

Floristic diversity and taxonomic structure of the Lower Amu Darya State Biosphere Reserve (Uzbekistan): a grid-based assessment

Janibek Babajanov¹, Komiljon Sh. Tojibaev¹

1 *Institute of Botany, the Academy of Sciences of the Republic of Uzbekistan, 32 Durmon Yuli St., Tashkent, 100125, Uzbekistan*

Corresponding authors: Komiljon Sh. Tojibaev (ktojibaev@mail.ru)

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Abstract

Floristic knowledge of arid deltaic ecosystems remains limited by fragmented data and inconsistent methodologies, constraining reliable assessment of biodiversity patterns and long-term ecological change. Addressing this gap, we present a grid-based floristic assessment of the Lower Amu Darya State Biosphere Reserve (Uzbekistan), a representative ecotonal system at the interface of desert and riparian environments. Using a regular 2×2 km grid comprising 89 cells, we compiled an integrated dataset combining herbarium records, field collections, photographic observations, and recent geo-referenced occurrence data. In total, 310 vascular plant taxa (173 genera, 44 families) were recorded. The flora is dominated by *Amaranthaceae*, *Asteraceae*, *Poaceae*, *Brassicaceae*, and *Fabaceae*, a taxonomic composition characteristic of the Turanian floristic province and shaped by arid and saline environmental conditions. Taxonomic structure is characterized by relative stability at the family level but higher turnover at the genus level. The flora also shows increasing dominance of xerophytic and halophytic taxa, accompanied by a decline of hygrophilous elements. Grid-based assessment revealed pronounced spatial heterogeneity in species richness and only partial correspondence with collection density, indicating uneven floristic coverage across the reserve. These patterns suggest ongoing floristic reorganization that may be associated with aridification, hydrological alteration, and anthropogenic pressure linked to the desiccation of the Aral Sea. Beyond the regional context, the study demonstrates the value of grid-based approaches for detecting biodiversity change in data-limited dryland systems and provides a transferable framework for long-term ecological monitoring.

Keywords

Floristic diversity, grid-based mapping, species richness, tugai ecosystems, Lower Amu Darya, riparian vegetation, arid ecosystems, Central Asia

Introduction

The Lower Amu Darya State Biosphere Reserve, situated in the lower reaches of the Amu Darya River in northwestern Uzbekistan, represents an important protected area within the arid landscapes of the region. Its natural environment is characterized by the interaction between desert conditions and riverine habitats, where water availability plays a fundamental role in determining vegetation distribution and community composition. Within this environmental setting, riparian habitats support vegetation that differs substantially from the surrounding desert communities in its ecological requirements and structural organization (Bakhiev et al. 2008). The reserve therefore provides an important setting for investigating floristic diversity across contrasting habitats and understanding the contribution of riverine ecosystems to regional plant diversity.

Desert vegetation constitutes a major component of the arid lowland ecosystems of Central Asia, where plant communities develop under conditions of limited precipitation, high evaporative demand, and pronounced seasonal fluctuations in water availability. The vegetation of these landscapes comprises a diverse range of ecological and structural types, including xerophytic shrublands, desert herbaceous communities, and riparian vegetation associated with major river systems (Bakhiev et al. 1987).

Among these vegetation types, tugai (Uzbek: to‘qay) represents a distinctive component of arid ecosystems, occurring primarily as narrow riparian belts along major rivers (Korovin 1961). Although traditionally regarded as a forest type, tugai is now understood as a structurally complex mosaic of tree, shrub, and herbaceous communities shaped by hydrological dynamics, conservation status, and varying degrees of anthropogenic transformation (Bakhiev et al. 1994; Treshkin 2011; Kuzmina and Treshkin 2012; Rakhimova et al. 2023). These ecosystems contribute to the ecological and floristic heterogeneity of desert landscapes by supporting plant assemblages associated with riverine environments.

Tugai vegetation constitutes a major component of the reserve's vegetation cover and is closely associated with the hydrological conditions of the Amu Darya River. In Uzbekistan, tugai ecosystems occurring along major rivers, particularly the Amu Darya and Syr Darya, form distinctive riparian forests embedded within the desert landscapes of Central Asia. These ecosystems comprise a heterogeneous assemblage of tree, shrub, and herbaceous communities, whose composition and spatial distribution are influenced by river dynamics and the availability of water (Korolyuk et al. 2024). The Amu Darya delta and its tugai ecosystems represent a distinctive component of Central Asian flora, characterized by a specific taxonomic

composition and vegetation structure rather than exceptionally high species richness (Korolyuk et al. 2025). The most comprehensive account of the regional flora was provided by Bakhiev et al. (1987), who documented 655 vascular plant species belonging to 304 genera and 75 families, representing approximately 64.8% of the flora of Karakalpakstan. However, subsequent studies have reported substantially lower estimates. For example, Khaydarov et al. (2016) recorded 301 species belonging to 157 genera and 61 families. These discrepancies may reflect differences in spatial delimitation, sampling design, taxonomic treatment, and data standardization, highlighting the need for systematic and spatially consistent floristic assessments.

The ecological importance of these ecosystems is further emphasized by ongoing changes in the composition and structure of riparian vegetation. Evidence from the Lower Amu Darya indicates a progressive homogenization of tugai vegetation, with the proportion of plant communities sharing similar species composition increasing markedly over recent decades. This trend reflects a substantial reduction in compositional heterogeneity and suggests ongoing degradation of riparian ecosystems. Consistent with this pattern, analyses of vegetation structure across tree, shrub, and herbaceous layers have revealed declines in key dominant species, including *Populus euphratica* and *P. pruinosa*, accompanied by reductions in shrub and perennial grass abundance (Rakhimova et al. 2023; Korolyuk et al. 2024). Together, these changes indicate a simplification of floristic composition and a shift towards more xerophytic assemblages under altered hydrological regimes and climatic stress.

Against this background, protected areas play an important role in conserving regional biodiversity and providing reference systems for assessing changes in vegetation and floristic composition. However, understanding the conservation significance of such areas requires more than a general inventory of plant species. Reliable assessments must also consider taxonomic composition, spatial patterns of species richness, and variation in sampling intensity. In particular, differences in sampling effort can influence observed patterns of floristic diversity and complicate comparisons among individual areas (Vallet et al. 2012). A grid-based approach provides a spatially explicit framework for organizing floristic records, examining the distribution of documented species richness, and identifying areas where additional botanical surveys may be required (Seregin 2013). Applying this approach to the Lower Amu Darya State Biosphere Reserve is therefore important for improving the understanding of its floristic composition, evaluating the spatial distribution of documented plant diversity, and establishing a consistent basis for future biodiversity monitoring.

The aim of this study is to provide a comprehensive assessment of vascular plant diversity and taxonomic structure within the Lower Amu Darya State Biosphere Reserve using a grid-based approach (Seregin 2013). Specifically, we (i) document the current composition of the flora, (ii) analyse its taxonomic structure, and (iii) assess spatial patterns of species richness and sampling intensity. By integrating historical and contemporary floristic data within a spatially explicit analytical framework

The reserve is situated within the Irano-Turanian floristic region and the lower Amu Darya botanical-geographical context of Uzbekistan, and is characterized by a heterogeneous mosaic of ecosystems, including riparian forests, wetlands, desert communities, and anthropogenically modified landscapes (Takhtajan 1986; Tojibaev et al. 2014; Tojibaev et al. 2016; Tojibaev et al. 2017). Vegetation patterns are primarily structured by strong environmental gradients, particularly soil salinity, groundwater depth, and fluvial dynamics. Tugai communities are dominated by species such as *Populus euphratica*, *Elaeagnus angustifolia*, and *Tamarix* spp., while adjacent desert areas support psammophytic and halophytic vegetation, including representatives of *Haloxylon*, *Salsola*, and *Calligonum*. Wetland habitats host hydrophytic and hygrophytic species associated with periodically flooded environments (Bakhiev et al. 1987; Rakhimova et al. 2023).

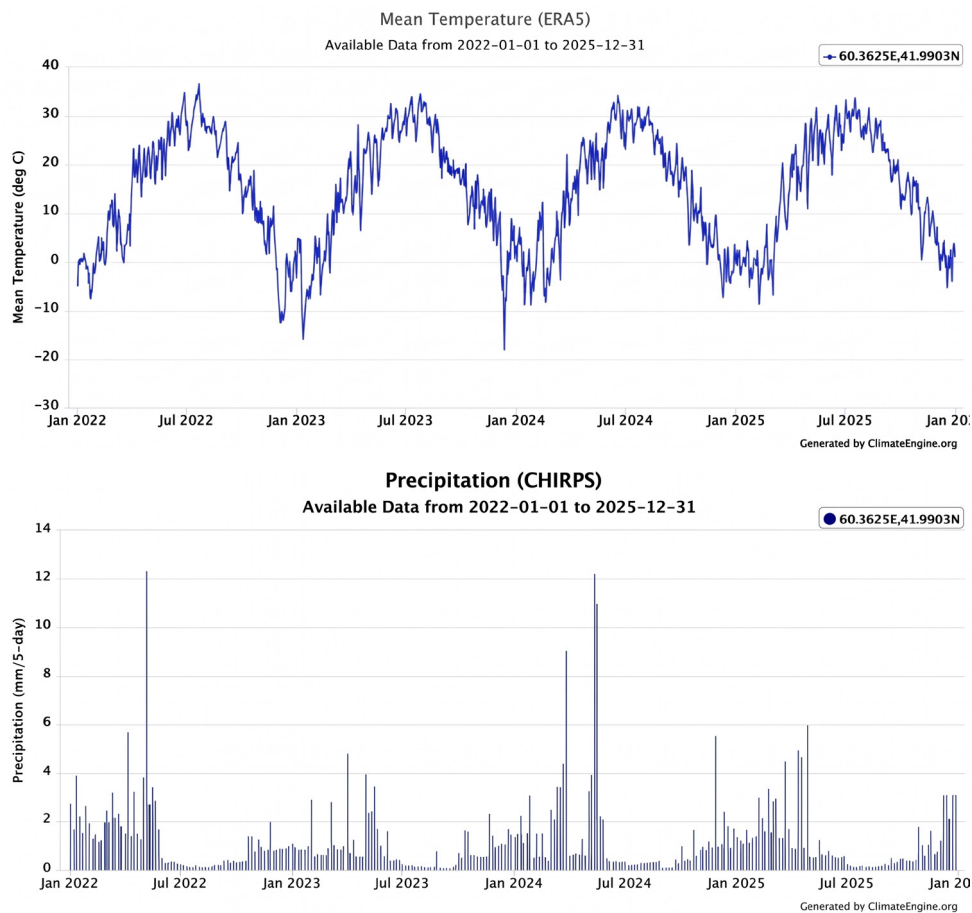
The geomorphology is dominated by flat alluvial plains formed through long-term sediment accumulation in the Amu Darya delta. The substrate consists of relatively young alluvial deposits, mainly sands, sandy loams, and clay sediments, associated with both active and abandoned river channels. This dynamic fluvial landscape reflects the river system's historical instability and plays a key role in shaping habitat heterogeneity and vegetation distribution. Soil conditions are highly variable, with widespread salinization and the presence of alluvial and meadow soils typical of arid deltaic environments (Bakhiev 1985).

The climate is sharply continental and extremely arid, with mean annual temperatures of 10–12°C. Winters are relatively cold (mean January temperature –4.5 to –7.6°C), while summers are hot and dry, with high solar radiation and temperatures frequently exceeding 40°C. Annual precipitation is very low (79–108 mm), with most falling in winter and spring, while summer precipitation is negligible. Potential evapotranspiration greatly exceeds precipitation, resulting in persistent water deficit and strong environmental stress typical of arid ecosystems (Korolyuk et al. 2024; Reymov et al. 2024).

Table 1. Geographic and recent climatic characteristics of the study area based on ClimateEngine point-based gridded datasets for 2022–2025, with supplementary temperature and precipitation diagrams

Parameter	Value / description
East longitude	60.3625°E
North latitude	41.9903°N
Study area	687.17 km ²
Altitude	55 m a.s.l.
Climate data source	ClimateEngine point-based gridded data
Temperature dataset	ERA5 daily mean temperature
Precipitation dataset	CHIRPS 5-day precipitation
Data period	2022–2025

Parameter	Value / description
Mean annual temperature	14.60°C
Mean annual precipitation	95.37 mm/year
Hottest month	July, mean 29.75°C
Coldest month	January, mean −1.82°C
Wettest month	May, mean 20.34 mm
Driest month	July, mean 1.53 mm
Climatic subzone	Arid



To complement the literature-based climatic description, recent climate parameters for the ClimateEngine extraction point representing the study area were calculated from ClimateEngine gridded datasets for 2022–2025 (Climate Engine 2026). ERA5 daily mean temperature data indicated a mean annual temperature of 14.60°C (Hersbach et al. 2020), whereas CHIRPS 5-day precipitation data indicated a mean annual precipitation of 95.37 mm/year (Funk et al. 2015).

Hydrological context

The Lower Amu Darya State Biosphere Reserve represents one of the last remaining hydromorphic areas with tree and shrub vegetation within the desert plains of Central Asia. The reserve was established in the mid-1970s, coinciding with the construction of major hydroengineering structures, including the Takhiatash (1974) and Tuyamuyun (1980) dams. These developments substantially altered the hydrological regime of the Amu Darya River, resulting in a decrease in water level by approximately 4.0–4.5 m over the subsequent decades (Kuzmina and Treshkin 2012). As a consequence, natural flooding events, which are critical to maintaining tugai ecosystems, have largely been absent. Between 1976 and 1998, no flooding was recorded within the reserve, with only episodic inundation events observed in 1998 and 2002. Under current conditions, the natural hydrological processes that support tugai vegetation have been significantly reduced (Rakhimova et al. 2023).

Despite these pressures, the reserve remains a key biodiversity refuge and supports the world's largest population of Bukhara deer (*Cervus elaphus bactrianus*), with more than 2,000 individuals. As one of the best-preserved remnants of deltaic tugai ecosystems, the Lower Amu Darya State Biosphere Reserve provides an important case study for assessing patterns of vascular plant diversity and evaluating the effectiveness of protected areas under ongoing environmental change (Rakhimova et al. 2023; Korolyuk et al. 2024; Reymov and Pulatov 2016; Reymov et al. 2024).

Floristic data collection and sampling design

Floristic data collection and spatial analysis were conducted using a grid-based framework, consistent with recent spatial floristic and conservation-oriented studies in Uzbekistan (Tojibaev et al. 2022; Tojibaev et al. 2023; Juramurodov et al. 2025). The study area was divided into regular 2 × 2 km grid cells, resulting in 89 cells.

Field surveys were conducted within each grid cell across the main habitat types. Sampling was conducted during the peak vegetation period in tugai ecosystems (April–mid-May), when most species are detectable and identifiable. Within each grid cell, fieldwork included route surveys, targeted collection of herbarium specimens, and recording of vascular plant occurrences to capture local environmental heterogeneity (Shcherbakov and Mayorov 2006a, 2006b).

The final dataset comprised 4,872 georeferenced occurrence records representing 310 vascular plant taxa, including 3,000 field-collected specimens, 372 historical herbarium specimens preserved in TASH and the herbarium of the Karakalpakstan branch of the Academy of Sciences, more than 850 georeferenced photographic records, and additional floristic observations from surveys conducted mainly during 2022–2025. Voucher specimens were prepared in accordance with standard herbarium protocols and deposited at the TASH. All occurrence records were critically evaluated for taxonomic consistency and spatial accuracy. Records with uncertain

identification, ambiguous locality information, or low spatial precision were excluded from the analysis. Historical records were georeferenced retrospectively based on locality descriptions.

Geographic coordinates were recorded during field surveys with GPS devices, whereas historical records were georeferenced retrospectively from locality descriptions using Google Earth and available cartographic resources. For species richness calculations, repeated records of the same species within a single grid cell were treated as a single occurrence. Each occurrence record was assigned to a habitat category, including tugai forest, floodplain, wetland margin, sandy desert, saline soil, takyr, and anthropogenically modified habitat.

All validated records were assigned to corresponding grid cells using GIS. Spatial analyses were conducted in ArcGIS 10.8.2. For each grid cell, species richness (SR) was calculated as the total number of recorded species. Collection density (CD) was calculated as the number of occurrence records per cell and used as a proxy for sampling effort (Seregin 2014; Tojibaev et al. 2022). These metrics were used to evaluate spatial variation in floristic diversity and sampling intensity and to identify under-sampled areas and potential biases in the dataset.

Taxonomic identification and data standardization

Species identification was based on field collections and critical examination of herbarium specimens. Taxonomic determination followed regional floras, including the Illustrated Guide to Higher Plants of Karakalpakstan and Khorezm (Korovina et al. 1982–1983), the latest editions of the Flora of Uzbekistan (Sennikov 2017a, 2017b, 2019, 2022, 2023a, 2023b), and the Conspectus Florae Asiae Mediae (Vvedensky 1968–1993). Identifications were verified through comparison with authenticated specimens in the TASH herbarium and by consulting international and regional databases. Nomenclature was standardized according to Plants of the World Online (POWO 2026), including GBIF (2026), supplemented by regional resources including GMOCA (2026) and Plantarium (2026). Taxonomically complex groups were critically evaluated in consultation with taxonomic specialists to ensure consistency in species delimitation.

The taxonomic circumscription of families follows PPG I (2016) for ferns and fern allies, Christenhusz et al. (2011) for gymnosperms, and APG IV (2016) for angiosperms.

A taxonomically verified checklist of vascular plant species recorded in the Lower Amu Darya State Biosphere Reserve is provided in the Suppl. material 1.

All records were critically revised to remove duplicates, resolve synonymy, and exclude doubtful identifications. Species were assigned to families and genera according to current taxonomic concepts.

Data limitations and uncertainty

Despite the integration of field and herbarium data, sampling intensity was uneven across the study area, as indicated by variation in CD among grid cells. This may have affected species richness estimates in some poorly accessible parts of the reserve. Historical herbarium records also do not necessarily reflect recent changes in species distributions within this rapidly changing deltaic system. In addition, species detectability varied across habitat types and survey periods, potentially affecting the completeness of the floristic inventory.

Results

Floristic composition and taxonomic structure

The floristic inventory of the Lower Amu Darya State Biosphere Reserve, based on a grid-based mapping approach, recorded 310 vascular plant taxa belonging to 173 genera and 44 families. The documented species represent approximately 47% of the flora of the Lower Amu Darya region (Bakhiev et al. 1987), indicating substantial coverage of the regional species pool within the study area.

Herbarium data contributed significantly to the compiled dataset. The primary sources included the TASH and the herbarium of the Karakalpakstan branch of the Academy of Sciences. These collections comprise 372 specimens representing 253 species, collected between 1928 and 2017 (Table 2). The integration of historical herbarium records with recent field data ensured comprehensive taxonomic coverage.

Table 2. Summary of herbarium specimens from the study area preserved in TASH and the Karakalpakstan herbarium, including collection period, number of families, genera, species, and specimens

Herbaria	Collection period	Family	Genera	Species	Specimens
TASH	1928–2017	23	73	125	147
Karakalpakstan herbaria	1960–1975	40	99	134	225
Total	1928–2017	43	140	253	372

Cultivated plants, including trees and shrubs introduced through human activity, were excluded from the analysis to ensure that the dataset reflects the natural and semi-natural flora of the reserve (Krasovskaya and Levichev 1986).

Taxonomic structure

The proportional representation of major taxonomic groups in the study area is presented in Table 3.

Table 3. Taxonomic composition of major plant groups in the flora of the Lower Amu Darya State Biosphere Reserve

Taxa	Species	%	Genus	%	Family	%
Equisetophyta	2	0.64	1	0.57	1	2.27
Pinophyta	3	0.97	1	0.57	1	2.27
Magnoliophyta:	305					
Magnoliopsida	258	83.22	139	80.36	33	75
Liliopsida	47	15.17	32	18.5	9	20.46
Total	310	100	173	100	44	100

Angiosperms constitute the vast majority of the documented flora, representing 305 species (98.4%) of all recorded taxa. Eudicots dominate this group with 258 species (83.22% of the total flora), whereas monocots comprise 47 species (15.17%). The overall ratio of monocots to eudicots is approximately 1:4.1, which is consistent with patterns reported for arid floras of the Turanian province. Notably, this ratio closely matches earlier data from the Lower Amu Darya region (Bakhiev et al. 1987), indicating the stability of this taxonomic structure despite the biosphere reserve's spatial delimitation.

An important metric for evaluating the overall taxonomic structure of a flora is the average number of genera and species per family. In the studied flora, each family comprises, on average, 3.9 genera and 7 species, indicating the predominance of several species-rich families (e.g., Asteraceae, Amaranthaceae, and Poaceae) together with numerous species-poor families.

Leading families and genera

General taxonomic proportions provide a broad overview of floristic structure; however, the composition and ranking of leading families offer a more informative measure of floristic organization (Kamelin 1973; Krasovskaya and Levichev 1986; Khokhryakov 2000; Tojibaev 2010). Among the studied flora, ten families are represented by six or more species and constitute the leading families (Table 4).

These leading families account for a substantial proportion of the total species richness and thus play a key role in shaping the taxonomic structure of the flora. To assess the stability and dynamics of this structure, the spectrum of leading families was compared with historical data for the Lower Amu Darya region (Bakhiev et al. 1987).

Table 4. Leading family spectrum of the flora of the Lower Amu Darya State Biosphere Reserve

Lower Amu Darya; Bakhiev 1987			Lower Amu Darya State Biosphere Reserve		
Family	Species	%	Family	Species	%
Amaranthaceae	110	16.79	Amaranthaceae	66	21.29
Asteraceae	82	12.52	Asteraceae	41	13.23
Poaceae	61	9.31	Poaceae	27	8.71
Brassicaceae	52	7.94	Brassicaceae	24	7.27
Fabaceae	38	5.80	Fabaceae	21	6.77
Boraginaceae	36	5.50	Boraginaceae	18	5.81
Polygonaceae	28	4.27	Polygonaceae	11	3.55
Cyperaceae	21	3.21	Convolvulaceae	9	2.9
Caryophyllaceae	17	2.60	Salicaceae	6	1.93
Ranunculaceae	12	1.83	Tamaricaceae	6	1.93
Total	457	69.77	Total	229	73.84

The comparison of the leading family spectra reveals a high degree of congruence in both the composition and ranking of the top three families, as well as in their relative contributions to the flora. This consistency indicates the long-term stability of the core taxonomic structure of the Lower Amu Darya flora and suggests that its primary floristic framework has remained largely unaffected by recent environmental changes.

In contrast, differences between the spectra are expressed mainly in the relative proportions and internal composition of dominant families. In the contemporary spectrum, the relatively high proportion of Amaranthaceae can be attributed in part to recent taxonomic revisions, particularly the inclusion of *Amaranthus* L. within this family. However, this factor is not decisive, as the genus is represented by only four species in the reserve and does not significantly affect the family's overall contribution. Instead, the dominance of Amaranthaceae is primarily driven by the high diversity of chenopod taxa (Chenopodiaceae s.l.), which account for approximately 60% of the family diversity recorded for the Lower Amu Darya.

In the broader regional flora of the Lower Amu Darya, Bakhiev et al. (1987) reported a high diversity of chenopod lineages within Amaranthaceae s.l., including genera such as *Alexandra*, *Arthrophytum*, *Borsczowia*, *Cornulaca*, *Girgensohnia*, *Haloepelis*, *Halimocnemis*, *Horaninovia*, *Kirilovia*, *Nanophyton*, *Panderia*, *Petrosimonia*, and *Piptoptera*. In the present reserve-level dataset, however, the dominance of Amaranthaceae is mainly associated with salt-tolerant genera recorded within the biosphere reserve, including *Anabasis*, *Atriplex*, *Bassia*, *Caroxylon*, *Halimocnemis*, *Salsola*, *Suaeda*, and related taxa.

This pattern reflects the ecological filtering of the flora towards salt-tolerant and drought-adapted lineages under increasing aridity and soil salinization.

The second rank of leading families is fully consistent with Bakhiev's (1987) data, further reinforcing the stability of the floristic core. However, slight quantitative deviations in species richness and relative contributions point to gradual rebalancing within these families rather than structural turnover.

More pronounced differences emerge in the third rank, where shifts in the composition and position of Polygonaceae, Convolvulaceae, and Salicaceae indicate reorganization among subdominant elements. In the present study, Polygonaceae occupies the leading position within this group, represented by 11 species, which is approximately 2.5 times lower than previously reported. While this difference partly reflects the more restricted spatial extent of the biosphere reserve (species–area effect), it also suggests a contraction or redistribution of suitable habitats for these taxa over time.

The most substantial divergence between the spectra concerns Cyperaceae. Previously included among the leading families with 21 species (3.21%) (Bakhiev et al. 1987), it is absent from the leading group in the current dataset. This shift represents not merely a taxonomic fluctuation but a structural change in the flora, linked to the loss and degradation of wetland habitats. As Cyperaceae is primarily composed of hygrophilous taxa, its decline reflects hydrological disruption, reduced flooding regimes, and the desiccation of deltaic ecosystems under both climatic and anthropogenic pressures. Historical dominance of genera such as *Carex*, *Cyperus*, and *Schoenoplectus* contrasts sharply with their current reduced representation.

The analysis of the leading genera spectrum provides a more refined understanding of floristic structure and internal differentiation than family-level patterns. This approach allows the identification of species-rich genera, the evaluation of their relative contributions, and the assessment of distribution patterns, thereby revealing key taxonomic centres that shape the flora (Tojibaev 2010; Tolmachev 1974). As such, the leading genera spectrum is widely used in modern floristic studies as an effective tool for comparative analysis and for detecting structural differences among regional floras.

Applying the same framework as for leading families, the spectrum of leading genera (Table 5) in the Lower Amu Darya State Biosphere Reserve was analysed in comparison with historical data (Bakhiev 1987). In contrast to the relative stability observed at the family level, the genus-level structure appears markedly more dynamic, limiting direct one-to-one comparisons. This reflects the higher sensitivity of genera to ecological filtering and environmental change.

According to Bakhiev et al. (1987), the leading genera of the Lower Amu Darya flora were *Astragalus* (19 species), *Artemisia* (13), and *Atriplex* (12), followed by *Suaeda* (11), *Tamarix* (10), and *Halimocnemis* (8). This composition clearly reflects the dominance of xerophytic and halophytic lineages under arid and saline conditions. In the contemporary flora of the biosphere reserve, *Astragalus* retains its leading position, indicating continuity of the floristic core. However, the remaining genera show substantial reorganization, with shifts in both ranking and species richness that prevent direct correspondence with the historical spectrum. At the same time,

a consistent pattern is observed in the continued prominence of halophytic genera within *Amaranthaceae* (e.g., *Suaeda*, *Halimocnemis*, *Atriplex*), as well as the stable presence of *Artemisia* and *Tamarix*, which remain key structural elements of the flora.

Table 5. Leading genera spectrum of the flora of the Lower Amu Darya State Biosphere Reserve

Lower Amu Darya Bakhiev 1987			Lower Amu Darya State Biosphere Reserve, 2026		
Genera	Species	%	Genera	Species	%
<i>Astragalus</i>	19	2.9	<i>Astragalus</i>	9	2.9
<i>Artemisia</i>	13	1.9	<i>Suaeda</i>	8	2.6
<i>Atriplex</i>	12	1.9	<i>Caroxylon</i>	6	1.9
<i>Suaeda</i>	11	1.7	<i>Halimocnemis</i>	6	1.9
<i>Tamarix</i>	10	1.5	<i>Heliotropium</i>	6	1.9
<i>Halimocnemis</i>	8	1.2	<i>Artemisia</i>	5	1.6
<i>Heliotropium</i>	7	1.1	<i>Atriplex</i>	5	1.6
<i>Cousinia</i>	8	1.2	<i>Convolvulus</i>	5	1.6
<i>Potamogeton</i>	8	1.2	<i>Tamarix</i>	5	1.6
Total	96	14.6	Total	55	17.7

Among the leading genera of the Lower Amu Darya State Biosphere Reserve, *Astragalus* retains its leading position (9 species; 2.9%), confirming its role as a stable taxonomic core of the regional flora (Tojibaev et al. 2015). However, beyond this persistent element, the genus-level structure shows substantial reorganization relative to historical data (Bakhiev et al. 1987). Only a limited subset of leading genera is shared between the two spectra, while several formerly dominant taxa have declined in rank or disappeared from the leading group, indicating a pronounced turnover at the genus level.

At the same time, key compositional similarities persist. Halophytic genera of *Amaranthaceae*, particularly *Suaeda*, *Caroxylon*, and *Atriplex*, remain consistently prominent, reflecting the continued dominance of salt-tolerant lineages. In addition, the relatively high ranking of *Heliotropium* (6; 1.9%), together with *Artemisia*, *Tamarix*, and *Convolvulus* (5 each; 1.6%), indicates the persistence of xerophytic and psammophytic elements as fundamental components of the flora.

The observed differences between the spectra arise from two distinct but interacting sources. First, part of the discrepancy is taxonomic in origin. Historical data (Bakhiev et al. 1987) were not supported by published voucher specimens or an explicit species list, limiting their reproducibility. This is exemplified by *Salsola* L., reported with 21 species but not represented among the leading genera in the present dataset. Subsequent molecular phylogenetic studies have demonstrated that *Salsola* s.l. comprises multiple distinct lineages, now segregated into genera such as

Caroxylon, *Kali*, *Climacoptera*, and *Halothamnus* (Akhani et al. 2007). Thus, part of the apparent turnover reflects improved taxonomic resolution rather than genuine floristic change.

Second, the restructuring of the genus spectrum may reflect ecological responses to increasing aridity, soil salinization, and reduced flooding frequency in the deltaic system. Conversely, the decline or disappearance of previously recorded genera suggests contraction of suitable habitats and loss of ecological niches under combined climatic and anthropogenic pressures.

Spatial framework and data coverage

Preliminary inspection of the grid-based data indicated pronounced spatial heterogeneity in taxon richness across the study area. Higher values were generally associated with tugai and floodplain habitats, whereas desert and highly saline areas showed lower richness.

In contrast, CD reveals a non-uniform sampling effort across the study area. Areas of high sampling intensity are primarily associated with accessible locations, while remote and less accessible zones remain comparatively under-sampled. Notably, spatial patterns of SR and CD do not fully coincide, indicating potential sampling bias and suggesting that some floristically rich areas may remain insufficiently documented.

Using a regular 2×2 km grid (89 cells), spatial patterns of floristic diversity were assessed across the Lower Amu Darya State Biosphere Reserve. The analysis was based on a final dataset of 4,872 georeferenced occurrence records representing 310 vascular plant taxa, including 372 historical herbarium specimens from collections in Tashkent and Nukus, 3,000 field-collected specimens, more than 850 georeferenced photographic records, and additional floristic observations from surveys conducted between 2022 and 2025, thereby ensuring broad spatial and temporal coverage of the study area.

SR across the Lower Amu Darya State Biosphere Reserve exhibits pronounced spatial heterogeneity. The highest richness was recorded in slightly more than 11% of grid cells (10 cells), each supporting 136–180 species. Intermediate-high values (103–135 species) were observed in 21 cells, followed by a similar number of cells (24) with 58–102 species. Very low richness levels (30–57 species) were documented in 34 cells. (Table 6, Fig. 2). High-richness cells are primarily concentrated within the core zone of the biosphere reserve, particularly in the Nazarhan and Baday sections. These areas correspond to remnant floodplain and tugai habitats, where relatively higher moisture availability and habitat heterogeneity support elevated plant diversity. In contrast, low-richness cells are predominantly found in deserts and highly saline areas, reflecting strong environmental constraints on species' occurrence.

Table 6. Summary statistics of species richness and collection density across grid cells

Category	Grid cells, n (%)		SR	Grid cells, n (%)		CD	Habitat type
High richness	10	11.2	136–180	20	22.4	153–186	Tugai forests, river valleys, wetland margins
Moderate richness	21	23.6	103–135	11	12.4	120–152	Stony and gravelly slopes, takyr
Low richness	24	27	58–102	24	27	68–119	River valleys, desert
Very low richness	34	38.2	30–57	34	38.2	40–67	Salt flats, solonchaks, highly saline

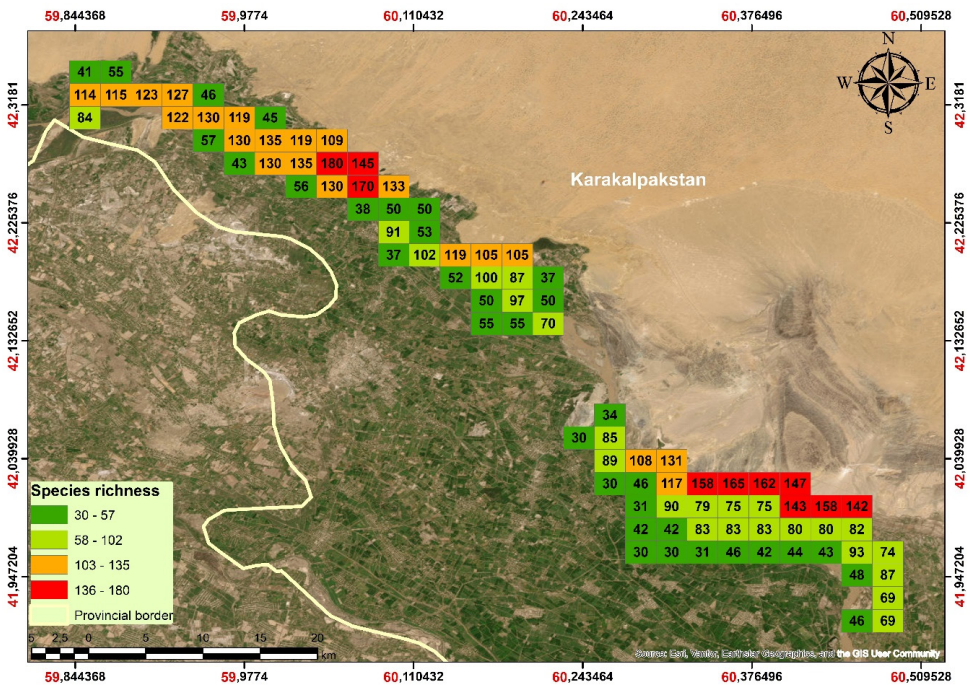


Figure 2. Species richness across the Lower Amu Darya State Biosphere Reserve.

CD also shows marked spatial variability across the reserve. The highest values (153–186 records per cell) were recorded in 20 grid cells. In addition, 11 cells, representing 12.4% of all grid cells, were characterized by relatively high sampling intensity (120–152 records per cell). Sampling effort declined across the remaining cells: 24 cells contained 68–119 records, and 34 cells contained 40–67 records (Table 6, Fig. 3).

A comparison of SR and CD patterns reveals a clear mismatch between species richness and sampling intensity. While areas of high SR generally coincide with

floodplain and tugai habitats, elevated CD values are partly associated with accessibility and survey focus. Several grid cells with moderate to high SR exhibit comparatively low CD, indicating that parts of the reserve remain undersampled.

Overall, these patterns reflect the combined influence of environmental gradients – particularly water availability and habitat heterogeneity – and uneven sampling effort. The identified discrepancies between SR and CD highlight priority areas for further floristic surveys and suggest that current estimates of species diversity may still underestimate the reserve's full floristic potential.

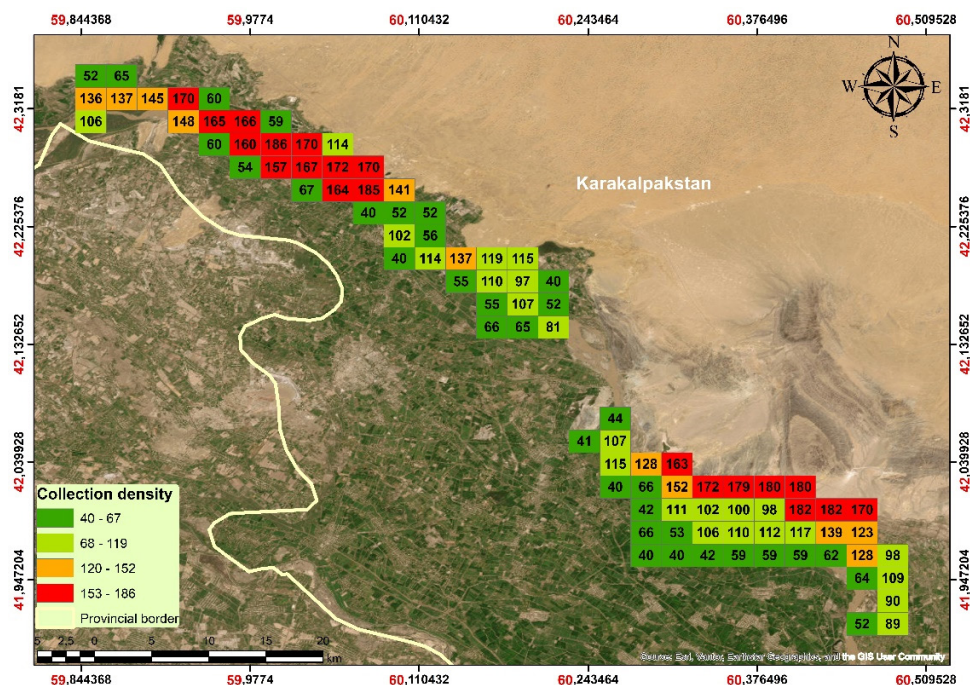


Figure 3. Collection density across the Lower Amu Darya State Biosphere Reserve.

Discussion

To our knowledge, this study represents the first comprehensive standardized, spatially explicit assessment of floristic diversity in the Lower Amu Darya State Biosphere Reserve using a grid-based mapping approach. It expands upon the preliminary grid-mapping results reported by Babadzhanov (2026) by integrating historical herbarium records, field-collected specimens, georeferenced photographic records, taxonomic standardization, species-richness and collection-density analyses, and comparison with historical floristic data. Unlike previous studies based on aggregated and non-standardized data, the present study provides a reproducible framework for analysing taxon richness, taxonomic structure, and the spatial organization of

plant diversity. By integrating historical and contemporary records, our results enable a comparison of floristic patterns over more than four decades.

The dominance of *Amaranthaceae*, *Asteraceae*, *Poaceae*, *Brassicaceae*, and *Fabaceae* is consistent with the floristic structure of the Irano-Turanian deserts and reflects adaptation to arid and saline environmental conditions. The stable presence of genera such as *Astragalus*, *Artemisia*, *Tamarix*, and *Suaeda* highlights the importance of xerophytic and halophytic elements in the flora.

The occurrence of hydrophilous taxa (e.g., *Populus*, *Salix*, *Phragmites*) reflects the contribution of floodplain and tugai habitats and emphasizes the ecotonal character of the flora.

Spatial patterns of SR reveal pronounced heterogeneity (Fig. 2), with diversity hotspots concentrated in the core zone (Nazarhan and Baday). These areas are associated with active floodplain processes and greater habitat heterogeneity.

The mismatch between SR and CD indicates uneven sampling effort across the reserve. Several grid cells with relatively high SR but low CD suggest that parts of the flora remain insufficiently documented.

In a temporal context, the results indicate substantial floristic reorganization over the past decades. While a stable taxonomic core persists, shifts in ecological composition are evident. In particular, the increasing prominence of halophytic and xerophytic taxa – reflected in the dominance of *Amaranthaceae* and associated genera (e.g., *Suaeda*, *Caroxylon*) – contrasts with the decline of hygrophilous elements, including taxa typically associated with wetland environments.

Importantly, floristic reorganization is expressed differently across taxonomic scales. While the leading families remain relatively stable (Table 4), genus-level patterns exhibit substantially higher turnover, indicating that ecological change is primarily manifested at finer taxonomic levels. This is accompanied by a clear shift in functional composition, with an increasing dominance of xerophytic and halophytic taxa – particularly within *Amaranthaceae* – and a decline of hygrophilous elements, including wetland-associated groups such as *Cyperaceae*. Together, these patterns suggest directional environmental filtering that is likely associated with aridification, salinization, and hydrological alteration.

This restructuring is consistent with regional-scale environmental change driven by the desiccation of the Aral Sea. Reduced flooding frequency, increased soil salinity, and the expansion of desertified substrates have likely promoted stress-tolerant assemblages while constraining wetland-dependent taxa. Similar shifts towards xerophytic and halophytic dominance have been reported in other arid regions of Central Asia under ongoing aridification.

Despite uneven sampling in some parts of the reserve, the study highlights the importance of the Lower Amu Darya State Biosphere Reserve as a key refuge of tugai-associated biodiversity within the rapidly changing landscapes of the Aral Sea region.

Conclusion

The present study provides the first standardized grid-based assessment of the flora of the Lower Amu Darya State Biosphere Reserve. By integrating field surveys, herbarium collections, photographic observations, and georeferenced occurrence records, the study documents 310 vascular plant taxa and reveals substantial spatial heterogeneity in species richness and collection density across the reserve. The results provide an updated floristic baseline for one of the largest remaining tugai ecosystems in Central Asia and enable future comparison of floristic patterns over time.

The observed mismatch between species richness and sampling intensity indicates that floristic diversity remains insufficiently documented in some parts of the reserve, particularly in environmentally heterogeneous and less accessible areas. Although uneven sampling effort remains a limitation, the grid-based framework made it possible to identify under-sampled territories and provides a practical basis for targeted future surveys and long-term floristic monitoring.

Overall, the study demonstrates the value of standardized grid-based approaches for floristic inventory and spatial analysis in arid riverine ecosystems of Central Asia. The compiled dataset and spatial framework provide an important foundation for future floristic, vegetation, and conservation studies in the lower Amu Darya region, particularly under ongoing aridification and hydrological changes associated with the Aral Sea crisis.

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Supplementary material 1

Annotated checklist of vascular plants recorded in the Lower Amu Darya State Biosphere Reserve

Authors: Janibek Babajanov, Komiljon Sh. Tojibaev

Data type: checklist

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