Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Rapid decline in a regionally important plant species across an aridity gradient is associated with increasing temperature and decreasing precipitation

Akbar Akhmedov

lagochilusbunge@gmail.com

Samarkand State University

Frank M. Thomas

Samarkand State University

Luiz Bondi

University of Rostock

Bo Li

Chinese Academy of Sciences

Andrew Kulmatiski

Utah State University

Tamir Klein

Weizmann Institute of Science

Research Article

Keywords: Herbarium samples, Leaf δ13C, Population dynamics, Climate sensitivity, Lagochilus inebrians

Posted Date: August 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10182297/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Lagochilus inebrians is a significant medicinal semi-shrub native to Central Asia and is one of many species that have recently been added to the endangered species list in Uzbekistan. Grazing and human harvesting negatively affect this species, but the role of climate remains less clear. We hypothesized that populations of *L. inebrians* are under more stress due to drought. To assess climate effects on *Lagochilus inebrians*, we analyzed: (1) population structure at three sites across a climatic aridity gradient over five years; (2) stable carbon isotope ratios ($\delta^{13}C$) of leaf tissues from historical and current herbarium samples as an indicator of drought stress over time and space, and (3) the Standardised Precipitation Evapotranspiration Index (SPEI) to assess aridity over the past 120 years across the study sites. Within our five years of observation, *L. inebrians* populations rapidly shifted to an older structure with few young individuals. $\delta^{13}C$ values increased with temperature and decreased with precipitation indicating greater drought stress. Our results suggest that warming and drying conditions in Uzbekistan are contributing to *L. inebrians* stress and decline. Given the expected drier and hotter climate in Central Asia in the upcoming decades, prioritizing the conservation of *L. inebrians* populations should be crucial. While assisted migration of arid-adapted populations may help preserve this species, it is important to note that population declines were observed across sites.

1. Introduction

Climate change is one of the most pressing issues of the 21st century. The impact of human activity on Earth's climate is becoming increasingly evident. Climate observations demonstrate a trend of global warming: the global average temperature has gone up by 0.8°C since 1900 [1] and while the temperature continues to rise [2]. The years 2015–2025 were the warmest years on record [3].

[4; 5]. Recent global analyses suggest that rising atmospheric evaporative demand, driven by warming, has intensified drought severity by approximately 40% since the early 1980s [6]. Climate extremes, such as droughts, are expected to increase in frequency and intensity due to global changes [7; 8]. Rising global temperatures and extended droughts are projected to make drylands increasingly arid and saline [9]. Central Asia is particularly vulnerable to climate change impacts [10] due to fragile ecosystems, frequent natural hazards, limited water resources, and rapid glacier melting. In Central Asia, temperatures have increased in recent decades, with the greatest increases in winter and spring. Precipitation has slightly increased in much of the year, but decreased in spring [11].

In Central Asia in the past 70 years, temperatures have increased of 1.2°C causing a 20% decrease in snow depth, longer summers, and a 20 more frost-free days per year [7; 12]. These changes have placed unprecedented stress on the components of Central Asia's climate system [13]. Climate projections for Uzbekistan indicate a 5–10% decline in mean annual precipitation and a 3.5°C rise in mean temperature by the end of this century [14; 15]). Further, projections for Central Asia suggest increasingly extreme precipitation patterns, featuring intensified rainfall events alternated with extended dry periods, which

are expected to pose challenges for water management and ecosystem resilience throughout the region [16].

Climate change affects individuals, populations, species, communities, ecosystems, and biomes [17; 18]. In arid environments water limits plant growth and changing aridity conditions are likely to have contributed to the increase in the number of endangered plant species from 163 to 324 in the past 30 years [19; 20]. Twenty-three of the 324 endangered species are in the Lamiaceae family and these 23 species represent 11% of the Lamiaceae in Uzbekistan [21]. The genus *Lagochilus* belongs to the economically most important genera of the Lamiaceae. In Uzbekistan, the genus *Lagochilus* contains 13–18 species, of which four - *Lagochilus inebrians* Bunge, *Lagochilus olgae* Kamelin, *Lagochilus proskorjakovii* Ikramov, and *Lagochilus vvedenskyi* Kamelin & Tzukerv.

- are listed in the Red Book of the Republic of Uzbekistan [22]. *Lagochilus* species are primarily distributed in Central Asia and are commonly used in traditional medicine as sedatives and haemostatics. The leaves of this genus contain various substances, including alcohols, lagochilin (ranging from 0.6% to 2%), essential oils (0.03%), and vitamin K [23]. Most members of the genus also contain narcotic and haemostatic compounds, and compounds used to treat prostate cancer [24].

A previous study investigated the climate sensitivity and population dynamics of endemic and rare *Lagochilus* species in Uzbekistan [20]. That study found decreased regeneration of *Lagochilus* populations in low precipitation in recent years. Six *Lagochilus* species have been declining in abundance across Uzbekistan [20]. While drought is likely to be decreasing *Lagochilus* regeneration, overgrazing, harvesting for fodder and fuel, collecting medicinal raw materials, and trampling also affect *Lagochilus* growth [25].

Stable isotope analyses provide a powerful tool for understanding climate effects on plant ecology, distribution, and resource use efficiency [26; 27; 28; 29]. For example, plant $\delta^{13}C$ values provide a water stress indicator. This is because, under well-watered conditions, plants preferentially fix $^{12}CO_2$ relative to $^{13}CO_2$ resulting in low $\delta^{13}C$ values. However, in drought conditions, plants close stomata and fix a higher proportion of all $^{12}CO_2$ and $^{13}CO_2$ molecules, resulting in high $\delta^{13}C$ values [30; 31; 32].

The goal of the research is to study the climate sensitivity and population dynamics of *L. inebrians* in Uzbekistan. *Lagochilus inebrians*, an endemic species to Central Asia, is a subshrub [21]. In this study, we combined a geobotanical approach with climate and stable carbon isotope analyses to examine the long-term effects of climate change on *L. inebrians* in Uzbekistan. This study was conducted over five consecutive years on populations of *L. inebrians* species at three sites that represent an aridity gradient in Uzbekistan. Leaf samples of *L. inebrians* were measured for $\delta^{13}C$ and compared to historical samples from herbarium collections, some of which are over 100 years old. We hypothesized that *L. inebrians* populations are experiencing increased drought stress, indicated by (1) a decrease in regeneration and (2) a decrease in ^{13}C discrimination, resulting in less negative $\delta^{13}C$ values. Such physiological and

demographic responses may indicate a decrease in water availability in the natural habitats of the species.

2. Materials and methods

2.1. Study sites and climate

Field sampling was conducted during the growing seasons from 2019 to 2023, and this research expands on Akhmedov [20]. The selected study areas are situated in three elevational sites: desert, foothill, and mountain, as previously classified by Zakirov [33]. Within each zone, we chose different study areas that vary in their soil and climatic conditions (Fig. 1; Fig. S1). Study site characteristics and climate are reported in Table 1. The Nuratau ridge and Tomditau belong to the central part of the Kyzyl-Kum desert. The Nuratau ridge is located at the northwestern edge of the Pamir-Alai mountain range. The plant community was determined according to Braun-Blanquet [34]. Below are geobotanical descriptions of each of the three sites and their larger regions.

2.1.1. Tomditau: It is represented by a low-elevation mountain range located in the Central part of the Kyzyl-Kum desert in Uzbekistan. On the low mountains of the Kyzyl-Kum desert, the prevailing type of soil is grey-brown and sandy soil (arenosols). The average elevation of the low mountain is 400–500 m a.s.l., the climate of the area is characterized by low annual rainfall and high air temperature (maximum temperature 48°C), (Fig. 2). The average annual temperature fluctuates within 15°C, and annual rainfall does not exceed 125 mm per year. The plant community, represented that the total projected cover of the grass stands reaches 20%, and the projected cover of the studied species in this community does not exceed 1%. Here, we noted 30 species of vascular plants belonging to different life forms. Dominated by *Ferula kyzylkumica*, Artemisia *juncea*, and Artemisia *turanica* in the plant cover. and *Ferula kyzylkumica* are subdominant. (Table S1), where the *L. inebrians* population was recorded, is characterized by a relatively rich botanical composition.

2.1.2. Gubdintau: This area is located in the southern part of the Nuratau mountain range in Samarkand region. It has similar climatic and soil conditions to Nuratau (Fig. 2). but has a lower elevation, ranging between 700–750 m a.s.l. The floristic composition of the *Iris-Artemisia* community, where this population was studied, is poor. The total projected cover of the grass stands reaches 25–30%, and the share of the studied species does not exceed 1%. It consists of only 10 species of vascular plants (Table S1).

2.1.3. Ukhum, Nuratau: The Nuratau mountain ridge, together with the low mountains of the Kyzyl-Kum desert, represents a western link of the mountains of Central Asia and stands out due to a rich flora (1285 species) and higher endemism (29 species). The highest point of Nuratau reaches 2169 m above sea level. The climate is Mediterranean, the average minimum temperature is 13.3°C and the average maximum temperature is 43°C (Fig. 2). Annual rainfall is 206 mm. Soils are grey-brown, sandy, and brown [33], and are cambisols according to the international soil type classification. The botanical

composition of the communities consists of 15 species of flowering plants. The total projected cover of the grass stand does not exceed 30–35%. The projected cover of the studied species is about 2–3%. *Alhagi pseudalhagi* dominates the vegetation cover, with co-dominants being *Goebelia pachycarpa*, *Carex pachystylis*, and *Cynodon dactylon* (Table S1).

Long-term meteorological data are not available in Uzbekistan. Therefore, mean monthly precipitation and temperature data were obtained from the Climatic Research Unit (CRU) TS3.10 datasets [35], (Table 1). The characteristics of these sites and their climate are detailed in Table 1. Data of the Standardised Precipitation Evapotranspiration Index (SPEI), [36] were retrieved from https://spei.csic.es/database.html [37]. For the period 1901—2023, the following variables were computed on a monthly basis: annual means, annual minima, and annual amplitudes (difference between the months with the highest and the lowest SPEI), and the respective variables for the vegetation periods (April—September).

Table 1
Characteristics of the *L. inebrians* study sites. MAP, mean annual precipitation; MAT, mean annual temperature

Region	MAP (mm yr^{-1})	MAT (°C)	Soil	Landscape	N	E	M.A.S.L.
Tomditau	125	15.7	Grey-brown	Desert	41°41'008"	64°33`160"	417
Gubdintau	201	14.6	Grey-brown	Foothill	40°51'192"	66°18`112"	705
Nuratau	206	13.3	Grey-brown, Sandy and brown	Mountain	40 °55'109"	66°80`289"	785

2.2. Studied species

This study focuses on the red-listed species *L. inebrians*, which is endemic to Central Asia. It is a semi-shrub, growing 20–60 cm in height (Fig. 1). *Lagochilus inebrians* blooms from June to August, fruiting in July and September. This species mainly reproduces by seeds but has a low germination rate and slow individual development, yet rapid transition to flowering [21]. Locally, it is primarily used for medicinal purposes, such as blood-stopping and herbal tea. The Red List category is II according to Uzbekistan's Red Book, which is a state document that lists rare and endangered species of animals, plants, and fungi found within Uzbekistan's territory. “Rare species” (category II) are not currently under direct threat of extinction, but they exist in such small numbers or in limited and specific habitats that they can quickly become endangered. Therefore, careful monitoring is essential.

2.3. Population structure

Assessment of population structure was carried out using population traits [38]. At each of the sites, we set out five transects, starting from a common random point. From this point, one transect was established to the north, one to the south, and one to the east. Each transect was 1 m wide and 10 m long and was subdivided into ten squares of 1 m^2. In each of the squares, the number of individuals in each ontogenetic stage was counted (s - seedlings, j - juvenile, im - immature, v - virginal, g1 - young generative, g2 – mature generative, g3 - old generative, ss - subsenile, s – senile), [39; 40; 41]. The ontogenetic spectrum of the population was then determined according to the standard method by Uranov and Smirnova [42]. Four types of ontogenetic spectra can be distinguished [38], (Table S2).

2.4. Ontogenetic stages of L. inebrians

The seedling **(s)** of *L. inebrians* is a single-shoot plant with cotyledonous and green leaves, a well-defined hypocotyl, and a main root. Cotyledon leaves are elliptical, 0.3–0.5 cm long (with petiole) and 0.2 cm wide. After yellowing of the cotyledons, the individuals pass into the juvenile **(j)** ontogenetic state. Growing monopodially, 6–8 metameric, elongated shoots 1.5–2.5 cm tall are formed in the plants. In the second half of summer, individuals pass into the immature state **(im)**. Part of the leaves gradually turn yellow and die. The length of the leaf blade (together with the petiole) is 2–3 cm, the leaf width is 0.5–0.8 cm (6–8 pairs) and the leaves die in fall. The main root is 6–8 cm long; 1–2 lateral roots are formed in its apical part. In the second year, individuals move into the virginal **(v)** state. Monopodial growth is replaced by sympodial. The main root is more than 30–40 cm long and branches up to the 3rd order in the apical part. In the third year, individuals bloom. The bush is formed by 1–3 generative **(g1)** and 3–5 monocyclic elongated vegetative shoots. The generative shoot consists of 4 shortened and 6–8 elongated metameres. In the mature generative state **(g2)**, individuals reach their maximum size. The bush consists of 4–6 (8) winter monocyclic elongated branched generative shoots, from 10 to 60 cm of length, with green leaves of a trifoliate-lobed shape. In the old generative state **(g3)**, complete disintegration (particulation) of individuals occurs and a compact clone is formed, consisting of two or more parts. Gradually, part of the shoot axes in the particle is destroyed, and the number of particles in the clone is reduced due to their death. Individuals of the senile states **(ss, s)** are formed by 1–3 elongated shoots that unfold from dormant buds preserved on the living areas of the axes. The shoot bears 4–6 pairs of juvenile-type leaves. Part of the main root is preserved. The post-generative period lasts 2–3 years. Thus, under the conditions of Uzbekistan, the duration of the ontogeny of *L. inebrians* individuals is at least 25 years (Table 2).

Table 2
The ontogenetic stages of *L. inebrians*

Ontogenetic stage	**j**	**im**	**v**	**g1**	**g2**	**g3**	**ss**	**s**
Duration (year)	0.08	1	1	5–6	10–12	2–3	2–3	1–2

2.5. Historical herbarium specimens and current samples

Plant measurements were recorded at three populations of *L. inebrians* within three environmental zones. We collected samples of green and healthy leaves of current fresh specimens and from historical

of *L. inebrians* and prepared them for $\delta^{13}C$ isotope analyses. Specimens were collected between 1914 and 2021 (Table 3). Specimens were obtained from two herbarium sources: 1. The National Herbarium of Uzbekistan, located in Tashkent, 2. The herbarium collection of Samarkand State University.

Table 3
Historical and present herbarium samples of *L. inebrians*

Ontogenetic stages	Collection date	Sampling location	Environmental zone
G1	1914/4/4	Tomditau	Desert
G1	1915/5/28	Tomditau	Desert
G2	1921/6/9	Tomditau	Desert
G2	1927/6/3	Tomditau	Desert
G1	1928/5/13	Tomditau	Desert
G1	1954/5/30	Gubdintau	Foothill
G1	1956/5/25	Nuratau	Mountain
G2	1964/6/5	Nuratau	Mountain
G2	1975/7/20	Tomditau	Desert
G1	1992/5/6	Nuratau	Mountain
G2	2015/6/18	Gubdintau	Foothill
G2	2021/8/9	Nuratau	Mountain

2.6. Isotopic analysis of $\delta^{13}C$ in historical and current leaf samples

Isotopic analyses for $\delta^{13}C$were conducted at the Department of Plant & Environmental Sciences, Weizmann Institute of Science in Rehovot, Israel, using a Cavity Ring Down Spectroscopy (CRDS) method. An amount of 1 mg was mounted onto a combustion module equipped with an auto-sampler (ECS 4010, Costech Analytical, Valencia, CA, USA). The resultant CO_2 gas product was analyzed with cavity ring-down spectroscopy (Picarro G2131i, Picarro, Santa Clara, CA, USA), which was directly interfaced to the combustion module. Results were expressed as parts per thousand (‰) deviations from the international C isotope standard (Vienna Pee Dee Belemnite, VPDB). Samples were measured and averaged. An international standard (IAEA-CH-3, Cellulose, International Atomic Energy Agency, Vienna, Austria) was used, and internal standards (homogeneous *Spirulina* powder with a $\delta^{13}C$ of -29.2‰) and Glucose (Sigma) were used every 12 samples.

2.7. Statistical analysis

All statistical analyses were conducted using JMP statistical analysis software (version 1.8; SAS, Cary, NC, USA). We used ANOVA to test for differences among years (five years of measurements) in each of the developmental stages of the population and to account for site conditions (precipitation, temperature). In addition, a t-test was applied to test $\delta^{13}C$ differences between historical and current samples, and P-values were calculated for the correlation coefficients between the percent of young plants (g1) in each population in a specific year and the precipitation amount in that year. We tested time courses of the SPEI variables on significant trends using the Mann–Kendall trend test (τ-value) of the R-package 'trend' and the 'sens.slope' function [42]. The segmented package in R [43] was utilized to examine whether there were breaks in the time series of these variables at those two sites, which could indicate a change in trends during the studied period (Table 4).

3. Results

3.1. Climatic trends over the study sites in the past 120 years

The Tomditau site has an arid climate, whereas Gubdintau and Ukhum have a semi-arid climate (Table 1). Over the past 120 years, the minimum annual precipitation recorded across sites was 74.8 mm in Tomditau, Kyzyl-Kum desert in 1917, while the maximum was 615 mm in Ukhum pass, Nuratau in 1969 (Fig. 2). Mean annual precipitation did not change across the 120-year dataset. The Tomditau site was warmer than the other sites (Table 1). The minimum and maximum annual mean temperatures recorded over the past 120 years were 13.2°C and 16.4°C, respectively, with the highest temperature observed in Tomditau in 2016. Across sites, temperatures increased since the 1970s (Fig. 2).

Mean and minimum SPEI values decreased at the desert site, indicating that the climate has become drier since 1901 (Table 4). Further, the amplitude in SPEI values increased indicating larger differences between dry and moist months within a given year or season. The same trends were observed for the minimum SPEI and amplitude variables at the semi-arid and mountain sites; there, however, the mean SPEI values did not change over time (Table 4). At both of these sites, a breakpoint was identified in the year 1993. Following this breakpoint, the tested variables showed a significantly decreasing trend, indicating that the climate has become drier since 1993. However, there is an exception for the annual mean SPEI at Nuratau (foothill), which did not demonstrate a decreasing trend from 1993 onwards (Table 5).

Table 4
Results of analyses of temporal trends in SPEI variables (1901—2023) at the *L. inebrians* desert, semi-arid, and Mountain sites in Uzbekistan.

SPEI variable	Desert			Semi-arid			Mountain		
	τ*	***z***	***P***	***τ***	***z***	***P***	***τ***	***z***	***P***
Annual mean	-0.287	-4.698	**< 0.001**	-0.019	-0.310	0.756	-0.010	-0.157	0.875
Annual minimum	-0.507	-8.108	**< 0.001**	-0.199	-3.154	**0.002**	-0.221	-3.517	**< 0.001**
Annual amplitude	0.402	6.485	**< 0.001 ™**	0.244	3.914	**< 0.001 ™**	0.338	5.410	**< 0.001 ™**
Mean April-September	-0.265	-4.321	**< 0.001**	-0.068	-1.102	0.271	-0.066	-1.080	0.280
Minimum April-September	-0.416	-6.667	**< 0.001**	-0.173	-2.773	**0.006**	-0.137	-2.193	**0.028**
Amplitude April-September	0.243	3.917	**< 0.001 ™**	0.160	2.564	**0.010 ™**	0.203	3.260	**0.001 ™**

***** *τau is a test statistic of the Mann-Kendall trend test and the breakpoint analysis. z is the test statistic derived from the standard z-distribution and P, the probability.*

Table 5
Results of breakpoint analyses of temporal trends in SPEI variables (1901—2023) at the *L. inebrians* Gubdintau and Nuratau study sites in Uzbekistan and of trends in the period after the breakpoint.

SPEI variable	Gubdintau		Nuratau	
	Annual mean	**Mean April-September**	**Annual mean**	**Mean April-September**
Breakpoint ± standard error (years)	1993 ± 7.3	1993 ± 5.7	1993 ± 6.6	1993 ± 5.6
P of breakpoint	**0.020**	**0.042**	**0.009**	**0.032**
P of Davies test	**0.006**	**< 0.001**	**0.001**	**< 0.001**
Mann-Kendall's t after breakpoint	-0.261	-0.414	-0.245	-0.400
Mann-Kendall's *z* after breakpoint	-2.041	-3.248	-1.921	-3.129
Mann-Kendall's *P* after breakpoint	**0.041**	**0.001**	0.055	**0.002**

3.2. Changes in population structure of L. inebrians

All studied populations exhibited a centred ontogenetic spectrum with mature generative plants (g2) forming the largest fraction [38; 20]. However, the percentage of regenerating individuals decreased across the five years of observation (Fig. 3). The peak found in the spectra of the studied populations belonged to a group of middle generative (g2) plants in Tomditau. The percentage ratio of these mature (g2) and old generative stages (g3) was 83%, increased to 95%, and the percentage ratio of young plants (j, im, v) was very low at 1% in Tomditau. In Gubdintau, the percentage ratio of these middle and old generative stages was 61.1%, increased to 94.5%, and the percentage ratio of young plants was 6% through 39% (Table S3). The spectra of the studied populations showed a distinct peak associated with a group of mature generative plants in Nuratau. The percentage of mature and old generative stages was 59.1%, which increased to 84%. In contrast, the percentage of young plants was from 9% to 41% in Nuratau.

3.3. $\delta^{13}C$ analysis of historical and current leaf samples

The $\delta^{13}C$ values of 12 herbarium samples of plant leaves collected from the past and present reveal physiological differences among the plants over the years (Fig. 4a). There was no linear correlation between sampling year and $\delta^{13}C$ (Table 3). The leaf samples studied were from the desert, foothill and mountain region (Table 3). Focusing on these samples, $\delta^{13}C$ increased with mean annual temperature (Fig. 4b). Indeed, when looking at the relationship between $\delta^{13}C$ and annual precipitation, a negative effect emerged (Fig. 4c).

4. Discussion

This study investigated the climate sensitivity and population dynamics of *L. inebrians* in Uzbekistan. The results confirmed our hypotheses that *L. inebrians* populations face an increasing risk. This risk is evident through two main findings: (1) a decline in regeneration, correlating with lower precipitation levels in recent years, and (2) a high physiological sensitivity to drought, indicated by less negative $\delta^{13}C$ (a decrease in ^{13}C discrimination) during dry years compared to wet years. SPEI showed a significant downward trend, indicating that the climate has become drier across the sites since 1993.

Although warming at this temperature range (13–17°C) is typically considered beneficial for plant growth and development, the increase in $\delta^{13}C$ might indicate the associated effect of drying.

By examining a single species across a large aridity gradient, we show that both the population structure and physiological responses to drought are primarily influenced by local climatic conditions rather than by the specific traits of the species. This finding enhances our understanding of the relationships between climate, population dynamics, and isotopic data. It also provides stronger evidence that increasing aridity poses a direct threat to the long-term viability of *L. inebrians* populations throughout Uzbekistan.

4.1. Lagochilus inebrians populations under a changing climate

In this study, the mature stages of *L. inebrians* were relatively tolerant to drought. This species has a caudex, and it occurs as a form of vegetative reproduction [44]. The caudex of *L. inebrians* becomes more pronounced in older individuals, helping it survive in arid habitats. The absence of a young fraction in the populations and the peak in the middle generative plant range was probably connected to the biology of the species, as it has low seed germination. Middle and old generative individuals are preserved; they have a powerful root system that penetrates deep into the soil [45]. However, the species is negatively affected by the dryness of the climate, high temperature, and constant winds, which blow plant seeds over remote distances.

Anthropogenic disturbances may have contributed to a reduction in the duration of the middle generative state in *L. inebrians*, leading to a quicker transition to the old generative state and resulting in their rapid death. Specifically, the loss of a young fraction in this population of Tomditau in 2022–2023 was due to the irregularity of seed renewal. This was caused, on the one hand, by dry climate and relatively high temperature (MAT 15.6–16.1°C in 2022–2023), and on the other hand, by a constant wind (mean wind speed of 6.8 m s^{-1}; https://globalwindatlas.info) blowing plant seeds beyond the boundaries of the population. Temporal trends were significant for all SPEI indices tested for Tomditau and breakpoint analyses showed some SPEI drying trends after 1993. It is likely that SPEI can be associated with the Tomditau population of *L. inebrians'* loss of the young population fraction (seedlings and juveniles)

because they could not survive under the highest temperature (or heightened water stress) during the critical April-September period.

Our $\delta^{13}C$ measurements indicated that plants were more water limited in warmer and drier conditions (Fig. 4b, c). Higher $\delta^{13}C$ values occur when plants close their stomata due to water stress resulting in the fixation of a larger fraction of leaf-internal CO_2. Higher $\delta^{13}C$ values, therefore, provide a physiological / mechanistic link between aridity and decreased *L. inebrians* growth. Our results are in line with previous studies in related ecosystems, e.g., a meadow steppe [46]. Similarly, studying four alpine plant species in the Swiss Alps, herbarium records collected since 1889 revealed that trait distributions have shifted along elevational gradients due to a century of climate warming [47].

Populations of *Lagochilus* species are increasingly affected by human activities, such as overgrazing, harvesting for fodder, fuel, and medicinal purposes, as well as trampling. These factors have contributed to the reduction of their natural habitats [25]. *Lagochilus setulosus* is a medicinal plant in Kazakhstan, and its population density has decreased due to anthropogenic pressure and climate stress [48]. The populations of several rare endemic species in the Navoi region of Uzbekistan are currently facing serious challenges due to negative ecological factors and significant human impact (collecting medicinal plants, grazing) [49]. Distinct temporal periods (annual, semi-annual, and seasonal) from 1982 to 2020 have been identified, which are reflected in the population dynamics of the critically endangered *Moluccella bucharica*, a Lamiaceae species endemic to Uzbekistan. The findings of that study provide evidence that the factors contributing to the *M. bucharica* crisis, including alterations in the reproductive phase and seed damage by insects, also were related to climate change impacts [50]. Our results suggest that *L. inebrians* and related species are likely to continue to decline in Uzbekistan in the coming decades if warming and precipitation changes continue [20]. While it is reasonable to expect that more arid-adapted populations may be suitable for assisted migration, our results suggest that all populations are realizing decreasing growth with climate change and are becoming more drought resistant.

4.2. Implications for conservation

Shifts in precipitation regimes can profoundly influence plant growth in terrestrial ecosystems [51; 18], particularly within arid and semi-arid landscapes [52]. Rare and endangered species are especially susceptible to such environmental stresses [53]. In regions where *L. inebrians* populations occur, factors including global climate change, geological exploitation, and unregulated grazing practices have accelerated the decline of natural populations. International experience demonstrates that expanding networks of protected natural areas is among the most effective measures for safeguarding vulnerable species [53;54;55;56;57;58;59]. However, in Central Asia, such protected territories currently encompass less than 5.3% of the nation’s total area [60].

To ensure the conservation of *L. inebrians* populations, several key steps are required:

(1) Strengthening the protection of natural populations by mitigating human-induced pressures through public awareness initiatives and by promoting the cultivation of economically valuable species;

(2) Enhancing ecological understanding of the species' environmental requirements;

(3) Prioritizing the maintenance of existing populations and reserves while developing ex situ collections; and

(4) Establishing a long-term, nationwide monitoring framework for *L. inebrians* within Uzbekistan.

This study suggested highlighting the climatic risks threatening endemic plant species in Central Asia. We hope that this critical information can support stakeholders in executing the above conservation steps.

Declarations

The authors also declare that all plant names comply with the specified nomenclature guidelines. All vascular plants were identified by expert taxonomists: Dr. N. Beshko, Prof. H. Shomurodov (Tashkent Institute of Botany, Uzbek Academy of Science), and Dr. A. Akhmedov (Samarkand State University). Due acknowledgement has been given to Dr. N. Beshko and Prof. H. Shomurodov for identifying plants. Not applicable.

Ethics approval and consent to participate

The authors hereby declare that the fresh wild materials of *L. inebrians* Bunge have been sourced from the Kyzyl-Kum desert, Gubdintau foothill and Nuratau mountain in Uzbekistan (Desert 41°41'008 N, 64°33 $160E, F\infty thill 40^\circ 51' 192N, 66^\circ 18112$ E, Mountain 40 °55'109 N, 66°80`289 E), where *L. inebrians* is growing and for distribution, without needing specified permissions. In terms of wild materials of *L. inebrians*, due acknowledgement has been given to the National Herbarium of Uzbekistan, Tashkent (TASH), and Samarkand State University (SamDU) for providing the plant materials. All herbarium specimens are available in these sources.

Consent to publication

Not applicable.

Competing interests

The authors declare no conflict of interest in conducting this study.

Funding

None.

Author Contribution

AA developed the research concept together with FT and TK. AA, FT, LB, BL, AK, and TK selected the study plots, climate data, the samples, and processed and analyzed them. TK and AA designed the analysis and the paper. AA, FT, and TK conducted data evaluation and statistical analyses and wrote the manuscript. All authors contributed to the manuscript and approved its final version.

Acknowledgement

The authors would like to kindly thank: (1) The Tree Lab of the Weizmann Institute of Science, Israel, and specifically, Dr Ido Rog, who performed the isotopic analysis; (2) The President's International Fellowship Initiative (PIFI) (Grant No. 2025PVB0064) of the Chinese Academy of Sciences; (3) The National Herbarium of Uzbekistan, Tashkent (TASH); and (4) Samarkand State University (SamDU); (5) Tashkent Institute of Botany, Uzbek Academy of Science: Specifically, Dr. N. Beshko and Prof. H. Shomurodov identified plants.

Data Availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

References

1. Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M. (2006). Global temperature change. Proceedings of the National Academy of Sciences, 103(39), 14288–14293.
2. Tan C, Zhong J, Yang D, Huang W. (2025). Forecasting and analysing global average temperature trends based on LSTM and ARIMA models. PLoS ONE, 20(9), e0330645.
3. World M. Organization, 2026.
4. Lindsey R, Dahlman L. Climate change: Global temperature. Clim gov. 2020;16:1–5.
5. State of the Global Climate. WMO-No 1391. Geneva: WMO; 2025.
6. Gebrechorkos SH, Sheffield J, Vicente Serrano SM, Funk C, Miralles DG, Peng J, Dyer E, Talib J, Beck HE, Singer MB, Dadson SJ. Warming accelerates global drought severity. Nature. 2025;642(8068):628–35. https://doi.org/10.1038/s41586-025-09047-2.
7. Reyer CP, Leuzinger S, Rammig A, Wolf A, Bartholomeus RP, Bonfante A, Pereira M. A plant's perspective of extremes: terrestrial plant responses to changing climatic variability. Glob Change Biol. 2013;19(1):75–89.
8. Helfenstein IS, Sturm JT, Schmid B, Damm A, Schuman MC, Morsdorf F. (2025). Satellite Observations Reveal a Positive Relationship Between Trait-Based Diversity and Drought Response in

Temperate Forests. Glob Change Biol, 31(2), e70059.

9. Dantas BF, Moura MS, Pelacani CR, Angelotti F, Taura TA, Oliveira GM, Seal CE. Rainfall, not soil temperature, will limit the seed germination of dry forest species with climate change. Oecologia. 2020;192(2):529–41.
10. Saidaliyeva Z, Muccione V, Shahgedanova M, Bigler S, Adler C, Yapiyev V. (2024). Adaptation to climate change in the mountain regions of Central Asia: A systematic literature review. Wiley Interdisciplinary Reviews: Clim Change, 15(5), e891.
11. Haag I, Jones PD, Samimi C. Central Asia's changing climate: How temperature and precipitation have changed across time, space, and altitude. Climate. 2019;7(10):123.
12. Yao J, Chen Y, Chen J, Zhao Y, Tuoliewubieke D, Li J et al. (2021) Intensification of extreme precipitation in arid Central Asia. Journal of Hydrology, 598, 125760. Available from: https://doi.org/10.1016/j.jhydrol.2020.125760
13. Fallah B, Didovets I, Rostami M, Hamidi M. Climate change impacts on Central Asia: Trends, extremes and future projections. Int J Climatol. 2024;44(10):3191–213.
14. IPCC CC. (2001). The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, United Kingdom, 881. //IPCC AR6, in March 2023.
15. Mitchell D, Williams RB, Hudson D, Johnson P. A Monte Carlo analysis on the impact of climate change on future crop choice and water use in Uzbekistan. Food Secur. 2017;9(4):697–709.
16. Cao L, Suo N, Xu C, Song L, Lei X. (2023) 'Future dry wet climatic characteristics and drought trends over arid Central Asia', Frontiers in Earth Science, 11, article 110263. This study projects increased drought frequency, intensity, and duration alongside more intense precipitation under high-emission SSP-RCP scenarios.
17. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. Impacts of climate change on the future of biodiversity. Ecol Lett. 2012;15(4):365–77.
18. Lerner D, Fernandez-Martinez M, Livne-Luzon S, Belmaker J, Penuelas J, Klein T. (2022). Climatic heterogeneity and low precipitation dictate the global distribution of range-edge hotspots of major tree species.
19. Winters G, Otieno D, Cohen S, et al. Tree Growth and Water- Use in Hyper- Arid Acacia Occurs During the Hottest and Driest Season. Oecologia. 2018;188:695–705. https://doi.org/10.1007/s00442-018-4250-z.
20. Akhmedov A, Rog I, Bachar A, Shomurodov H, Nasirov M, Klein T. Higher Risk for Six Endemic and Endangered Lagochilus Species in Central Asia Under Drying Climate. Perspectives in Plant Ecology. Evol Syst. 2021;48:125586. https://doi.org/10.1016/j.ppees.2020.125586.
21. Vvedensky AI. Labiatae family. A.I. Vvedensky. Flora of Uzbekistan, Tashkent, Academy of Sciences of the Uzbek S. S R. 1961;5:364–73.
22. Red Book of Uzbekistan. Plants and Fungi. (2009) Tashkent: Chinor Publishing House. Volume P. 356.

23. Pratov UP, Kholmatov HK, Makhsumov MM. 2006. Nat Medicaments Tashkent, 208 p.
24. Akramov, D. K., Mamadalieva, N. Z., Porzel, A., Hussain, H., Dube, M., Akhmedov, A.,… Wessjohann, L. A. (2021). Sugar containing compounds and biological activities ofLagochilus setulosus. Molecules, 26(6), 1755..
25. Shomurodov HF, Akhmedov A, Saribayeva SU. Distribution and the current state of Lagochilus acutilobus (Lamiaceae) in connection with the oil and gas sector development in Uzbekistan. Ecol Questions. 2014;19:45–9.
26. McPherson GR, Boutton TW, Midwood AJ. Stable carbon isotope analysis of soil organic matter illustrates vegetation change at the grassland/woodland boundary in southeastern Arizona. USA Oecologia. 1993;93(1):95–101.
27. Boutton TW, Archer SR, Midwood AJ, Zitzer SF, Bol R. δ13C values of soil organic carbon and their use in documenting vegetation change in a subtropical savanna ecosystem. Geoderma. 1998;82(1–3):5–41.
28. Biedenbender SH, McClaran MP, Quade J, Weltz MA. Landscape patterns of vegetation change indicated by soil carbon isotope composition. Geoderma. 2004;119(1–2):69–83.
29. Bai E, Boutton TW, Wu XB, Liu F, Archer SR. Landscape-scale vegetation dynamics inferred from spatial patterns of soil δ13C in a subtropical savanna parkland. J Geophys Research: Biogeosciences. 2009;114:G1.
30. Klein T, Hemming D, Lin T, Grünzweig JM, Maseyk K, Rotenberg E, Yakir D. Association between tree-ring and needle δ13C and leaf gas exchange in Pinus halepensis under semi-arid conditions. Oecologia. 2005;144(1):45–54.
31. Ehleringer JR, Cerling TE, Helliker BR. C 4 photosynthesis, atmospheric CO 2, and climate. Oecologia. 1997;112(3):285–99.
32. Kohn MJ. 2010. Carbon isotope compositions of terrestrial C3 plants as indicators of (paleo) ecology and (paleo) climate. Proc. Natl. Acad. Sci. 107 (46), 19691–19695.
33. Zakirov P. (1971) Botanical geography of Kyzylkum lowlands and Nuratau ridge. Tashkent fan, Uzbekistan 155 pp.
34. Braun-Blanquet J. Plant sociology: the study of plant communities. Transley review. London: Hafner; 1965.
35. Harris IPDJ, Jones PD, Osborn TJ, Lister DH. Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset. Int J Climatol. 2014;34(3):623–42.
36. Vicente-Serrano SM, Beguería S, López-Moreno JI. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. J Clim. 2010;23(7):1696–718. 10.1175/2009jcli2909.1.
37. Beguería S, Vicente-Serrano SM, Angulo-Martínez M. A multiscalar global drought dataset: the SPEIbase: a new gridded product for the analysis of drought variability and impacts. Bull Am Meteorol Soc. 2010;91(10):1351–6. 10.1175/2010bams2988.1.

38. Zaugolnova LB. (1994) The Structure of the Populations of Seed Plants and Monitoring. Résumé of Dissertation for Doctor of Biological Sciences, St. Petersburg, 70 pp.
39. Rabotnov TA. Life cycles of perennial grass plants in meadow populations. Moscow: Transactions of Institute of Botany of Academy of Sciences of USSR, Geobotany; 1950. p. 176.
40. Uranov AA. Age spectrum of phytocoenopopulation as a function of time and energy wave processes. Scientific lectures of higher schools. Biol Sci. 1975;2:7–34.
41. Coenopopulations plants (basic concepts and structure). (1976) World Scientific. 217 pp.
42. Pohlert T. Trend: non-parametric trend tests and change-point detection. R package version 1.1.5. org/ packa ge= trend; 2023. (Accessed on 19.02.2025. https://. CRAN.R- proje ct.
43. Muggeo VMR. (2008). segmented: An R Package to Fit Regression Models with Broken-Line Relationships. R News 8/1. https://journal.r-project.org/articles/RN-2008-004/RN-2008-004.pdf
44. Akhmedov A. 2018. Ontogenetic structure and population state of rare and endemic species of the genus *Lagochilus Bunge* (Lamiaceae) in the flora of Uzbekistan. PhD thesis, Tashkent Botany Institute, Uzbekistan.
45. Akhmedov A. Assessment of the Current Condition of Populations of the Red List species Lagochilus proskorjakovii Ikram and Lagochilus olgae R.Kam. (Lamiaceae) in Nuratau mountain ridge, Uzbekistan. United Nations University Land Restoration Training Programme [final project]; 2017.
46. Wang Y, Meng B, Zhong S, Wang D, Ma J, Sun W. Above ground biomass and root/shoot ratio regulated drought susceptibility of ecosystem carbon exchange in a meadow steppe. Plant Soil. 2018;432:259–72. https://doi.org/10.1007/s11104-018-3790-7.
47. Jaroszynska F, Rixen C, Woodin S, Lenoir J, Wipf S. Resampling alpine herbarium records reveals changes in plant traits over space and time. J Ecol. 2023;111(2):338–55. https://doi.org/10.1111/1365-2745.14062.
48. Eshibaev A, Aimenova Z, Akynova L, Nurseitova L, Kopabaeva A. The population status of *Lagochilus setulosus* Vved. and its biochemical composition. Ecol Questions. 2021;32(2):111–8. https://doi.org/10.12775/EQ.2021.018.
49. Rakhimova T, Rakhimova N, Sharipova V, Beshko N, Rizamat H. Current state of coenopopulations of some rare endemic species in Navoi region. Uzbekistan Ekológia. 2021;40(4):357–63.
50. Khabibullaev BS, Shomurodov KF, Adilov BA. Impact of long-term climate change on Moluccella bucharica (B. Fedtsch.) Ryding population decline in Uzbekistan. Plant Sci Today. 2022;9(2):357–63.
51. Klein T, Randin C, Körner C. Water availability predicts forest canopy height at the global scale. Ecol Lett. 2015;18(12):1311–20.
52. Livne-Luzon S, Grunwald Y, Pozner E, Rotenberg E, Yakir D, Klein T. Persistent increase in understory vegetation following thinning and grazing exclusion in a semiarid pine forest. Forestry: An International Journal of Forest Research; 2025. p. cpaf031.

53. Guo, W. Y., Serra-Diaz, J. M., Schrodt, F., Eiserhardt, W. L., Maitner, B. S., Merow,C., … Svenning, J. C. (2022). High exposure of global tree diversity to human pressure.Proceedings of the National Academy of Sciences, 119(25), e2026733119.
54. Pozner, E., Bar-On, P., Livne-Luzon, S., Moran, U., Tsamir-Rimon, M., Dener, E., …Klein, T. (2022). A hidden mechanism of forest loss under climate change: The role of drought in eliminating forest regeneration at the edge of its distribution. Forest Ecology and Management, 506, 119966.
55. Lyu Y, Shi P, Han G, Liu L, Guo L, Hu X, Zhang G. Desertification control practices in China. Sustainability. 2020;12(8):3258.
56. Padilla FM, Miranda JDD, Pugnaire FI. Early root growth plasticity in seedlings of three Mediterranean woody species. Plant Soil. 2007;296:103–13.
57. Reyer CP, Otto IM, Adams S, Albrecht T, Baarsch F, Cartsburg M et al. (2017) Climate change impacts in Central Asia and their implications for development. Regional Environ-mental Change, 17(6), 1639–1650. Available from: https://doi.org/10.1007/s10113-015-0893-z
58. Roy P, Pal SC, Chakrabortty R, et al. Climate Change and Geo-Environmental Factors Influencing Desertification: A Critical Review. Environ Sci Pollut Res. 2024. https://doi.org/10.1007/s11356-024-32432-9.
59. Slette, I. J., Post, A. K., Awad, M., Even, T., Punzalan, A., Williams, S., … Knapp,A. K. (2019). How ecologists define drought, and why we should do better. Global Change Biology, 25(10), 3193–3200..
60. Farhadinia MS, Waldron A, Kaszta Ż, Eid E, Hughes A, Ambarlı H, Al-Hikmani H, Buuveibaatar B, Gritsina MA, Haidir I, Islam ZU, Kabir M, Khanal G, Koshkin MA, Kulenbekov R, Kubanychbekov Z, Maheshwari A, Penjor U, Raza H, Rosen T, Yachmennikova A, Rozhnov VV, Yamaguchi N, Johnson PJ, Macdonald DW. (2022). Current trends suggest most Asian countries are unlikely to meet future biodiversity targets on protected areas. Commun Biol. 29;5(1):1221. 10.1038/s42003-022-04061-w
61. POWO. 2025. Plants of the World Online. Royal Botanic Gardens, Kew. https://powo.science.kew.org/ (Accessed: 3 February 2025).

Figures

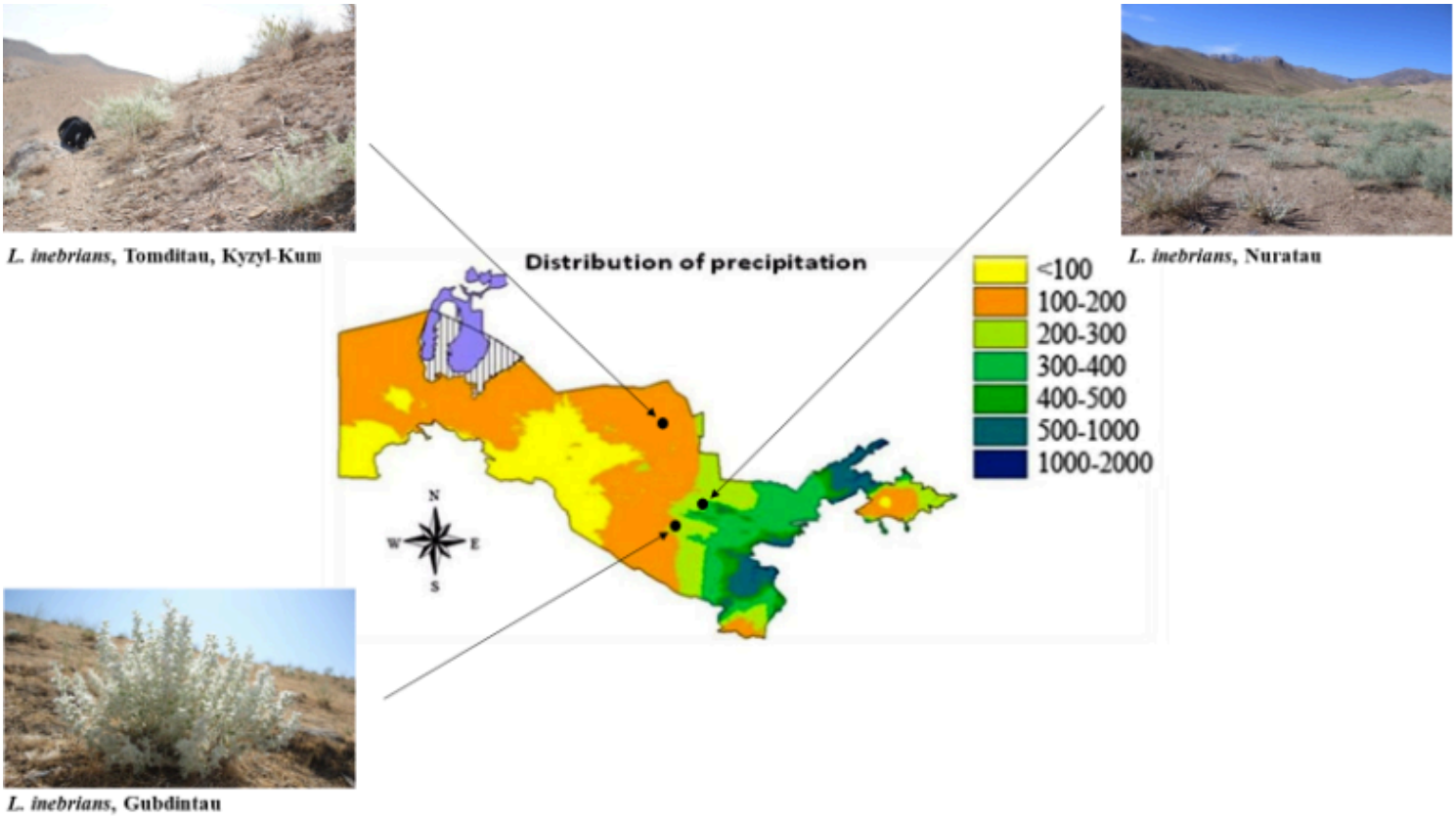


Figure 1

The studied *L. inebrians* populations and sampling sites across Uzbekistan. Colours on the map specify the mean annual precipitation (mm yr^{-1}).

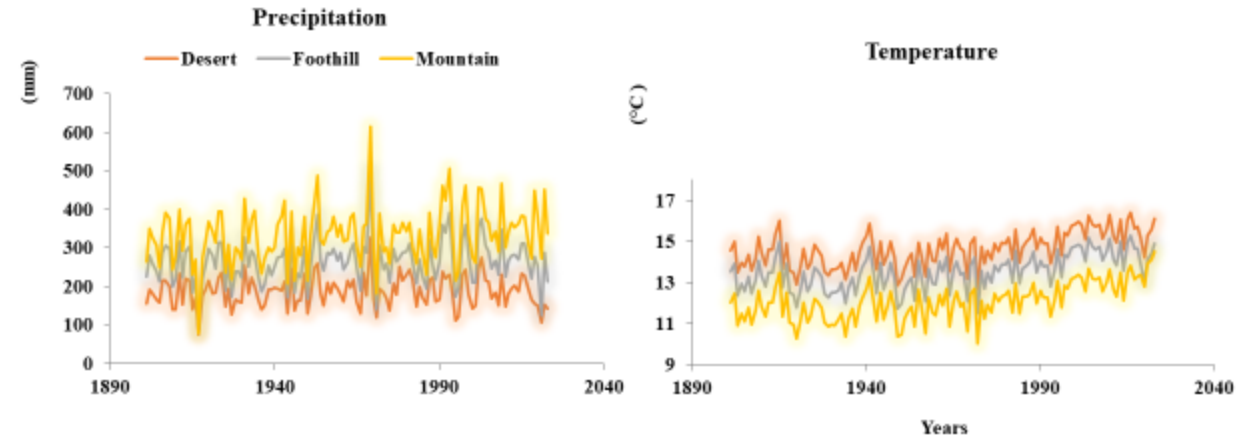


Figure 2

.Climate conditions (mean annual precipitation and temperature) in *L. inebrians* sites in Uzbekistan over the past 120 years.

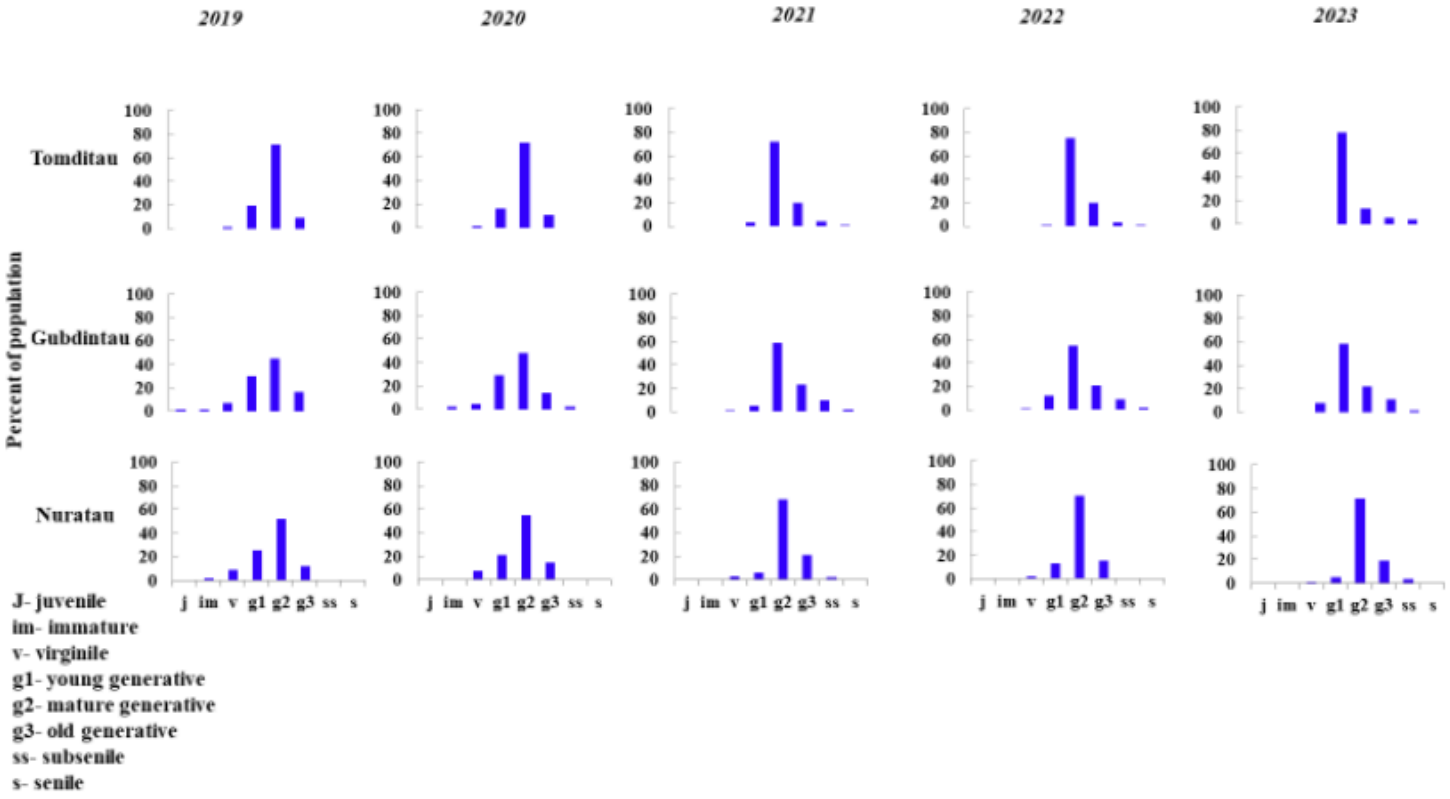


Figure 3

Dynamics of population partitioning to developmental stages of *L. inebrians* across three sites in Uzbekistan in 2019-2023.

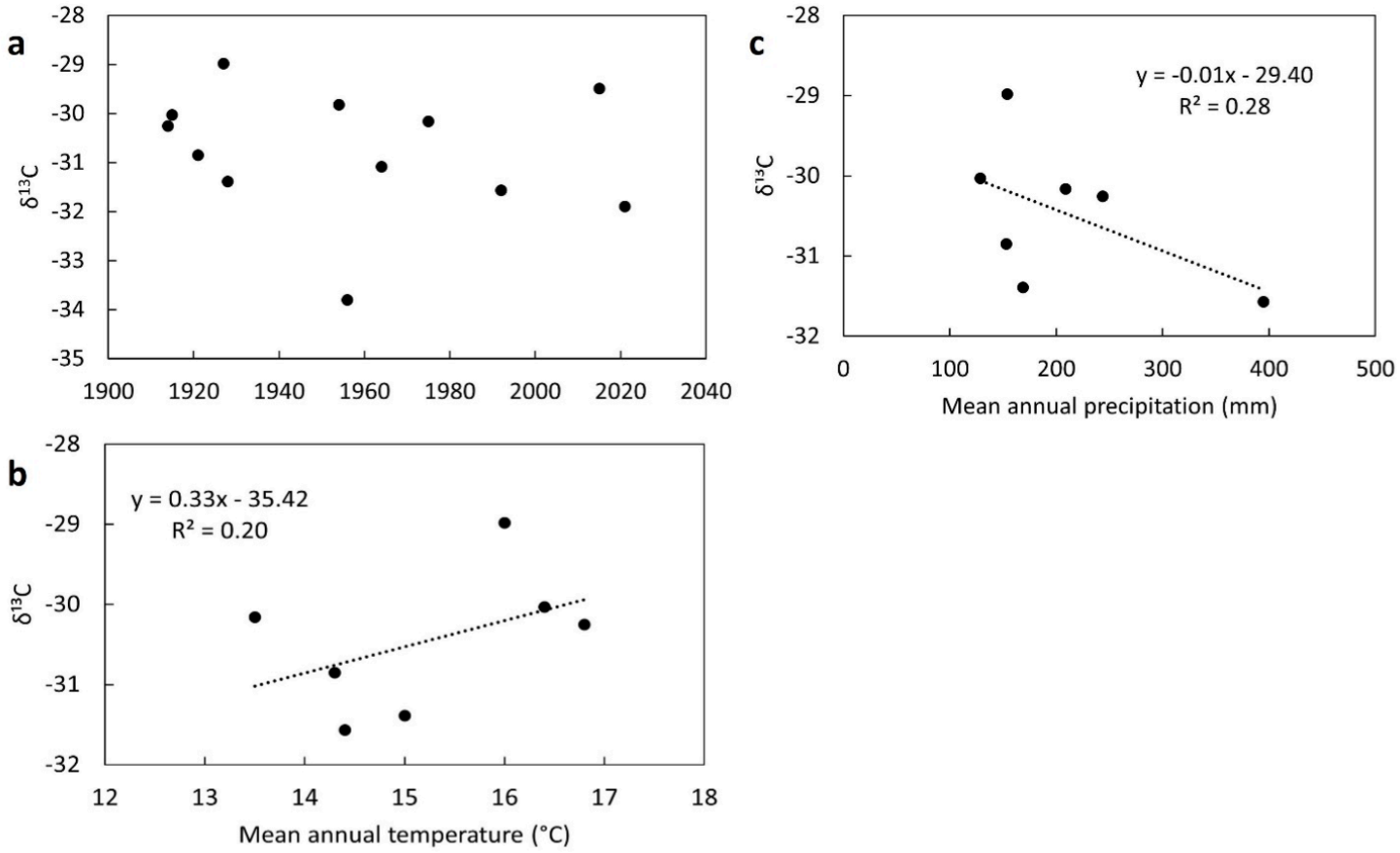


Figure 4

a. $\delta^{13}C$ of herbarium leaf samples of *L. inebrians* from the study sites. **b.** Relationships between $\delta^{13}C$ and annual temperature. **c.** Relationships between $\delta^{13}C$ and annual precipitation.

Supplementary Files

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

- Sumplimentary2026..docx