Journal of Asia-Pacific Biodiversity xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Asia-Pacific Biodiversity

journal homepage: http://www.elsevier.com/locate/japb

Original Article

Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?

Dekhkonov Davron [a,b,†], Asatulloev Temur [a,c,†], Tojiboeva Umida [d], Idris Sari [e], Abdupattaeva Shoxida [a], Abdullayev Shuxrat [a], Sun Weibang [c], Yusupov Ziyoviddin [b], Tojibaev Sh. Komiljon [b,*]

[a] Namangan State University, Namangan, 60107161, Uzbekistan
[b] Institute of Botany, Academy of Sciences of the Republic of Uzbekistan, Tashkent, 100125, Uzbekistan
[c] Yunnan Key Laboratory for Integrative Conservation of Plant Species with Extremely Small Populations, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming, Yunnan, 650201, China
[d] Key Laboratory for Plant Diversity and Biogeography of East Asia, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming, Yunnan, 650201, China
[e] Department of Biology, Faculty of Science and Art, Erzincan Binali Yıldırım University, Erzincan, 24100, Turkey

ARTICLE INFO

Article history:
Received 9 March 2024
Received in revised form
5 May 2024
Accepted 10 May 2024
Available online xxx

Keywords:
climate change
conservation
maximum entropy
species distribution model (SDM)
Tulipa

ABSTRACT

Tulipa (Liliaceae) is a well-known ornamental plant that supports a horticultural trade worth over a billion euros. Existing research highlights the expanding array of risks faced by *Tulipa* species, with climate change emerging as a significant and escalating threat. However, the fate of phytogeographically restricted red-flowering species of tulips in the Pamir-Alay mountain system is crucial, as they are also harvested by local people or visitors purely for their ornamental attractiveness. To study this, 41 bioclimatic and ecologic variables were utilized in the investigation. The suitable areas for *T. ingens* are expected to increase nearly twofold, while for *T. affinis* and *T. carinata*, they will remain constant. However, suitable habitats for *T. tubergeniana* are projected to decrease considerably. Surprisingly, the western Tian-Shan, where these species are not native, was highlighted as climatically suitable and may be an important area for translocation efforts in the future for *T. affinis, T. carinata*, and *T. ingens*. We also identified protected areas that could provide suitable habitats for these species. Additionally, we recommend creating living collections of *T. tubergeniana*, given the significant decrease in suitable habitat. Ultimately, relocating these species to protected regions with projected suitable habitats plays a crucial role in supporting their survival.

© 2024 National Science Museum of Korea (NSMK) and Korea National Arboretum (KNA), Publishing Services by Elsevier. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Introduction

Tulips (*Tulipa* spp.) are among the most popular and diverse ornamental plants in the world, with around 76–87 (Zonneveld 2009; Christenhusz et al. 2013) species distributed from Central Asia to southern Europe and northern Africa. Most species of wild tulips are native to Central Asia (Christenhusz et al. 2013; Tojibaev and Beshko 2014; Tojibaev et al. 2022), a region that harbors a high level of plant endemism and biodiversity (Li et al. 2020), but also faces severe environmental and socio-economic challenges (Asatulloev et al. 2023; Dekhkonov et al. 2023a; Dekhkonov et al. 2023b; Wilson et al. 2021). A previous study (Khassanov 2019) found that wild tulips are often neglected and threatened by various factors, such as habitat loss, overgrazing, climate change, and illegal collection. Therefore, the conservation of wild tulips in Central Asia is of great importance for preserving the genetic diversity and evolutionary potential of this charismatic genus, as well as for maintaining the ecological integrity and cultural heritage of the region (Wilson 2023).

Protected areas, such as national parks, nature reserves, and biosphere reserves, serve as safe habitats for endangered plants (Joseph et al. 2020). These areas provide undisturbed habitats where species can thrive without direct human interference. Fragmentation due to urbanization, agriculture, and infrastructure isolate plant populations. This isolation reduces genetic exchange

* Corresponding author. ORCID.: 0000-0003-2846-5777
E-mail address: ktojibaev@mail.ru (TS Komiljon).
Peer review under responsibility of National Science Museum of Korea (NSMK) and Korea National Arboretum (KNA).
† Both authors equally contributed.

https://doi.org/10.1016/j.japb.2024.05.005
pISSN2287-884X eISSN2287-9544/© 2024 National Science Museum of Korea (NSMK) and Korea National Arboretum (KNA), Publishing Services by Elsevier. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

and increases vulnerability. Translocation into protected areas bridges these gaps, connecting fragmented populations and promoting gene flow (Magro et al. 2023). Such as in Uzbekistan, especially, there are several protected areas that are currently maintaining endangered wildlife to survive or recover their populations (Djurayev and Kurbanova 2024). For both endangered plant and animal species, protected areas can be important habitats. However, whether they provide suitability for these species or not is considered a scientific challenge. The most useful way is to develop climatic scenarios based on distribution models.

One of the main tools for assessing the conservation status and planning conservation actions for endangered plant species, including wild tulips, is species distribution modeling (SDM), which uses environmental variables and occurrence records to predict the potential distribution and suitable habitat of a species (Wilson et al. 2021; Pearson et al. 2014). Among the various methods of SDM, maximum entropy (MaxEnt, Phillips et al. 2006) is a widely used and robust technique that has been successfully applied to model the distribution of many plant species, including tulips. MaxEnt estimates the most uniform distribution across the study area, subject to the constraints that the expected value of each environmental variable under this distribution matches its empirical average over the occurrence records (Phillips et al. 2006). MaxEnt can also incorporate different types of environmental variables, such as climatic, topographic, and biotic factors, and can produce different types of model outputs, such as probability of presence or habitat suitability (Elith et al. 2006).

Previous outstanding research on Central Asian tulips, where most of them are concentrated in western Tian-Shan, determined that suitable habitats for nine species will notably decrease. In addition, Asatulloev et al. (2022) used ecological niche modeling to determine the ecological distribution of five species of *Tulipa* sect. *Kolpakowskianae* in western Tian-Shan, *T. ferganica*, *T. intermedia,* and *T. scharipovii,* and suggested possible places to translocate if extinction risk will appear in their current territory. However, there is a gap in the current and future status of species of *Tulipa* in the Pamir-Alay mountain system, represented mainly by *Tulipa* sect. *Lanatae* (Raamsd) Zonn. Hence, in this study, we used MaxEnt to model the distribution of four endangered species of *Tulipa*, *T. affinis*, *T. carinata*, *T. ingens* and *T. tubergeniana* (nationally, Khassanov 2019) with unique morphologic (Dekhkonov et al. 2022) and phytogeographical characteristics (Asatulloev et al. 2023; Dekhkonov et al. 2021). However, these species were assessed by the IUCN Red List as following: *T. affinis* and *T. carinata* as VU (vulnerable) (Wilson et al. 2022a; 2022b), *T. ingens* and *T. tubergeniana* as NT (near threatened) (Wilson et al. 2022c; 2022d). The species concepts used in this study follow the morphological descriptions of Tojibaev et al. (2022) and checked Plants of the World Online (POWO; https://powo.science.kew.org/results?q=Tulipa) whether they are accepted or not.

The aims of this study were:

- to model the current and future distributions of these species across different climate change scenarios.
- To identify suitable protected areas for translocation efforts to mitigate threats.

Material and methods

Data collection

The distribution data of the species of *Tulipa* were based on specimens in the herbaria National Herbarium of Uzbekistan (TASH), The Herbarium Fund of the Institute of Botany, Plant Physiology and Genetics of Tajikistan (TAD) and Institute of Biology, Bishkek, Kyrgyzstan (FRU) and in the Global Biodiversity Information Facility (GBIF) database (GBIF, 2023). Our field studies were conducted from 2020 to 2023 in diverse regions of Uzbekistan, Kyrgyzstan, and Tajikistan. We used a Global Positioning System (GPS) to record the locations of the populations we studied. All the collection records were checked to see whether they have unreliable points that were removed by utilizing the 'enmSdm' R package to mitigate errors in the subsequent analysis (Morelli et al, 2020). Ultimately, 31 locations for *T. tubergeniana*, 53 for *T. ingens*, 70 for *T. affinis*, and 29 for *T. carinata* were obtained to build the SDM of each species. Photos of the study objects are shown in Figure 1.

Preparing and choosing predictor variables

A total of 41 variables were used in this study, encompassing 19 bioclimatic (Fick and Hijmans 2017), 18 Envirem (Title & Bemmels 2018), 3 topographic, and soil data (Fischer et al. 2008). Bioclimatic variables were obtained from the Worldclim website at a 30 arcsec resolution and cropped. Additional topographic variables were either created or obtained, as detailed in Appendices A and B.

Central Asia the correlations between all the variables were assessed using Spearman correlation analysis implemented in the SDMtune package in R software (R Core Team 2013; Vignali et al. 2020), and we removed the variables that have a Spearman correlation coefficient $|rs| \leq 0.7$. Variable importance was determined by employing the 'SDMTune' R package, which included functions for variable selection during the modeling pre-processing phase for variable selection through cross-validated maximum entropy modeling, 'using the predictions from the R libraries and the correlations between variable pairs, we pinpointed several sets of variables that could be influential in the current distribution of each species. Subsequently, the 'Ellipsenm' R package (Cobos et al. 2019) was employed to evaluate and select the best model according to the criteria, where the best model was the one statistically significant, with low omission rates and low prevalence by calibrating candidate models. All variables that were predicted to be included in the distribution models fitted can be seen in Appendix B.

Modeling species niches and future predictions (CCMs)

Maximum entropy is the one of the most well-known and extensively utilized techniques in scientific research for SDM (Fitzpatrick et al. 2013; Fourcade et al. 2014). In the model processing stage, we used the SDMtune package for SDM and climate change modeling (CCMs). During modeling the niches of tulips with limited data, the performance of algorithms can be influenced by how pseudo-absences are distributed across the calibration area (Barbet-Massin et al. 2012). A 20 km radius buffer zone was created around each record for all species, taking into account their ecology, dispersal capabilities, and geographical barriers.

To achieve unbiased and robust model outputs for all distribution modeling, we employed several techniques, including: (1) using target-background sites instead of random background sites: this reduces bias by selecting background locations that are ecologically similar to the areas where the species might occur (Phillips et al. 2009). Evaluating models using random cross-validation: this assesses model performance by splitting the data into training and testing sets, ensuring the model generalizes well to unseen data (Elith et al. 2006). (3) Analyzing geographic space for the degree to which predictions are extrapolated using Multivariate Environmental Similarity Surface plots: this helps to identify areas where the model predictions are based on environmental conditions outside the range of the training data (Elith et al. 2010).

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

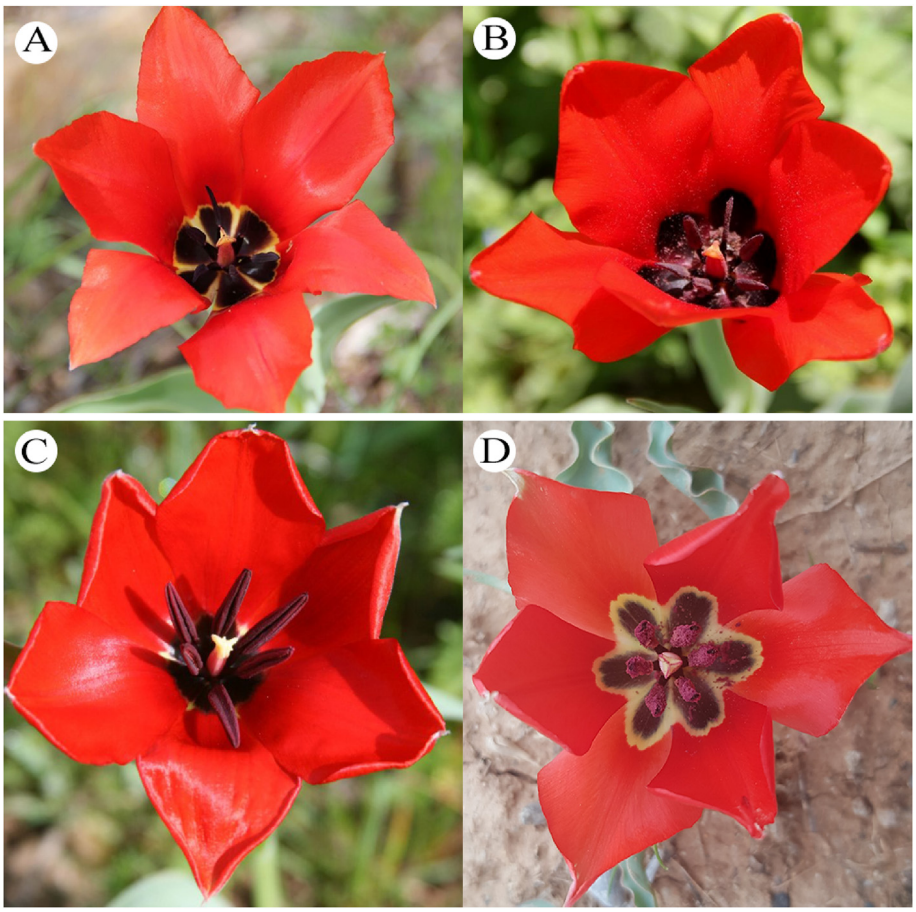


Figure 1. A, *T. affinis*; B, *T. ingens*; C, *T. carinata*; D, *T. tubergeniana*.

A Maxent premodel was constructed using environmental variables, allocating 25% of the data for testing and 75% for training.

For climate change modeling, we selected the Beijing Climate Center (BCC) BCC-CSM2-MR model (Wu et al. 2021). The scenarios employed were the Shared Socioeconomic Pathways (SSPs), which are important inputs for the latest global climate models (Riahi et al. 2017). The shared socio-economic pathway scenarios are based on narratives describing various socio-economic developments, such as sustainable growth, regional competition, inequality, fossil-fueled development, and moderate progress. For modeling future plant species distributions, we considered SSP2_45 and SSP5_85 as climate scenarios. Notably, SSP2_45 differs from SSP5_85 due to its higher CO_2 emissions. We utilized three global circulation models (MIROC-ES2L, MIROC6, and MRI-ESM2-0) to represent the two concentration pathways (ssp245 and ssp585). Accordingly, using the SSP2_45 and SSP5_85 scenarios, we predicted the potential future distribution areas of the species for the time periods 2041 to 2060 (averaged for 2050) and 2081 to 2100 (averaged for 2090), respectively. Finally, we calculated the combined area of all the predicted regions, ranging from unsuitable to highly suitable, for both the current and future distribution areas of the species based on the SDM and CCMs employed in our projections.

Model evaluation and creating suitability maps

For model evaluation, we used area under the curve (AUC) and true skill statistics (TSS) in all ecological niche models (ENMs) and climate change models (CCMs) of the species. Threshold values were established as follows: Values $\geq$ 0.9 were best, 0.9 $>$ Values $\geq$ 0.8 very good, 0.8 $>$ Values $\geq$ 0.7 good, and Values $<$ 0.7 weak (Allouche et al. 2006; Leroy et al. 2018). We employed these four threshold values in the creation of maps for the species, where '0–0.25' represents unsuitable areas, '0.25–0.5' indicates areas of low suitability, '0.5–0.75' signifies areas of moderate suitability, and '0.75–1' denotes highly suitable areas following Shrestha and Bawa (2014).

The elevation ranges were calculated using the GPSVisualizer tool (https://www.gpsvisualizer.com/elevation) for each species using all available coordinates. Protected areas of Uzbekistan were derived from the Protected Planet database (UNEP-WCMC and IUCN 2024).

Results

In this study, we modeled current (Figure 2) and future prediction (CCMs) (Figure 3) projections for four species of *Tulipa* sect. *Lanatae*. First, the accuracy of the MaxEnt models was assessed using AUC and TSS (Table 1).

The model AUC and TSS values varied from 0.96 to 0.99 and 0.85 to 0.95, respectively. We removed highly correlated variables and determined important variables (used in the modeling) as following: for *T. tubergeniana* were bio13 (precipitation of the wettest month), bio15 (precipitation seasonality), bio7 (temperature annual range), PETWettestQuarter (potential evaporation of wettest quarter), for *T. affinis* were bio16 (precipitation of wettest quarter), bio18 (precipitation of warmest quarter), bio2 (mean Diurnal Range), and bio3 (isothermality), for *T. carinata* were bio19 (mean temperature of driest quarter), bio14 (precipitation of driest month), bio2, bio3, for *T. ingens* were the aridity index of

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

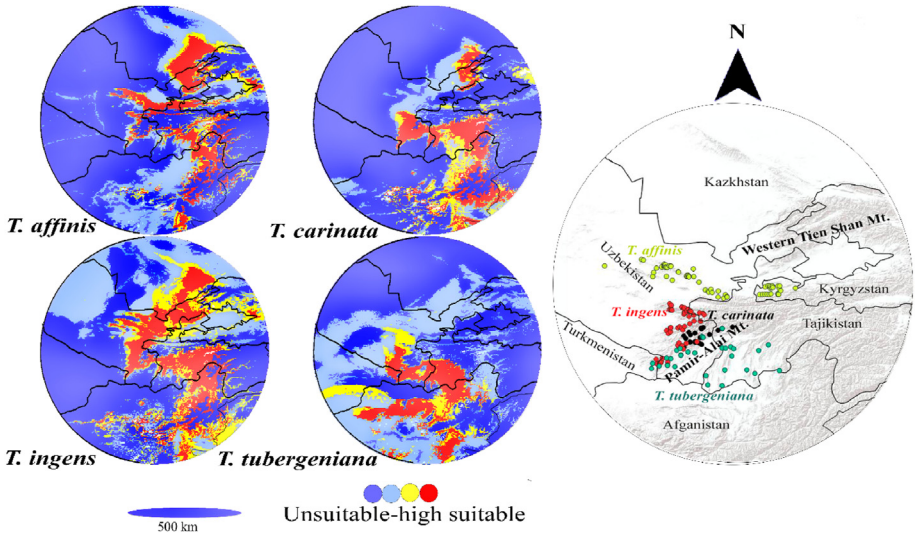


Figure 2. Current SDM of the selected species. SDM = species distribution model.

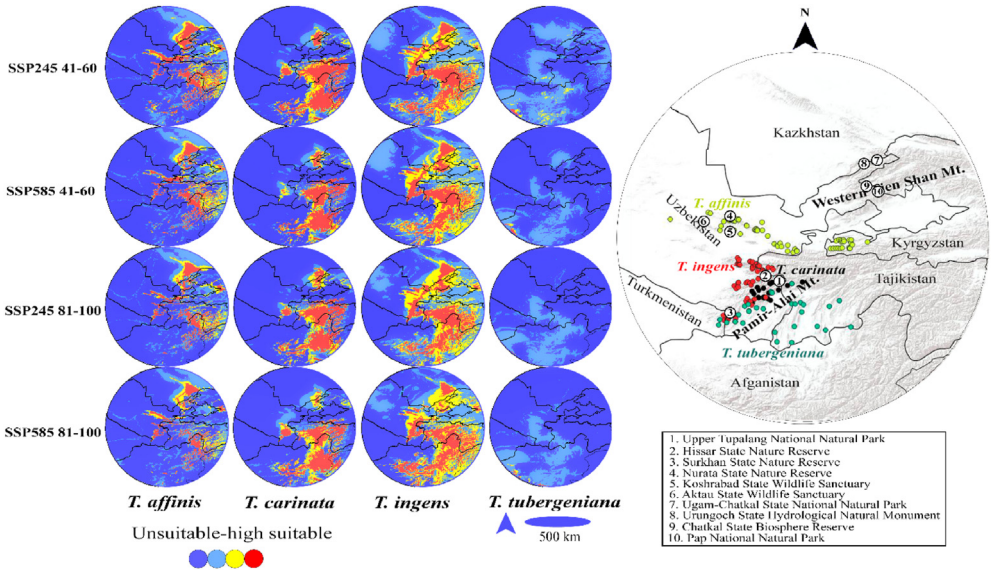


Figure 3. Future CCMs of the selected species and protected areas. CCMs = climate change models.

Thornthwaite (aridity index of Thornthwaite), bio19, bio14, and bio2 (permutation importance can be seen in Appendix C).

Our model projections indicated that while the Pamir-Alay region contains the vast majority of areas with a highly suitable climate, neighboring regions contain a majority of areas with low or unsuitable climates for all four species of *Tulipa* species in current scenarios.

Interestingly, other Central Asian mountain ranges, such as the Tian-Shan (Chatkal, Pskem, and some parts of the Karatu ranges) and Hindu-Kush also exhibits climatic conditions conducive to *T. affinis, T. carinata,* and *T. ingens*, albeit beyond their current native range. For *T. tubergeniana*, the Pamir-Alay and Hindu Kush mountains were determined to be suitable. SSP2_45 and SSP5_85 scenarios predicted almost similar expansion and contraction of suitable habitats for all species. In the future, according to the results from both scenarios, suitable areas for *T. ingens* will increase nearly twofold, and for *T. affinis* and *T. carinata,* it will remain constant, while for *T. tubergeniana,* it will decrease greatly (Figure 3 and Table 2).In the future, the following protected areas have been designated as suitable habitats: Upper Tupalang National Natural Park, the Surkhan State Nature Reserve, Nurata State Nature Reserve, Aktau State Wildlife Sanctuary, and Koshrabad State Wildlife Sanctuary are suitable for *T. affinis*. Meanwhile, Surkhan State Nature Reserve and the Hissar State Nature Reserve are identified as suitable for *T. carinata*, and Hissar State Nature Reserve, Upper Tupalang National Natural Park, and Babatag National Natural Park are determined to be suitable for *T. ingens*.

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

Table 1. Assessment of MaxEnt models accuracy.

Models	*T. affinis*	*T. carinata*	*T. ingens*	*T. tubergeniana*
AUC	0.96	0.96	0.98	0.97
TSS	0.89	0.85	0.93	0.91

AUC = area under the curve; TSS = true skill statistics.

Table 2. Unsuitable-high suitable area (km^2) under current and different future projections (SSP2_45 and SSP5_85 are moderate and normal development scenarios, respectively).

Scenarios	Unsuitable	Low suitable	Suitable	High suitable
T. affinis				
Current	526,390	190,403	57,581	105,937
SSP2_45 41-60	655,067	181613	71,537	100,518
SSP5_85 41-60	683,861	17,7825	67,599	79,456
SSP2_45 81-100	705,483	170,566	60,801	71,895
SSP5_85 81-100	721,018	173,632	51,797	62,326
T. carinata				
Current	609,181	105,369	67166	98,625
SSP2_45 41-60	695,902	92,599	70,147	149,973
SSP5_85 41-60	744,466	90,870	52,520	120,854
SSP2_45 81-100	718,609	86,224	70,180	133,639
SSP5_85 81-100	689,999	121,299	76,038	121,308
T. ingens				
Current	352,316	246,990	133,819	147,025
SSP2_45 41-60	401,452	283,357	164,715	159,003
SSP5_85 41-60	389,413	272,209	195,218	151,987
SSP2_45 81-100	396,131	252,293	204,194	156,036
SSP5_85 81-100	414,150	225,877	206,971	161,681
T. tubergeniana				
Current	395,376	328,493	63,073	93,959
SSP2_45 41-60	651,711	338,921	15,442	2719
SSP5_85 41-60	831,637	172,405	2222	2609
SSP2_45 81-100	811,191	196,841	339	455
SSP5_85 81-100	812,521	189,406	3124	3913

Table 3. Altitude range of studied species in m a.s.l.

Species	Altitude (max)	Altitude (min)
T. affinis	2600	411
T. carinata	3330	747
T. ingens	3569	957
T. tubergeniana	1732	422

We also determined the altitude range of selected species in this study (Table 3). According to the results, *T. carinata* and *T. ingens* prefer higher altitudes occurring between 747–57 m a.s.l. to 3339–3569 m a.s.l., respectively. *Tulipa affinnis* and *T. tubergeniana* thrive between 411–422 m a.s.l. to 2600–1732 m a.s.l., respectively.

Discussion

In this study, we assessed the present and projected future suitable habitats for four wild tulip species found in the Pamir-Alay mountains. The general results showed that tulips deemed native to Pamir-Alay may grow in western Tian-Shan, according to the models. These findings were obtained by Wilson et al. (2021) when ten species of *Tulipa* in western Tian-Shan and adjacent areas were modeled using the MaxEnt approach. Their results showed that Pamir-Alay can provide suitable habitats for some of those species as well. Because Tian-Shan and Pamir-Alay mountains exhibit similar climatic conditions in specific regions, potentially enabling species native to one range to thrive in the other. However, additional factors not accounted for in species distribution models could hinder their survival in these habitats. Below, we discuss the main findings of this study for each species.

Recommendations to conserve species based on modeling

Tulipa affinis mostly occurs in the Nuratau mountains, a northwestern branch of the Pamir-Alay, Malguzar, and Turkestan ridges (Uzbekistan, Kyrgyzstan, and Tajikistan). *Tulipa affinis* is typically found on the fine-earth, stony slopes of the mid-mountains with shrubs and in juniper forests. It thrives in direct sunlight and tends to grow in open areas on slopes where other shrubs are absent. Some populations of *T. affinis* are commonly clustered together in specific areas of a slope that offer optimal conditions for their growth. Currently, *T. affinis* populations are affected by anthropogenic threats such as urbanization, agricultural expansion, overexploitation, and overgrazing (Khassanov 2019, pp. 141; Hisoriev 2017; Shukurov 2006). Even microbial invasion was also witnessed for this species (Dekhkonov et al. 2023a). Our model highlighted no significant loss of suitable habitat for this species in the future. However, other threats may lead to populations decline. Thus, we infer here that to mitigate population decrease, stakeholders must control anthropogenic threats to populations. The populations can also be translocated to higher elevations (till 2600–2800 m a.s.l.) where anthropogenic impact cannot reach. We also concluded that *T. affinis* can be introduced into Upper Tupalang National Natural Park and the Surkhan State Nature Reserve in the Pamir-Alay Mts. or to Nurata State Nature Reserve, Aktau State Wildlife Sanctuary, and Koshrabad State Wildlife Sanctuary, as both elevation and environmental conditions enable it to adapt to these habitats. Additionally, the western Tian-Shan mountains, which are included in the territories of Uzbekistan and Kazakhstan, may provide stable habitat for *T. affinis*, as highlighted by our model.

Tulipa carinata is endemic to the SW Pamir-Alay region, which covers Tajikistan, Turkmenistan, Uzbekistan, and Afghanistan (Botschantzeva, 1962). In Uzbekistan, it is in the Kughitang and Hissar ranges, as well as in the Baysun mountains (Tojibaev and Kadirov, 2010). It typically thrives in habitats with fine earth, stony slopes, and rock ledges (Pechenitsyn et al. 2020). The main threats are urbanization and overgrazing. It can be found in Surkhan State Nature Reserve (Dekhkonov et al. 2023a). Our model showed that suitable habitats for *Tulipa carinata* will increase in the future. Even when we used coordinates that are mostly within southern Uzbekistan, the model predicted that western Kyrgyzstan and the northern Afghanistan parts of the Pamir-Alay can be most suitable habitats and maybe even potential territory for translocation for *Tulipa carinata*. Furthermore, our model highlighted the Kurama and Chatkal ranges of western Tian-Shan are suitable for this species. In Uzbekistan, in addition to the Surkhan State Nature Reserve, the Hissar State Nature Reserve can also provide suitable habitat for the translocation of *T. carinata*. Translocation ranges of 3000 m–3500 m a.s.l. elevation can be considered suitable.

Tulipa ingens grows around or in juniper forests on rocky slopes and in red clays in the Hissar and Baysuntau ranges of western Pamir-Alay and in the Surkhan State Nature Reserve, and the main threats are urbanization, agriculture, overgrazing, and parasitism

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

(Dekhkonov et al. 2023a; Tojibaev and Kadirov, 2010; Hisoriev, 2017). As our model predicted, suitable habitat will slightly increase for *T. ingens* in the future (however, the territory of the Surkhan State Nature Reserve is not included in this expansion). *Tulipa ingens* can be translocated to the Hissar State Nature Reserve, Upper Tupalang National Natural Park and Babatag National Natural Park. The same as for the two previous species of *Tulipa*, the western Tian-Shan is also predicted to be suitable, even though *T. ingens* does not occur there now. For introductions, elevation should also be considered an important factor. The selected territory must be within 1000 m−3500 m a.s.l.

Tulipa tubergeniana is endemic to the SW Pamir-Alay (Tajikistan, Uzbekistan); it is in various regions of Uzbekistan, such as the Hissar, Kughitang, and Babatag ranges and in the Baysun Mts. (Botschantzeva, 1962). It typically thrives in habitats characterized by outcrops of variegated beds, clayey slopes, among pistachio stands, in the foothills and in the lower mountain belt (Pechenitsyn et al, 2020). The main threats to *T. tubergeniana* are urbanization and agriculture. From 2013 to 2017, urban development led to the disappearance of 38% (10 out of 26) of the populations of *T. tubergeniana* in the foothills of Pashkhurt village in the Sherabad district and currently it is also protected in the Surkhan State Nature Reserve (Dekhkonov et al. 2023a; Shukrullozoda et al. 2023). In Tajikistan, this species lacks study; however, is threatened by agriculture, overgrazing, and illegal harvesting (Hisoriev 2017). Unfortunately, our model showed that suitable habitat for *T. tubergeniana* will decrease by 95%−96% within the next 80 years. Thus, urgent conservation action must be taken, including establishing ex-situ collections in botanical gardens.

Limitations of the model

Despite our valuable climatic modeling, this study has several limitations related to species-environment relationships (Kaky et al. 2020), land use changes, and invasive species (Early et al. 2016). Also, we couldn't get the occurrence point from Afghanistan as it is unavailable and used in the modeling. Additionally, certain geographic barriers—such as mountains, deserts, and urbanized areas—often impact species distribution ranges, but are typically overlooked. For instance, our model suggests that the western Tian-Shan mountains could be suitable for three of the studied species, even though the Pamir-Alay mountains serve as their primary habitat. However, between the Pamir-Alay and western Tian-Shan mountains lie numerous urbanized territories and agricultural lands, which act as significant barriers to species dispersal. Also, our model showed western Tian-Shan is suitable for three species; however, it must be checked to see if this mountain can provide suitable habitat for them, comparing specific properties with the Pamir-Alay mountains. To enhance accuracy, future research should consider a broader range of relevant factors (both abiotic and biotic) and explore more adaptable algorithms. Additionally, investigating species responses during the Last Glacial Maximum and the mid-Holocene will provide further insights into their adaptation to climate change (Breiner et al. 2015; Wang et al. 2017).

Conclusion

Tulips are highly ornamental plants that are valued for their renowned beauty. Previous studies emphasize that wild tulips, which serve as the ancestors of cultivated varieties face risks due to various human-induced activities such as overgrazing and excessive exploitation. To better understand the anthropogenic threats and the impacts of climate change on four large red-flowering species of tulip of particular interest to people we used species distribution modeling to develop current and predict future distributions. Our research findings reveal that three out of the four modeled tulip species do not exhibit a decline in suitable habitat areas due to climate change. However, our models indicate that *T. tubergeniana* will experience a significant reduction in its habitat. While climate change impacts tulip species, the effects are not always consistent across all species. Despite some species remaining unaffected by climate change, they still face threats from human activities. Consequently, we have identified several protected areas that could serve as secure habitats based on their modeled ranges. Interestingly, although the Pamir-Alay mountains cover much of the native range for these species (as supported by our models), areas in the Hindu Kush and western Tien-Shan also offer potentially suitable climates for translocation efforts. These proposed conservation measures warrant further investigation for feasibility but could enhance the survival prospects of these species in the face of both climate-related and anthropogenic threats.

CRediT authorship contribution statement

Dekhkonov Davron: Writing − original draft, Formal analysis, Conceptualization. **Asatulloev Temur:** Writing − original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Tojiboeva Umida:** Resources, Methodology, Investigation, Formal analysis. **Idris Sari:** Visualization, Methodology. **Abdupattaeva Shoxida:** Investigation. **Abdullayev Shuxrat:** Investigation. **Sun Weibang:** Writing − review & editing, Conceptualization. **Yusupov Ziyoviddin:** Writing − review & editing, Supervision. **Tojibaev Sh. Komiljon:** Writing − review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Acknowledgments

This study was carried out with the support of Taxonomic revision of polymorphic plant families of the flora of Uzbekistan (FZ-20200929321) and Tree of Life: Monocots of Uzbekistan (PFI-5). We thank David Boufford of Harvard University for his kind help with the English editing.

References

Allouche O, Tsoar A, Kadmon R. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of applied ecology* 43:1223−1232.

Asatulloev T, Dekhkonov D, Tojibaev K. 2022. What determines the distribution of *Tulipa* species in Uzbekistan? *Plant Diversity of Central Asia* 1:127−137.

Asatulloev T, Dekhkonov D, Yusupov Z, et al. 2023. Ecoregional and phytogeographical insights into the distribution of Tulipa in the 'Nature Imperiled' area of Central Asia for effective conservation. *Diversity* 15:1195.

Barbet-Massin M, Jiguet F, Albert CH, et al. 2012. Selecting pseudo-absences for species distribution models: How, where and how many? *Methods in Ecology and Evolution* 3:327–338.

Boehner J, Koethe R, Conrad O. 2002. Soil regionalisation by means of terrain analysis and process parameterisation. In: Micheli E, Nachtergaele F, Montanarella L, editors. *Soil Classification 2001*. Luxembourg: European Soil Bureau, Research Report No. 7, EUR 20398 EN. pp. 213–222.

Botschantzeva Z. 1962. *Tulips. Taxonomy, morphology, cytology, phytogeography and physiology (Russian edn)*. Rotterdam: Balkema. English translation: Varekamp H (1982).

Breiner FT, Guisan A, Bergamini A, et al. 2015. Overcoming limitations of modelling rare species by using ensembles of small models. *Methods in Ecology and Evolution* 6:1210–1218.

Christenhusz MJ, Govaerts R, David JC, et al. 2013. Tiptoe through the tulips–cultural history, molecular phylogenetics and classification of Tulipa (Liliaceae). *Botanical Journal of the Linnean Society* 172:280–328.

Cobos M, Osorio-Olvera L, Soberon J. 2019. Ellipsenm: an R package for ecological niche's characterization using ellipsoids. Version R package version 0.3.4, https://github.com/marlonecobos/ellipsenm. [Accessed 27 October 2023].

Dekhkonov D, Asatulloev T, Akbarov F, et al. 2023a. Conservation strategy and diversity of Tulipa (Liliaceae) in Uzbekistan. *Plant Diversity of Central Asia* 4:1–42.

Dekhkonov D, Asatulloev T, Tojiboeva U, et al. 2023b. Suitable habitat prediction with a huge set of variables on some Central Asian tulips. *Journal of Asia-Pacific Biodiversity* 16:75–82.

Dekhkonov D, Tojibaev K, Yusupov Z, et al. 2022. Morphology of tulips (Tulipa, Liliaceae) in its primary centre of diversity. *Plant Diversity of Central Asia* 1:52–70.

Dekhkonov D, Tojibaev KS, Makhmudjanov D, et al. 2021. Mapping and analyzing the distribution of the species in the genus Tulipa (Liliaceae) in the Ferghana Valley of Central Asia. *Korean Journal of Plant Taxonomy* 51:181–191.

Djurayev ME, Kurbanova CT. 2024. Protected areas in wilderness landscapes and ensuring ecological security in Uzbekistan. *Journal of Geography and Natural Resources* 4:146–152.

Early R, Bradley BA, Dukes JS, et al. 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature communications* 7:12485.

Elith J, Graham C, Anderson R, et al. 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography* 29:129–151.

Elith J, Kearney MR, Phillips SJ. 2010. The story of MaxEnt: Combining proximate and mechanistic models for ecology. *Ecography* 33:169–177.

Fick SE, Hijmans RJ. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37:4302–4315.

Fischer G, Nachtergaele F, Prieler S, et al. 2008. *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)*. Laxenburg, Austria: IIASA. FAO, Rome.

Fitzpatrick MC, Gotelli NJ, Ellison AM. 2013. MaxEnt versus MaxLike: empirical comparisons with ant species distributions. *Ecosphere* 4:1–15.

Fourcade Y, Engler JO, Rödder D, et al. 2014. Mapping species distributions with MAXENT using a geographically biased sample of presence data: a performance assessment of methods for correcting sampling bias. *PLoS One* 9:e97122.

GBIF. 2023. GBIF Occurrence Download. https://doi.org/10.15468/dl.2nbp94. [Accessed 1 June 2023].

Hisoriev H. 2017. *The Red Book of the Republic of Tajikistan*. 2nd ed. Dushanbe: Ganch press.

Kaky E, Nolan V, Alatawi A, et al. 2020. A comparison between Ensemble and MaxEnt species distribution modelling approaches for conservation: A case study with Egyptian medicinal plants. *Ecological Informatics* 60:101150.

Khassanov F. 2019. *The Red Data Book of the Republic of Uzbekistan. Volme 1. Plants*. Tashkent: Chinor ENK Press.

Leroy B, Delsol R, Hugueny B. 2018. Without quality presence–absence data, discrimination metrics such as TSS can be misleading measures of model performance. *Journal of Biogeography* 45:1994–2002.

Li W, Tojibaev KS, Hisoriev H, et al. 2020. Mapping Asia Plants: Current status of floristic information for Central Asian flora. *Global Ecology and Conservation* 24:e01220.

Magro MA, de Souza LJ, Rocha AB, et al. 2023. Genetic Management Applied to Conservation of Reduced and Fragmented Wild Populations. In: *Conservation Genetics in the Neotropics*. Cham: Springer International Publishing. pp. 227–249.

Metzger MJ, Bunce RG, Jongman RH, et al. 2013. A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. *Global Ecology and Biogeography* 22:630–638.

Morelli TL, Smith AB, Mancini AN, et al. 2020. The fate of Madagascar's rainforest habitat. *Nature Climate Change* 10:89–96.

Phillips SJ, Dudík M, Schapire RE. 2009. Modeling species distributions with MaxEnt: New directions and opportunities. *Ecography* 32:250–270.

Pechenitsyn VP, Turgunov MD, Beshko NY, et al. 2020. Rare species of *Tulipa* (Liliaceae) from Tashkent Botanical Garden. *Acta Biologica Sibirica* 6:385–397.

Pearson RG, Stanton JC, Shoemaker KT, et al. 2014. Life history and spatial traits predict extinction risk due to climate change. *Nature Climate Change* 4:217–221.

Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modeling of species geographic distributions. *Ecological modelling* 190:231–259.

R Core Team R. 2013. *R: A language and environment for statistical computing*.

Riahi K, van Vuuren DP, Kriegler E, et al. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009. ISSN 0959-3780.

Rivas-Martínez S, Rivas-Sáenz S. 2009. Synoptical worldwide bioclimatic classification system. www.globalbioclimatics.org/. [Accessed 16 February 2024].

Shrestha UB, Bawa KS. 2014. Impact of climate change on potential distribution of Chinese caterpillar fungus (*Ophiocordyceps sinensis*) in Nepal Himalaya. *PLoS one* 9:e106405.

Shukrullozoda R, Dekhkonov D, Khaydarov Kh, et al. 2023. Analysis of the Distribution of Tulipa fosteriana and Tulipa ingens. The Importance of Protecting Wild Plants, in Particular Tulips All over the World. *American Journal of Plant Sciences* 14:613–624.

Shukurov E. 2006. *The Red Data Book of Kyrgyz Republic*. 2nd ed. Bishkek: State Agency on Environment Protection and Forestry under the Government of Kyrgyz Republic, Institute of Biology and Pedology of National Academy of Sciences of Kyrgyz Republic & Ecological Movement "Aleine" of Kyrgyzstan. p. 543.

Thornthwaite CW. 1948. An approach toward a rational classification of climate. *Geographical review* 38:55–94.

Title PO, Bemmels JB. 2018. ENVIREM: an expanded set of bioclimatic and topographic variables increases flexibility and improves performance of ecological niche modeling. *Ecography* 41:291–307.

Tojibaev K, Beshko N. 2014. Reassessment of diversity and analysis of distribution in *Tulipa* (Liliaceae) in Uzbekistan. *Nordic Journal of Botany* 33:224–234.

Tojibaev K, Dekhkonov D, Ergashov I, et al. 2022. The synopsis of the genus Tulipa (Liliaceae) in Uzbekistan. *Phytotaxa* 573:163–214.

Tojibaev K, Kadirov R. 2010. *Tulips of Uzbekistan*. Tashkent: Shark Press.

UNEP-WCMC and IUCN. 2024. *Protected Planet: The World Database on Protected Areas (WDPA), [May 2024]*. Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

Vignali S, Barras AG, Arlettaz R, et al. 2020. SDMtune: An R package to tune and evaluate species distribution models. *Ecology and Evolution* 10:11488–11506.

Wang S, Xu X, Shrestha N, et al. 2017. Response of spatial vegetation distribution in China to climate changes since the Last Glacial Maximum (LGM). *PLoS ONE* 12:e0175742.

Willmott CJ, Feddema JJ. 1992. A more rational climatic moisture index. The *Professional Geographer* 44:84–88.

Wilson B, Dolotbakov A, Burgess B, et al. 2021. Central Asian wild tulip conservation requires a regional approach, especially in the face of climate change. *Biodiversity and Conservation* 30:1705–1730.

Wilson B, Sultangaziev OE, Beshko N, et al. 2022. *Tulipa affinis. The IUCN Red List of Threatened Species* 2022: e.T215067631A215067667. https://dx.doi.org/10.2305/IUCN.UK.2022-2.RLTS.T215067631A215067667.en. [Accessed 22 April 2024].

Wilson B, Sultangaziev OE, Turakulov T, et al. 2022. *Tulipa carinata. The IUCN Red List of Threatened Species* 2022: e.T184529788A184539233. https://dx.doi.org/10.2305/IUCN.UK.2022-2.RLTS.T184529788A184539233.en. [Accessed 22 April 2024].

Wilson B, Sultangaziev OE, Turakulov T, et al. 2022. *Tulipa ingens. The IUCN Red List of Threatened Species* 2022: e.T184531192A184539288. https://dx.doi.org/10.2305/IUCN.UK.2022-2.RLTS.T184531192A184539288.en. [Accessed 22 April 2024].

Wilson B, Sultangaziev OE, Beshko N, et al. 2022. *Tulipa tubergeniana. The IUCN Red List of Threatened Species* 2022: e.T218305193A218315764. https://dx.doi.org/10.2305/IUCN.UK.2022-2.RLTS.T218305193A218315764.en. [Accessed 22 April 2024].

Wilson B. 2023. *Tulipa: the taxonomy and evolutionary history of the genus and its impact on conservation priorities in Central Asia*. University of Cambridge. p. 258. https://doi.org/10.17863/CAM.94432. Doctoral dissertation.

Wu T, Yu R, Lu Y, et al. 2021. BCC-CSM2-HR: A high-resolution version of the Beijing climate center climate system model. *Geoscientific Model Development* 14:2977–3006. https://doi.org/10.5194/gmd-14-2977-2021.

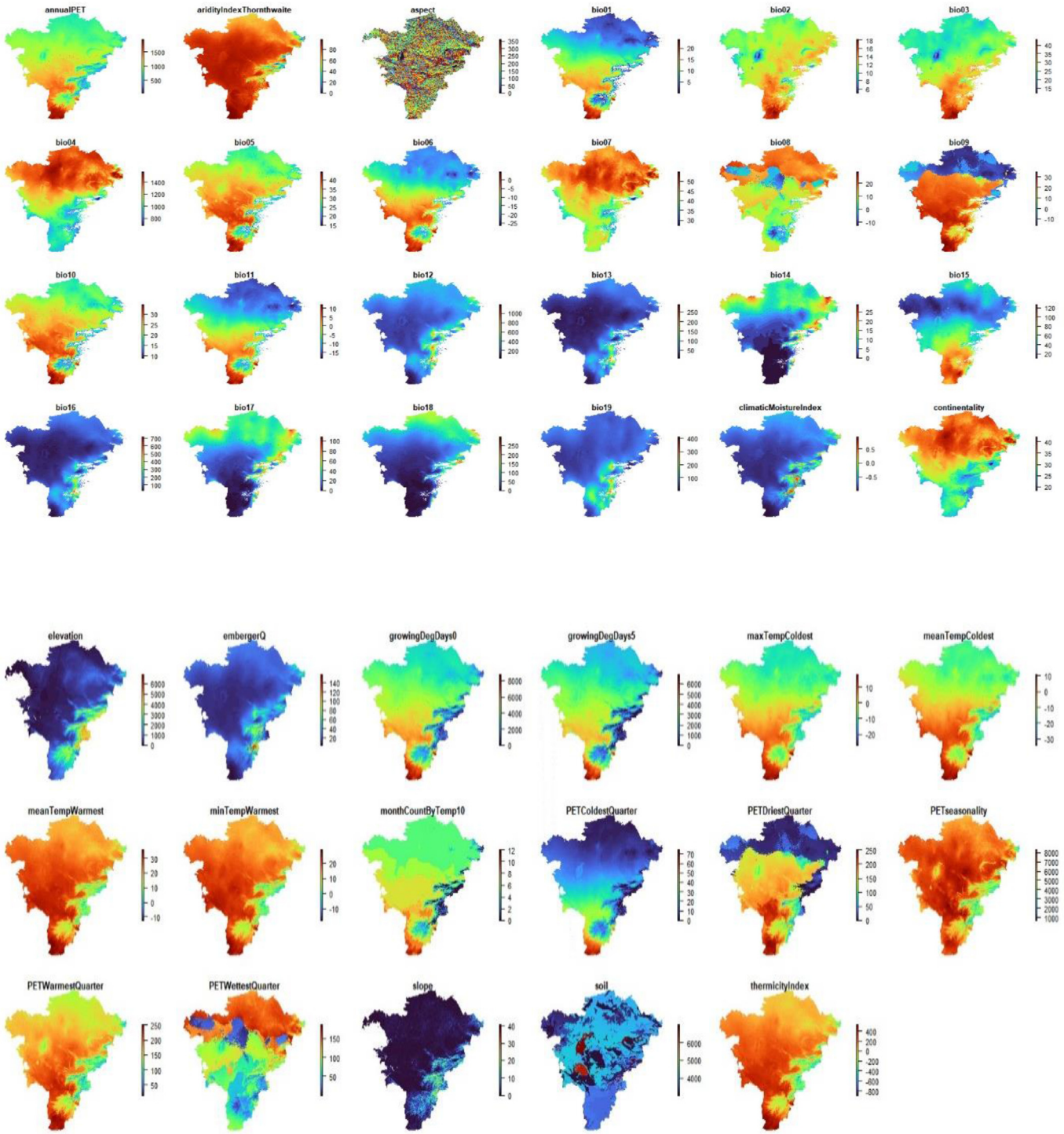
Zomer RJ, Trabucco A, Bossio DA, et al. 2008. Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment* 126:67–80.

Zonneveld BJ. 2009. The systematic value of nuclear genome size for "all" species of *Tulipa* L. (Liliaceae). *Plant Systematics and Evolution* 281:217–245.

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

Appendix

Appendix A. Predictor variables used in modeling studies.



Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

Appendix B. Variables used in modeling studies and recommendations to be included in the models by different methods built in R library.

Variables	Source database	Which R package/packages recommended it to be included in the species ENMs?	Source
BIO1 (annual mean temperature)	Worldclim.org		(Fick and Hijmans 2017)
BIO2 (mean diurnal range)	–	(Ecospat); (Ecospat); (Embarcadero); (Ecospat); (Embarcadero)	(Fick and Hijmans 2017)
BIO3 (isothermality)	–	(Ecospat); (SDMTune); (Embarcadero); (Ecospat); (Ecospat)	(Fick and Hijmans 2017)
BIO4 (temperature seasonality)	–	(Embarcadero); (Ecospat); (Embarcadero); (SDMTune); (Ecospat)	(Fick and Hijmans 2017)
BIO5 (max temperature of warmest month)	–	(Embarcadero)	(Fick and Hijmans 2017)
BIO6 (min temperature of coldest month)	–	(SDMTune); (SDMTune); (Embarcadero); (Ecospat)	(Fick and Hijmans 2017)
BIO7 (temperature annual range)	–	(SDMTune); (Embarcadero)	(Fick and Hijmans 2017)
BIO8 (mean temperature of wettest quarter)	–	(Ecospat); (SDMTune)	(Fick and Hijmans 2017)
BIO9 (Mean Temperature of Driest Quarter)	–		(Fick and Hijmans 2017)
BIO10 (mean temperature of warmest quarter)	–		(Fick and Hijmans 2017)
BIO11 (mean temperature of coldest quarter)	–		(Fick and Hijmans 2017)
BIO12 (annual precipitation)	–		(Fick and Hijmans 2017)
BIO13 (precipitation of wettest month)	–	(SDMTune); (SDMTune)	(Fick and Hijmans 2017)
BIO14 (precipitation of driest month)	–	(Ecospat); (SDMTune); (Embarcadero); (Ecospat)	(Fick and Hijmans 2017)
BIO15 (precipitation seasonality)	–	(SDMTune); (Ecospat); (SDMTune); (Embarcadero); (SDMTune); (SDMTune); (Ecospat); (SDMTune); (Embarcadero); (Ecospat)	(Fick and Hijmans 2017)
BIO16 (precipitation of wettest quarter)	–		(Fick and Hijmans 2017)
BIO17 (precipitation of driest quarter)	–	(Embarcadero); (Ecospat)	(Fick and Hijmans 2017)
BIO18 (precipitation of warmest quarter)	–	(SDMTune); (SDMTune)	(Fick and Hijmans 2017)
BIO19 (precipitation of coldest quarter)	–	(Embarcadero); (SDMTune); (SDMTune); (SDMTune); (Embarcadero); (Ecospat)	(Fick and Hijmans 2017)
annualPET (annual potential evapotranspiration)	Worldclim and Envirem		(Zomer et al. 2008)
aridityIndexThornthwaite (Thornthwaite aridity index)	–	(Embarcadero); (Ecospat)	(Thornthwaite 1948)
climaticMoistureIndex (a metric of relative wetness and aridity)	–	(SDMTune); (Ecospat)	(Willmott and Feddema 1992; Vörösmarty et al. 2005)
continentality (average temp. of warmest month - average temp. of coldest month)	–		(Rivas-Martínez and Rivas-Sáenz 2009 (internet resource!))
embergerQ (Emberger's pluviothermic quotient)	–	(Embarcadero)	(Title & Bemmels 2018)
growingDegDays0(sum of mean monthly temperature for months temperature greater than 0°C multiplied by number of days)	–		(Metzger et al. 2013)
growingDegDays5 (temperature greater than	–		(Metzger et al. 2013)

(*continued on next page*)

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005

ARTICLE IN PRESS

(*continued*)

Variables	Source database	Which R package/packages recommended it to be included in the species ENMs?	Source
5°C multiplied by number of days)			
maxTempColdestMonth (maximum temperature of the coldest month)	–		(Metzger et al. 2013)
meanTempColdestMonth (maximum temperature of the coldest month)		(Embarcadero);	
minTempWarmestMonth (minimum temperature of the warmest month)	–		(Metzger et al. 2013)
PETColdestQuarter (mean monthly PET of coldest quarter)	–	(SDMTune); (Embarcadero); (SDMTune)	(Metzger et al. 2013)
PETDriestQuarter (mean monthly PET of driest quarter)	–	(SDMTune); (SDMTune)	(Metzger et al. 2013)
PETseasonality (monthly variability in potential evapotranspiration)	–	(Embarcadero); (SDMTune); (Ecospat)	(Metzger et al. 2013)
PETWarmestQuarter (mean monthly PET of warmest quarter)	–	(Embarcadero)	(Metzger et al. 2013)
PETWettestQuarter (mean monthly PET of wettest quarter)	–	(SDMTune)	(Metzger et al. 2013)
thermInd (compensated thermicity index)	–		(Rivas-Martínez and Rivas-Sáenz 2009 (internet resource!))
tri (terrain roughness index)			(Wilson et al. 2007)
topoWet (SAGA-GIS topographic wetness index)	(Title and Bemmels 2016; Worldclim 2022)		(Boehner et al. 2002)
Elevation	Obtained from SRTM data	(Embarcadero); (Ecospat); (Ecospat); (Embarcadero)	(Worldclim 2022)
Slope	Created using spatial analyst tool in ArcMap	(SDMTune); (SDMTune)	Created using spatial analyst tools in ArcMap
Aspect	Created using spatial analyst tool in ArcMap	(Ecospat)	Created using spatial analyst tools in ArcMap
Soil	Created using spatial analyst tool in ArcMap		(Fischer et al. 2008)

Appendix C. Variable importance for the species of *Tulipa*.

	Algorithm	Variables	Permutation importance
T. tubergeniana			
1	MaxEnt	bio13	24
2		bio15	28.2
3		bio7	21.4
4		PETWettestQuarter	26.4
T. affinis			
1	MaxEnt	bio16	21.7
2		bio18	39.6
3		bio2	22.2
4		bio3	16.5
T. carinata			
1	MaxEnt	bio14	25.7
2		bio19	23.9
3		bio2	25.8
4		bio3	24.6
T. ingens			
1	MaxEnt	aridityIndexThornthwaite	23.4
2		bio14	22.7
3		bio19	21.5
4		bio2	32.4

Please cite this article as: Davron D et al., Beauty demands sacrifices: is it possible to overcome both climate change and anthropogenic impact for Pamir-Alay Tulips (Liliaceae)?, Journal of Asia-Pacific Biodiversity, https://doi.org/10.1016/j.japb.2024.05.005