarios. AUC values above 0.9 indicate excellent model predictive performance. The diagonal line represents random prediction (AUC = 0.5), used here as a baseline for comparison (Fig. 2).

Model evaluation under climate scenarios

The figure presents the model evaluation results for *T. ingens* generated using MaxEnt based on three climate conditions: Current, SSP1-2.6 (moderate emissions) and SSP5-8.5 (high

Table 2. Projected changes in global mean temperature and annual precipitation under two SSP scenarios (2041-2060), relative to the baseline period (1995-2014)

Scenario	Air temperature (°C)		Atmospheric precipitation (%)	
	Mean	Range	Mean	Range
SSP1-1.9	0.9 °C	0.4°C-1.4°C	2.9 %	0.9-5 %
SSP1-2.6	1.0 °C	0.5°C-1.5°C	2.7 %	0.5-5 %
SSP2-4.5	1.3 °C	0.7°C-1.8°C	2.8 %	0.7-4.8 %
SSP3-7.0	1.4 °C	0.8°C-2.0°C	2.4 %	-0.3-5.1 %
SSP5-8.5	1.7 °C	1.0°C-2.4°C	3.8 %	0.7-6.8 %

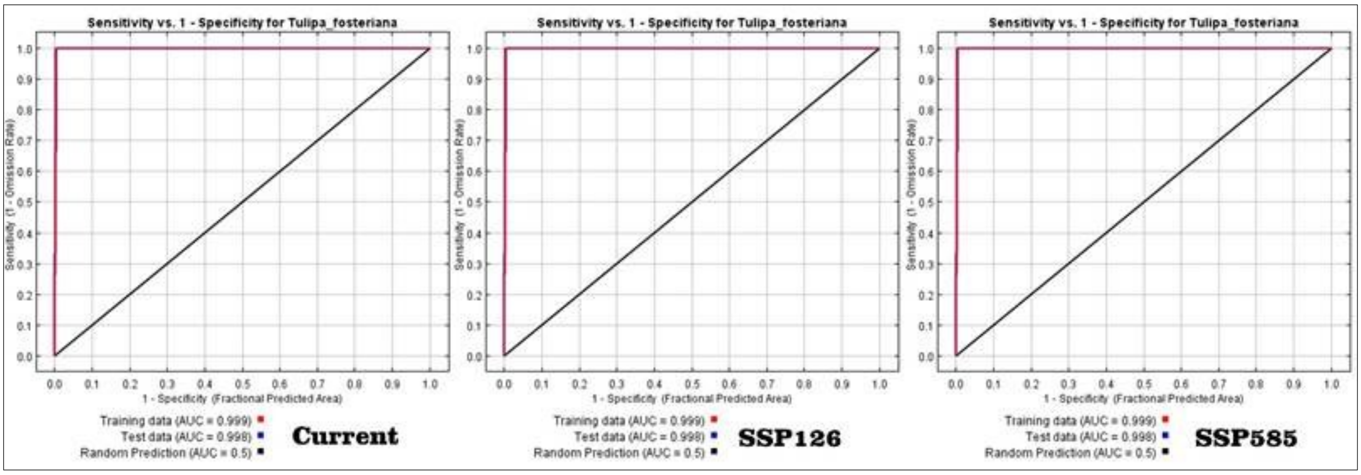

Fig. 1. Receiver Operating Characteristic (ROC) curves and Area Under the Curve (AUC) values for *T. fosteriana* under current and future climate scenarios.

Table 3. Performance evaluation of MaxEnt models for *T. fosteriana* and *T. ingens* under current and future climate scenarios

Species	Time period	AUC (Training)	AUC (Test)	RP (Random Prediction)
T. fosteriana	Current	0.999	0.998	0.5
	SSP126	0.999	0.998	0.5
	SSP585	0.999	0.998	0.5
	Average	**0.999**	**0.998**	**0.5**
T. ingens	Current	0.996	0.974	0.5
	SSP126	0.992	0.993	0.5
	SSP585	0.992	0.993	0.5
	Average	**0.993**	**0.986**	**0.5**

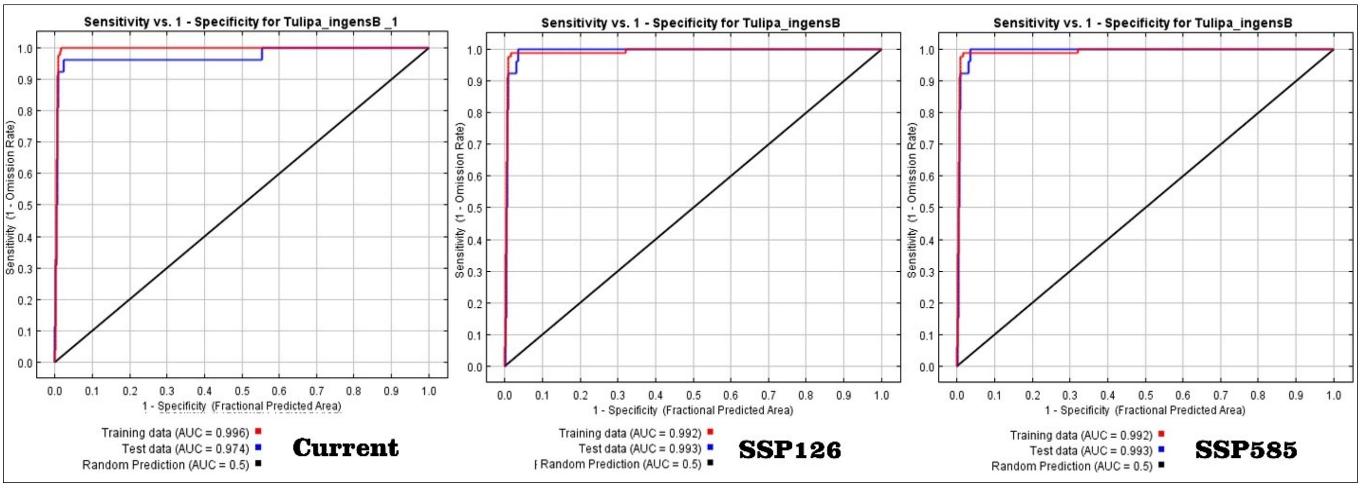

Fig. 2. Receiver Operating Characteristic (ROC) curves and Area Under the Curve (AUC) values for *T. ingens* under current and future climate scenarios.

emissions). Each ROC plot shows the relationship between sensitivity and 1 - specificity for both training and test datasets. The AUC values for training data were 0.996 (Current), 0.992 (SSP126) and 0.992 (SSP585), while test data AUCs were 0.974, 0.993 and 0.993, respectively. AUC values exceeding 0.9 indicate excellent model predictive performance. The diagonal line represents random prediction (AUC = 0.5), used here as a baseline for comparison.

Key environmental variables influencing habitat suitability

The jackknife analysis identified BIO19 (Precipitation of the coldest quarter) and soil depth-related variables as the most significant factors influencing species distribution. For *T. fosteriana*, BIO19 contributed 29.8 %, followed by BDTICM (Depth to Bedrock) at 20.8 %. This suggests that winter precipitation is crucial for habitat suitability, while soil depth affects root development and water retention (19).

For *T. ingens*, BIO19 contributed 36.3 %, with BDRICM (Rock Depth) at 16.0 %. This indicates that precipitation in winter months is vital for survival and reduced moisture availability could severely impact the species (20). This figure illustrates the percent contribution of the top ten environmental variables influencing the predicted distribution of *T. ingens* in the MaxEnt species distribution model (Fig. 3). Variables include bioclimatic factors (BIO2, BIO3, BIO11, BIO13, BIO14, BIO16, BIO18, BIO19) and edaphic parameters (BDRICM - depth to rock; BDTICM - absolute depth to bedrock). BIO19 (precipitation of the coldest quarter) exhibited the highest contribution, indicating its critical role in shaping habitat suitability. Box plots show the variability in contribution across model replicates, highlighting the relative importance of each variable in the modeling process (Fig. 4).

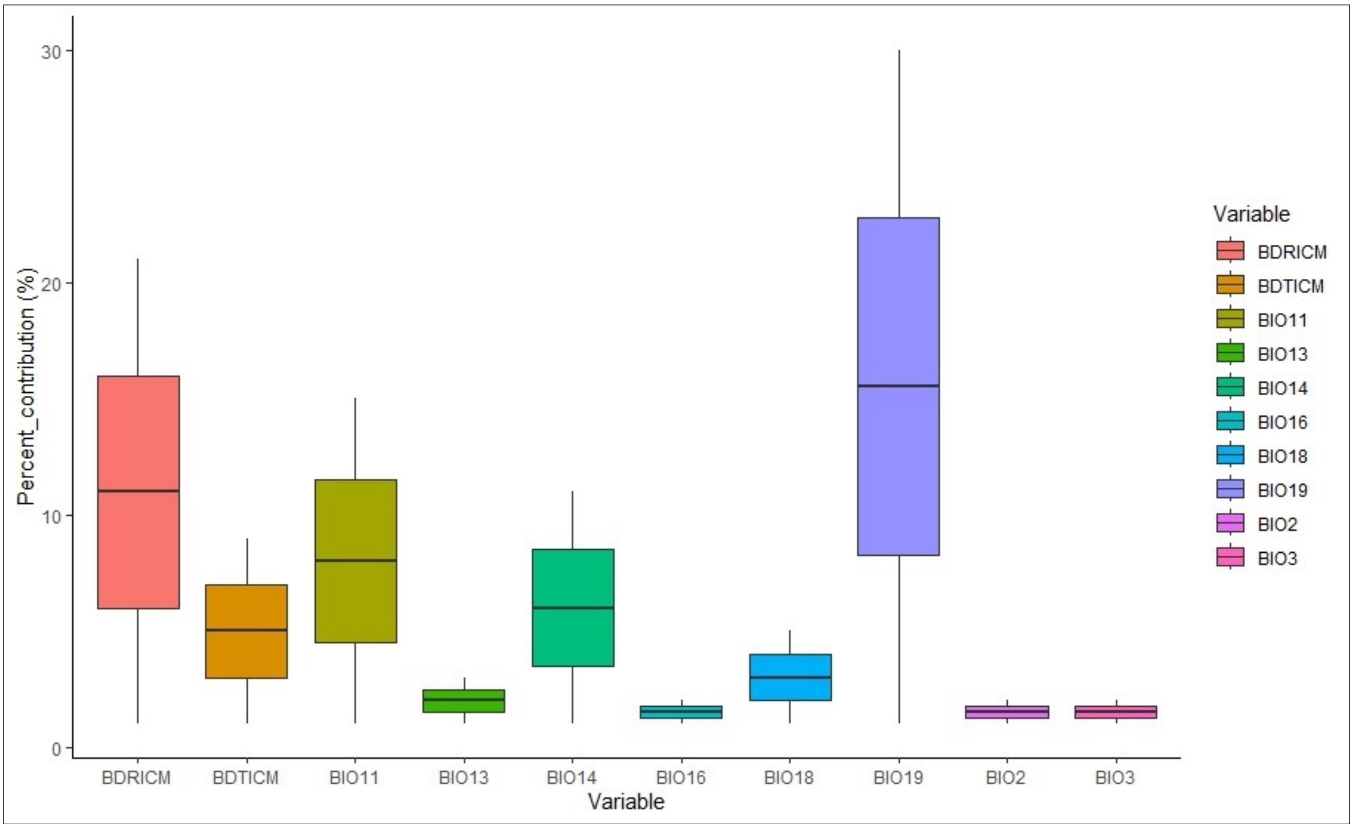

Fig. 3. Contribution of environmental variables to the MaxEnt model for *T. ingens*.

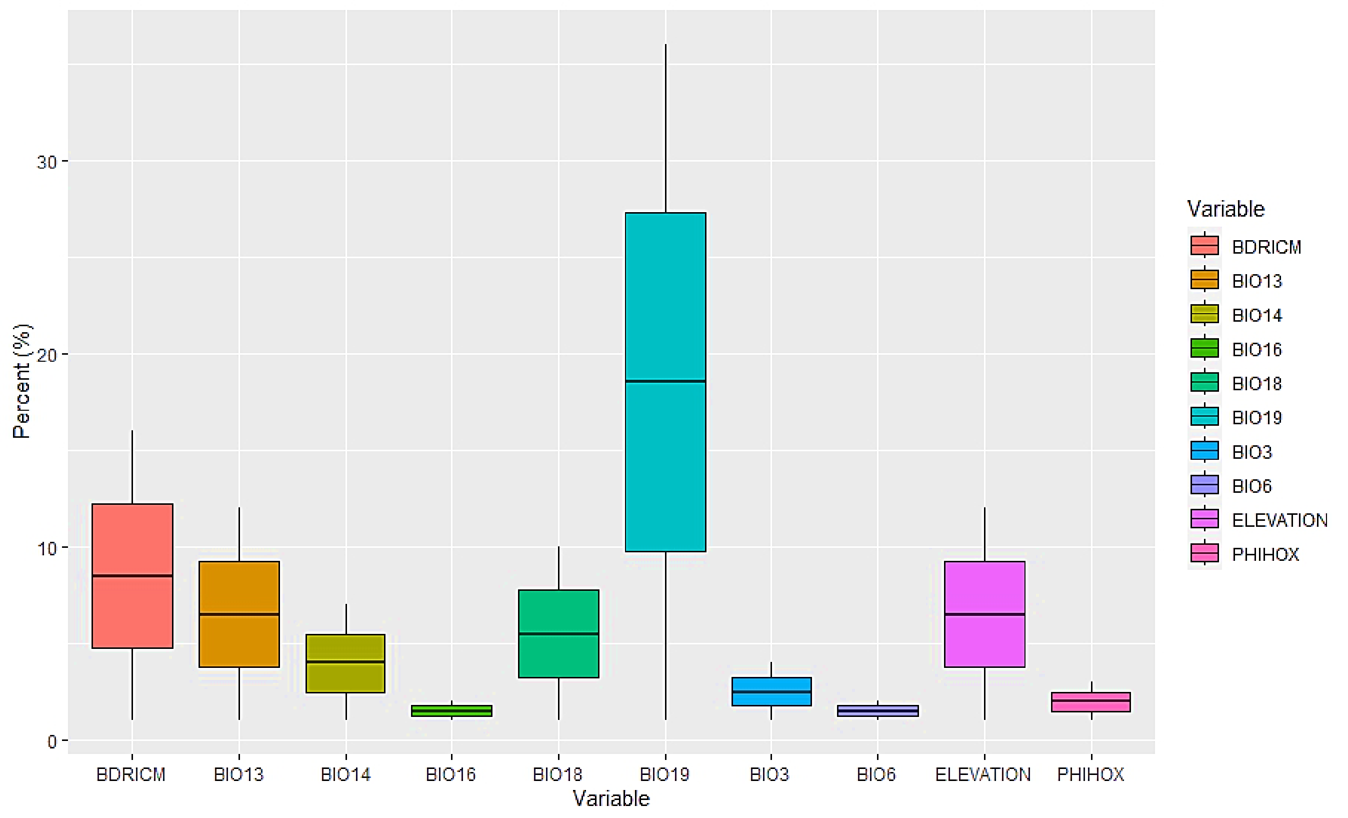

Fig. 4. Contribution of environmental variables to the MaxEnt model for *T. fosteriana*.

This figure displays the percent contribution of the top environmental predictors used in the species distribution model for *T. fosteriana*. BIO19 (precipitation of the coldest quarter) emerged as the most influential variable, followed by BDRICM (depth to bedrock) and BIO18 (precipitation of the warmest quarter). Additional variables such as elevation and soil pH (PHIHOX) also contributed to model performance, indicating the importance of both climatic and edaphic factors in shaping habitat suitability.

Current and future distribution patterns of *T. fosteriana*

The model predicts an increase in the potential habitat range for *T. fosteriana* under both climate change scenarios (21). The current suitable habitat area is estimated at 1520 km^2. Under the SSP126 scenario, which reflects moderate greenhouse gas emissions, the predicted suitable area increases to 1860 km^2, reflecting a 22 % expansion. Under the SSP585 scenario, representing high emissions, the suitable habitat area further increases to 1971 km^2, showing a 29 % growth compared to the current extent.

Future projections suggest that *T. fosteriana* will expand its range toward the Hissar and Bobotog mountain ranges, with new suitable habitats emerging in the Kugitang and Baysun regions (22). This expansion trend is more pronounced under the SSP585 high-emissions scenario, indicating that *T. fosteriana* may benefit from warmer temperatures and increased precipitation variability (23). Habitat areas in all scenarios are categorized into five suitability classes ranging from 'Unsuitable' to 'Very High'. Values represent area coverage in square kilometers under current, Ssp126 and Ssp5855 scenarios (Table 4) (Fig. 5).

The map illustrates the spatial distribution of suitable habitats for *T. fosteriana* under present climatic conditions. Suitability levels are categorized into five classes, ranging from unsuitable (0-20 %) to very high suitability (81-100 %), with highest suitability areas concentrated in the Hissar and Bobotog mountain ranges within Samarkand, Kashkadarya and Surkhandarya regions. The inset highlights core areas of habitat concentration, supporting the species' current ecological niche (Fig. 6).

This map displays modeled habitat suitability for *T. fosteriana* using MaxEnt under the Ssp126 climate scenario. The simulation predicts an expansion of suitable areas compared to the current range, particularly in the Hissar (Kugitang and Baysun) and Bobotog mountain ranges. Suitability classes are categorized from unsuitable (0-20 %) to very high suitability (81-100 %), with high-suitability zones highlighted in red and orange. The inset emphasizes new habitat emergence in southern regions, supporting future conservation planning (Fig. 7).

Fig. 4. Contribution of environmental variables to the MaxEnt model for *T. fosteriana*.

Suitability level	Current	SSP126	SSP585
Unsuitable	418847	409155	405226
Low	15047	20008	21800
Moderate	8214	8620	9356
High	5272	9257	10547
Very High	1520	1860	1971
Total	448900	448900	448900

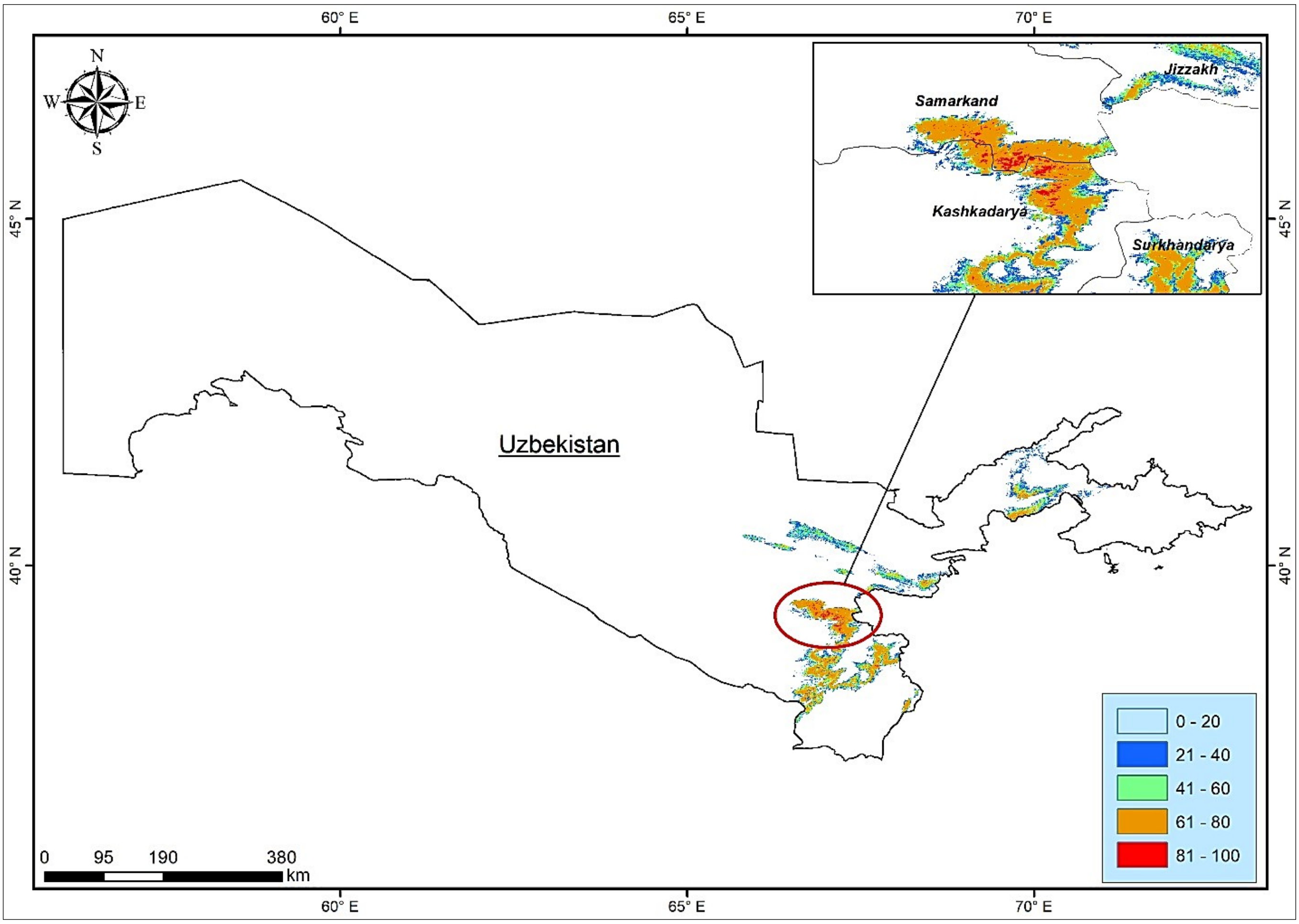

Fig. 5. Predicted current potential distribution of *T. fosteriana* in Uzbekistan based on MaxEnt habitat suitability modeling.

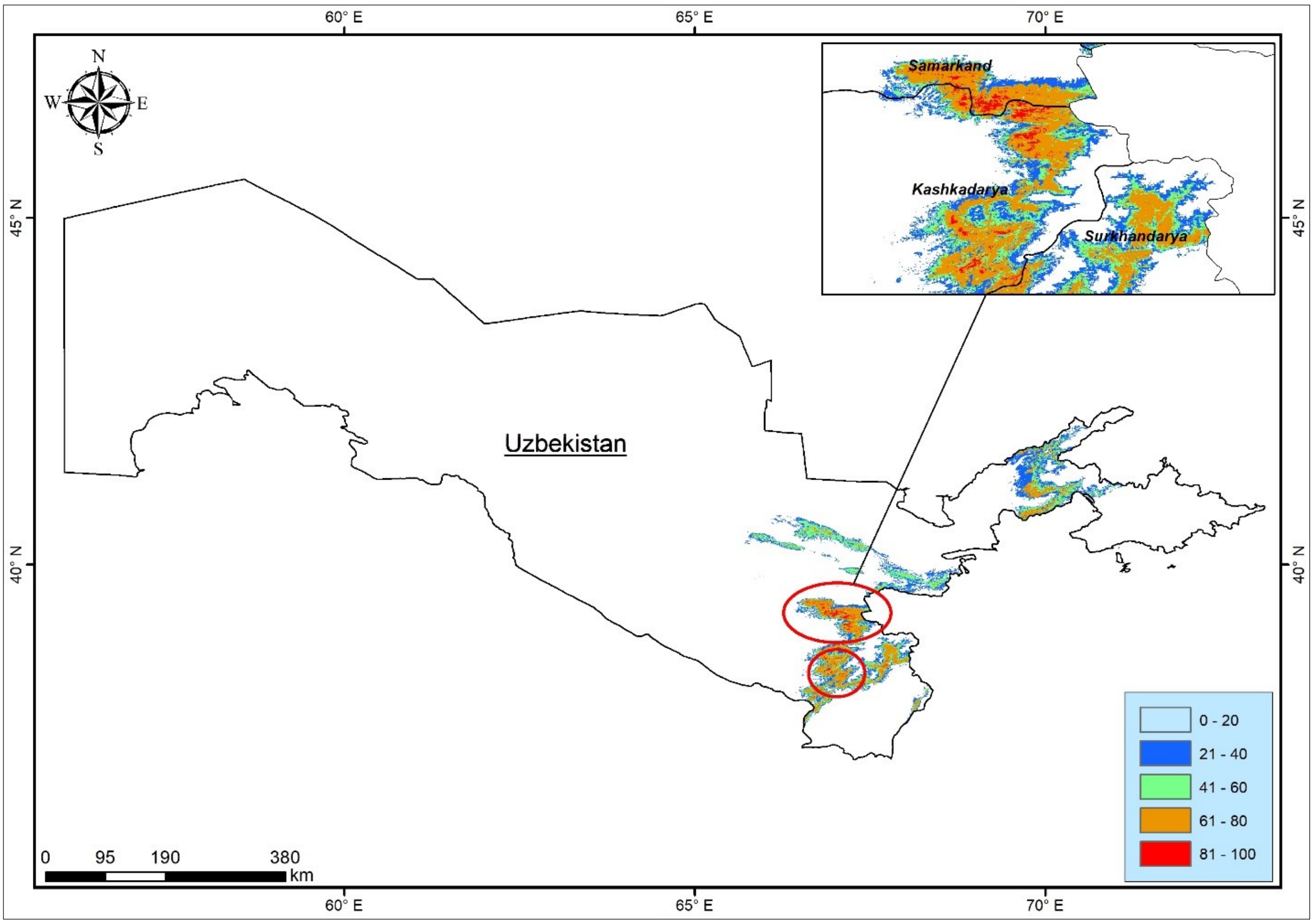

Fig. 6. Projected potential distribution of *T. fosteriana* under the Ssp126 moderate emissions scenario (2041-2060) in Uzbekistan.

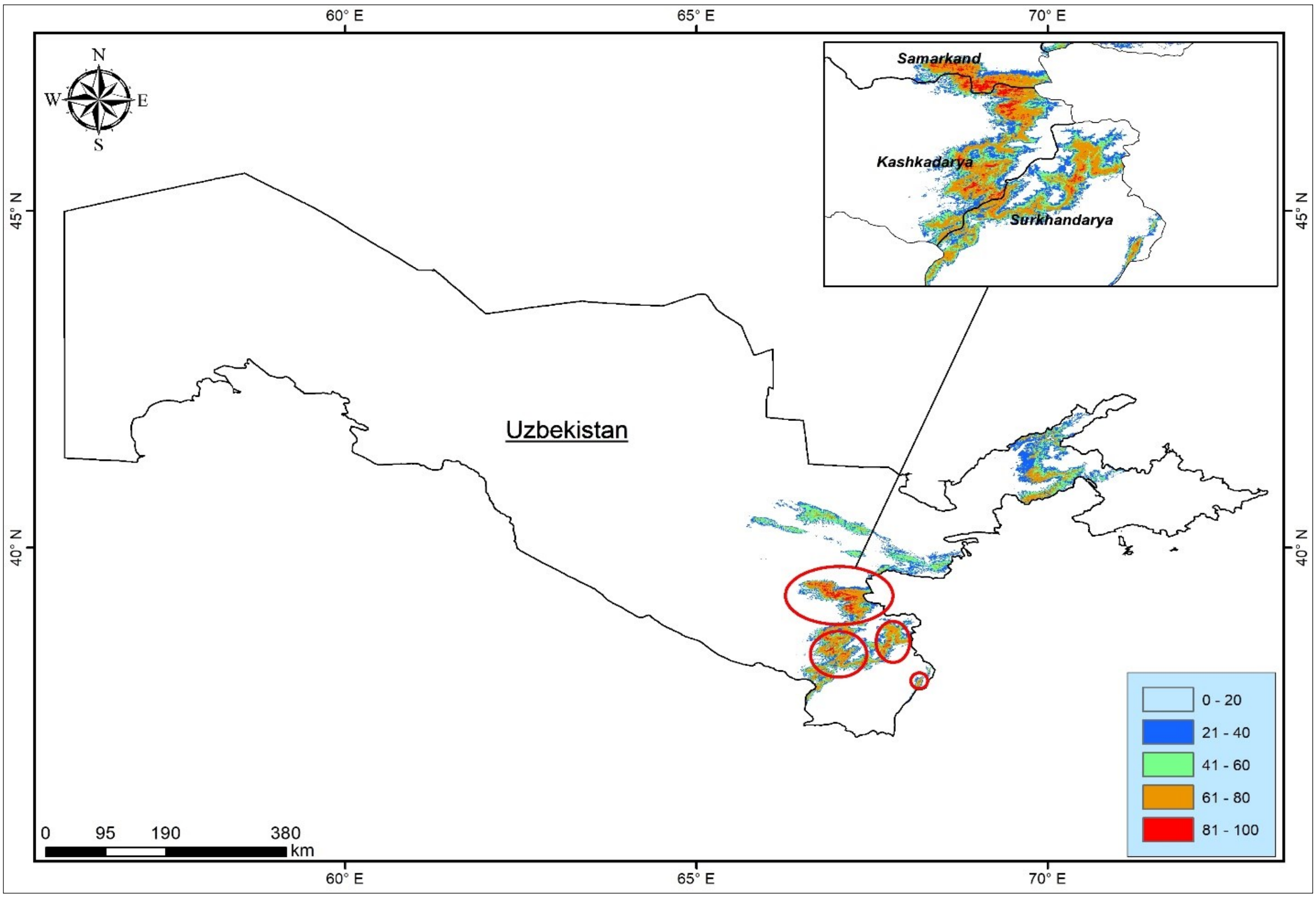

Fig. 7. Projected potential distribution of *T. fosteriana* under the Ssp585 high emissions scenario (2041-2060) in Uzbekistan.

This map illustrates the expected spatial expansion of *T. fosteriana* habitat under the high-emissions climate scenario Ssp585. The MaxEnt model predicts further increase in suitable areas compared to both current and moderate projections, particularly in the southern Hissar (Kugitang and Baysun) and Bobotog mountain ranges. Habitat suitability classes range from unsuitable (0-20 %) to very high suitability (81-100 %), with red and orange zones indicating optimal conditions (24). The inset highlights newly emerging habitats, reflecting the species' potential adaptation to warmer and wetter future climates.

Current and future distribution patterns of *T. ingens*

Unlike *T. fosteriana*, the distribution of *T. ingens* is projected to undergo a severe reduction in suitable habitat, particularly under the high-emission climate scenario (25).

Current suitable habitat area: 205 km^2

Projected habitat under Ssp126 (moderate emissions): 138 km^2 (-33 % decrease)

Projected habitat under Ssp585 (high emissions): 17 km^2 (-92 % decrease)

The Zarafshan and Hissar mountain ranges (including Kugitang, Baysun and Sangardak) remain the primary refugia for *T. ingens* under the Ssp126 scenario. However, under the Ssp585 high-emission scenario, nearly all suitable habitats disappear, leaving only small, fragmented populations in the Zarafshan range. This indicates an elevated risk of local extinction if climate conditions continue to deteriorate (Fig. 8).

The map displays habitat suitability for *T. ingens* under present-day climate conditions (1995-2014 baseline). Areas are classified into five suitability categories ranging from 'unsuitable' (0-20 %) to 'very high' (81-100 %). The highest suitability zones are concentrated within the Zarafshan and Hissar mountain systems, particularly in the Kugitang, Baysun and Sangardak regions. The inset magnifies priority areas in southern Uzbekistan, reflecting known distribution patterns of *T. ingens* confirmed through field observations. This map serves as a reference for comparison with future climate projections and conservation planning (Fig. 9) (Table 5).

This map illustrates the anticipated habitat suitability for *T. ingens* based on moderate-emission climate projections. The distribution model reveals a contraction in highly suitable habitats compared to current conditions, with suitable zones concentrated in the Zarafshan and Hissar mountain systems, particularly around Kugitang, Baysun and Sangardak. Suitability classes range from 'unsuitable' (0-20 %) to 'very high' (81-100 %). The inset zooms into ecologically significant regions to highlight localized changes. These results emphasize the species' sensitivity to future climate variability and the importance of targeted conservation efforts (Fig. 10).

This map visualizes the modeled habitat suitability for *T. ingens* based on a high-emission climate trajectory. Under Ssp585, a dramatic contraction in suitable habitat is evident, with highly suitable zones (81-100 %) nearly disappearing and remaining suitable areas reduced to fragmented patches within the Zarafshan mountain range. Compared to current and Ssp126 scenarios, this model indicates a critical decline in habitat availability. The inset highlights the last remaining ecological refugia, stressing the urgent need for conservation measures amid severe climate-induced range loss.

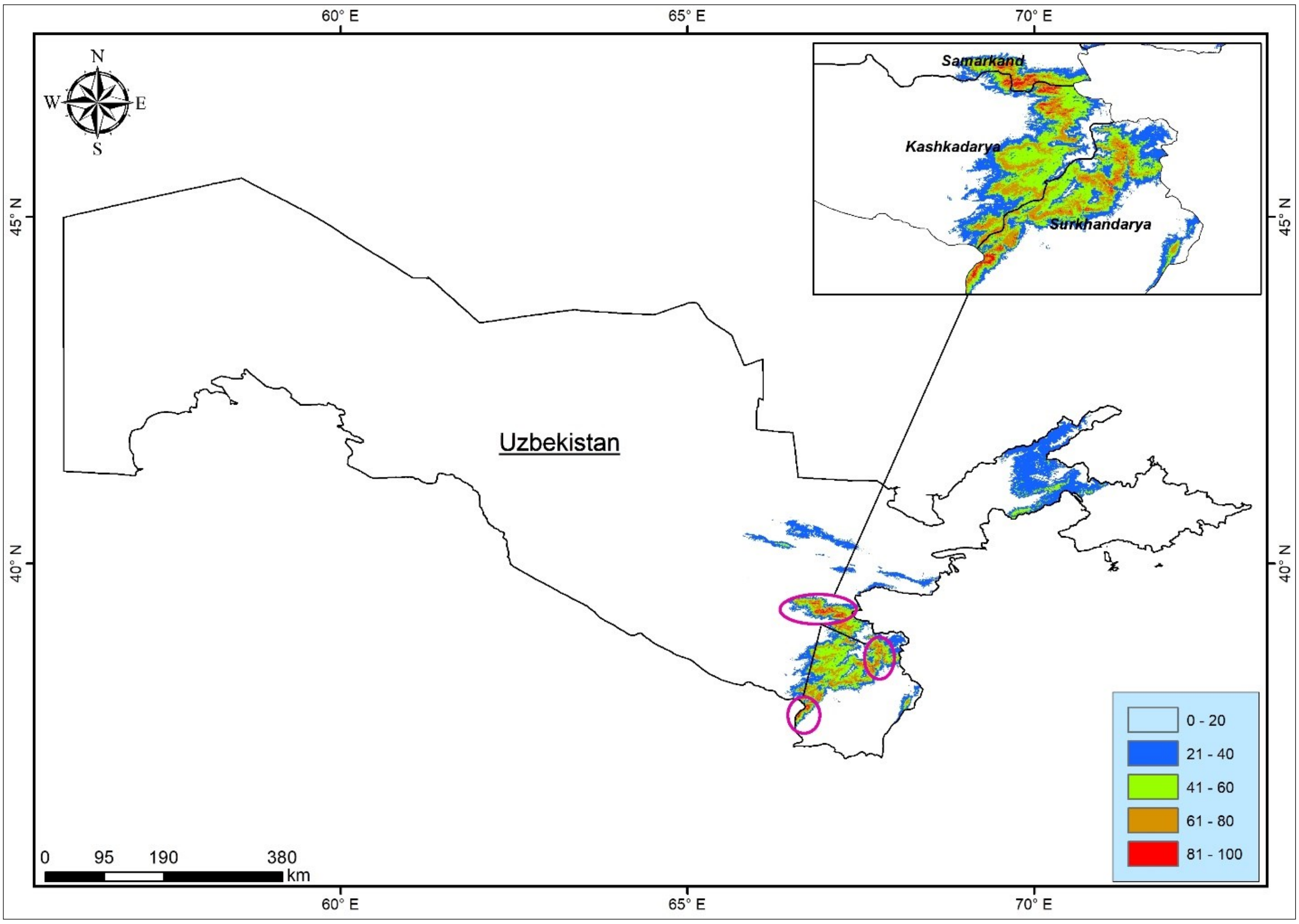

Fig. 8. Modeled current potential distribution of *T. ingens* across Uzbekistan based on MaxEnt analysis.

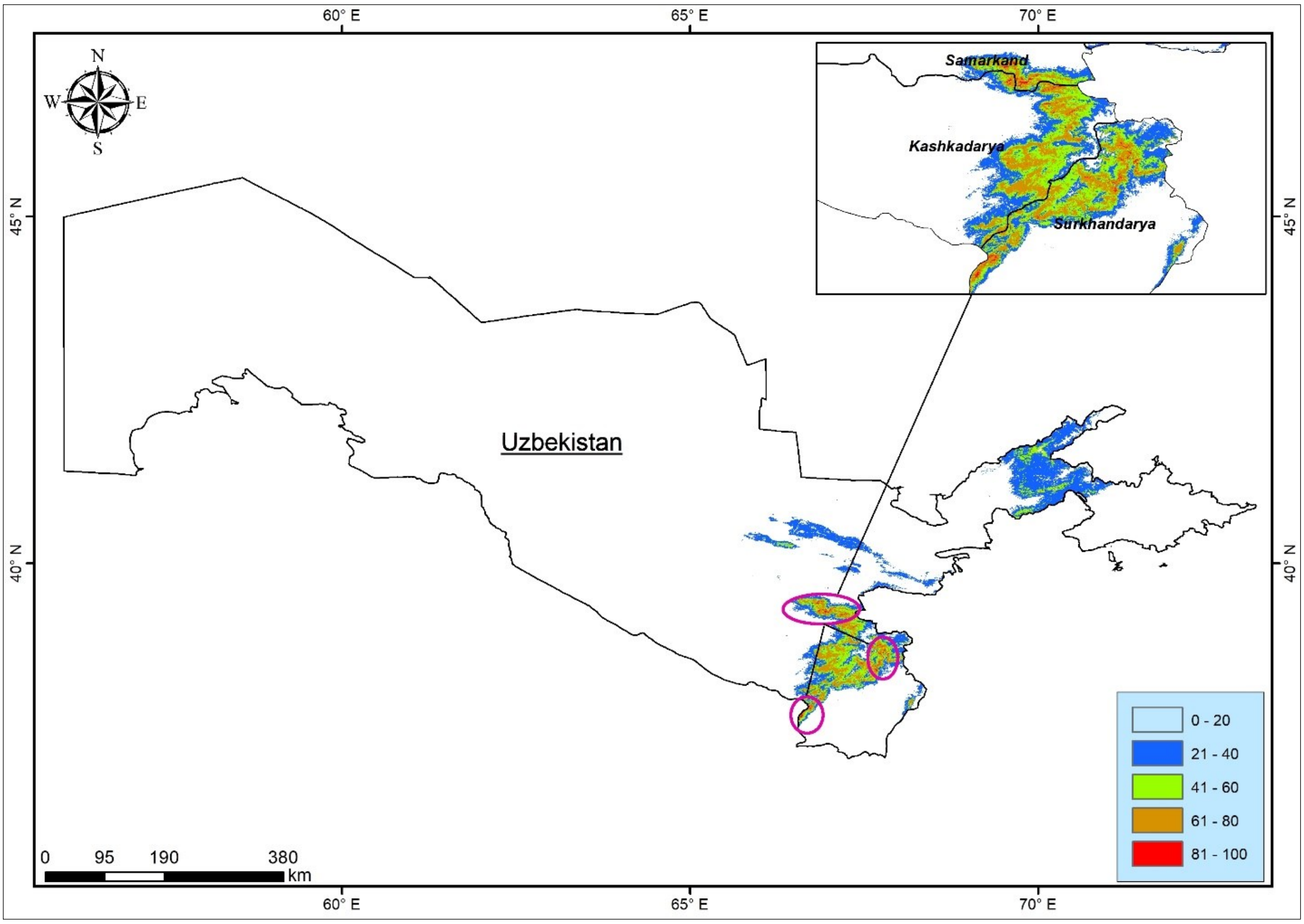

Fig. 9. Projected potential distribution of *T. ingens* in Uzbekistan under the Ssp126 climate change scenario (2041-2060).

Table 5. Predicted habitat suitability for *T. ingens* under current and future climate scenarios (2041-2060) in Uzbekistan

Suitability level	Current	SSP126	SSP585
Unsuitable	417913	420706	416911
Low	21407	18786	22340
Moderate	7845	6400	6684
High	1530	2870	2948
Very High	205	138	17
Total	**448900**	**448900**	**448900**

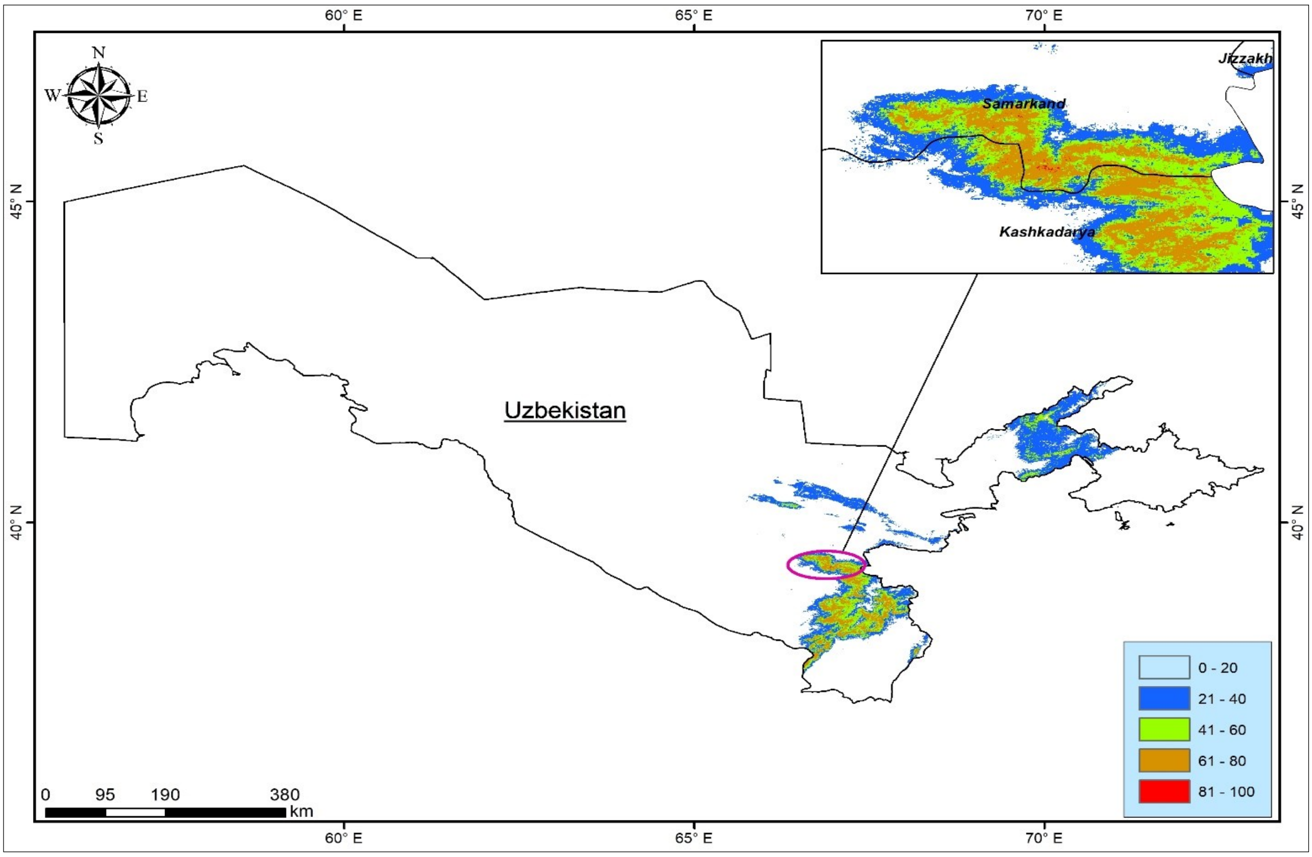

Fig. 10. Projected potential distribution of *T. ingens* in Uzbekistan under the Ssp585 high-emission scenario (2041-2060).

Comparison of range changes

The contrasting responses of *T. fosteriana* and *T. ingens* to climate change highlight species-specific vulnerabilities. While *T. fosteriana* is projected to expand southward, *T. ingens* is expected to face a severe habitat loss, with Ssp585 showing a drastic reduction in suitable areas.

T. fosteriana is projected to experience a 22-29 % habitat expansion, indicating that it may benefit from warming conditions. In contrast, *T. ingens* loses 33-92 % of its current range, signaling a critical need for conservation intervention.

These findings emphasize the importance of developing targeted conservation strategies, including:

Protected area expansion for *T. fosteriana* in regions where suitable habitat is projected to increase.

Ex-situ conservation measures (such as botanical garden preservation and seed banking) for *T. ingens* to prevent potential local extinction.

Key findings summary

MaxEnt models demonstrated high accuracy, with AUC values exceeding 0.98 for both species.

T. fosteriana is projected to increase its suitable habitat, particularly in the Hissar and Bobotog mountain ranges.

T. ingens faces severe habitat loss, with only 17 km^2 of suitable habitat remaining under the Ssp585 scenario.

BIO19 (cold-season precipitation) and depth to bedrock were identified as the most influential environmental factors affecting species distribution.

Conservation actions are urgently needed for *T. ingens* to prevent its potential local extinction. This study provides a comprehensive assessment of the current and future potential distribution of *T. fosteriana* and *T. ingens* using bioclimatic niche modeling. The results indicate that these two species respond differently to climate change, with *T. fosteriana* projected to expand its habitat, while *T. ingens* face severe habitat contraction. These findings emphasize the need for targeted conservation strategies to mitigate the impacts of climate change on these endemic species.

The projections suggest that *T. fosteriana* may benefit from climate change, as its suitable habitat is expected to expand under both Ssp126 and Ssp585 scenarios. The model indicates a southward range shift, with newly suitable areas emerging in the Hissar and Bobotog mountain ranges, particularly in Kugitang and Baysun. This pattern suggests that *T. fosteriana* has a higher degree of ecological tolerance, allowing it to adapt to warming temperatures and shifting precipitation patterns.

In contrast, *T. ingens* is predicted to experience a drastic reduction in suitable habitat, especially under the Ssp585 scenario, where more than 90 % of its currently suitable areas disappear. The remaining populations are expected to persist only in the Zarafshan and Hissar mountain ranges under Ssp126, while under Ssp585, nearly all suitable habitats are lost, leaving small and fragmented populations in the Zarafshan range. This outcome highlights the species' narrow ecological niche and vulnerability to climate-induced habitat loss.

The environmental factors influencing habitat suitability were primarily related to precipitation patterns and soil conditions. The analysis revealed that precipitation during the coldest quarter (BIO19) was the most significant predictor for both species. Soil depth-related factors, including absolute depth to bedrock (BDTICM) and rock depth (BDRICM), also played a crucial role, suggesting that moisture availability and soil structure are essential determinants of habitat suitability. While *T. fosteriana* appears more adaptable to a range of environmental conditions, *T. ingens* is highly dependent on specific climatic and edaphic conditions, making it more susceptible to habitat loss under future climate change scenarios.

The contrasting responses of these species underscore the need for conservation strategies tailored to their ecological requirements. Furthermore, recent studies have shown that large-scale renewable energy infrastructure can have unintended consequences on ecosystems and biodiversity, highlighting the complexity of human-induced environmental change. For *T. fosteriana*, expanding protected areas in the Hissar and Bobotog mountain ranges will be crucial to accommodate the predicted range expansion. *In-situ* conservation efforts should focus on preserving newly suitable habitats, while implementing habitat monitoring programs to track population dynamics.

For *T. ingens*, urgent conservation measures are needed to safeguard its remaining populations. Habitat protection in the Zarafshan and Hissar mountain ranges should be prioritized, along with *ex-situ* conservation efforts, including seed banking and cultivation in botanical gardens. Assisted migration may also be considered as a strategy to relocate populations to more stable habitats identified in the Ssp126 projections. During the projected period (2041-2060), the model predicts habitat expansion of *T. fosteriana* into regions characterized by mean annual temperatures of 10-14 ° C, annual precipitation below 450 mm and elevations between 1200-2200 m**,** especially under SSP585. These values represent slightly warmer and drier conditions compared to its current niche. In contrast, *T. ingens* shows reduced habitat suitability in areas where temperature exceeds 12 °C and precipitation drops below 500 mm, indicating sensitivity to warming and aridification. This shift in ecological suitability aligns with expected climate-induced stress on high-altitude species. In addition to habitat protection, restoring degraded mountain ecosystems and reducing anthropogenic pressures such as overgrazing and land-use change could help enhance species resilience. The findings align with other NDVI-based studies assessing the ecological consequences of land-use change and anthropogenic disturbance across rangeland areas in Central Asia. Integrating climate adaptation measures into conservation policies will be essential to ensure the long-term survival of these tulip species. The predicted suitable habitats align well with the known morphological and ecological traits of the studied species. *T. fosteriana*, adapted to drier low-to-mid elevation areas, displays xeromorphic traits such as thickened leaves and compact bulbs. In contrast, *T. ingens*, typically found in higher, moister altitudes, exhibits mesophytic adaptations including broader leaf surface and larger floral structures. These morphological traits support and validate the ecological patterns predicted by the MaxEnt model.

The application of bioclimatic modeling in this study demonstrates the value of predictive tools in guiding biodiversity conservation efforts. In addition, for conservation purposes, these species can now be successfully propagated *in vitro*, producing healthy microclones in large quantities. By incorporating model-based insights into conservation planning, decision-makers can develop more effective strategies to mitigate the impacts of climate change on rare and endemic species.

Although the MaxEnt model provides valuable predictions, some limitations should be considered (26). The model does not account for biotic interactions such as competition, pollination dependencies, or herbivory, which could influence species distributions. Future studies should integrate ecological monitoring and experimental research to validate model predictions (27). Additionally, while this study assumes that species distributions will respond primarily to climatic and edaphic factors, potential genetic adaptations to changing environments are not accounted for (28). Investigating the genetic diversity and adaptive potential of these species would provide further insights into their ability to persist under future climatic conditions.

Conclusion

This study assessed the current and future distributions of *T. fosteriana* and *T. ingens* under different climate change scenarios using bioclimatic niche modeling. The findings demonstrate that *T. fosteriana* may expand its potential range, particularly in the Hissar and Bobotog mountain ranges, suggesting a higher level of ecological adaptability. In contrast, *T. ingens* is projected to undergo significant habitat loss, especially under high-emission scenarios (Ssp585), indicating its vulnerability to climate change. Despite being located within the same broad mountain systems, the study sites exhibit both ecological commonalities and distinct differences. Common features include continental climate, stony or loamy soils and seasonal precipitation patterns. However, elevation ranges from 1020 m in the Zarafshan foothills to over 3000 m in the Gissar range, creating temperature and moisture gradients that influence species presence. *T. fosteriana* is generally found in lower-altitude, drier sites, while *T. ingens* is more prevalent in cooler, high-altitude habitats with greater precipitation. These contrasts explain the differing modeled suitability patterns and potential responses to climate change. The model results suggest that *T. fosteriana* shows a stronger association with areas of moderate elevation (1200-2000 m), relatively low precipitation and higher temperature variability. In contrast, *T. ingens* prefers higher altitudes (2000-3000 m), stable temperatures and areas with higher moisture availability. These species-specific responses highlight the importance of climatic gradients, particularly BIO1 (Annual Mean Temperature), BIO12 (Annual Precipitation) and Elevation, in shaping the distribution patterns of both species.

These outcomes highlight important ecological differences between the two endemic species and emphasize the need for differentiated conservation strategies. *T. fosteriana* may benefit from habitat expansion under moderate warming conditions, but still requires habitat monitoring to ensure its long-term viability. *T. ingens*, on the other hand, faces a critical threat of local extinction if suitable habitats continue to decline. Urgent *in-situ* and *ex-situ* conservation measures are needed to prevent irreversible loss. Several recent studies support the effectiveness of *in vitro* propagation for *Tulipa* species. For instance, the efficient adventitious bulblet formation in *T. tarda* using callus cultures under specific hormone and sucrose conditions (28). The highlighted optimized shoot induction protocols and microbulb formation in different *Tulipa* cultivars, emphasizing the importance of cytokinin concentration and explant type (28, 29). A regeneration protocol was developed via somatic embryogenesis, enhancing mass propagation potential (31). The tailored combinations of growth regulators and carbohydrate sources significantly improve multiplication efficiency in *T. gesneriana* cv.'Heart of Warsaw' (32). Recent works on *T. orthopoda* and *T. bifloriformis* also confirms the value of tissue culture for rare tulip species using advanced sterilization, hormonal and antibiotic treatments (33). These studies collectively demonstrate the potential of *in vitro* techniques for conservation and large-scale propagation of tulips.

By integrating bioclimatic modeling with conservation planning, this research provides a scientific foundation for protecting endemic tulips in Uzbekistan. It is important to note that the MaxEnt model assumes niche conservatism and does not account for future genetic adaptation or phenotypic plasticity. While natural selection may enable some level of adaptation to new climatic conditions, *T. ingens* is considered an ecologically specialized species with limited plasticity and dispersal ability. As such, the modeled projections reflect climatic suitability based on current niche parameters and should be interpreted as potential, not definitive, distribution forecasts.

The projections and maps generated in this study can inform regional biodiversity strategies and climate adaptation planning. Furthermore, future research could explore the use of biosensor-based monitoring systems (34) to detect early environmental stress signals in tulip habitats, enhancing proactive management efforts (35).

Overall, the study underscores the urgency of implementing climate-adaptive and species-specific conservation strategies. Protecting *T. fosteriana* and *T. ingens* not only supports biodiversity in Central Asia but also strengthens ecosystem resilience in the face of ongoing environmental change.

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Authors' contributions

RSh contributed to the writing of the manuscript and its submission to the journal; ST carried out the modeling processes of the article using software tools; ZU participated in the structuring and writing of the manuscript; BB provided practical assistance during the implementation of the research; NT provided financial support for the research work; MN contributed to ensuring compliance with ethical standards and legal regulations related to the study; BX assisted with the provision of technical equipment; MN also helped identify the locations of plant materials in their natural habitats; ND supervised the research process, in particular the collection of data from statistical sources.

Compliance with ethical standards

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

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