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Soil properties drive population abundance of the rare, endemic *Euphorbia yaroslavii* in the Zailiyskiy Alatau, Kazakhstan

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Abstract. *Turgara Z, Ametov A, Kulymbet K, Childibayeva A, Nazarbekova S, Ryskali T, Erezhetova U, Tastanbekova A. 2025. Soil properties drive population abundance of the rare, endemic* Euphorbia yaroslavii *in the Zailiyskiy Alatau, Kazakhstan. Biodiversitas 26: 5881-5890.* This study investigates the ecological and soil-chemical factors influencing the population abundance of the rare herbaceous perennial geophyte *Euphorbia yaroslavii* in the Zailiyskiy Alatau Mountains, Southeastern Kazakhstan. Field surveys were conducted across three gorges - Ushkonyr, Shamalgan, and Kaskelen - comprising nine cenopopulations. A total of 337 individuals were recorded, with the highest abundance observed in Ushkonyr (188 individuals) and the lowest in Kaskelen (56 individuals). Soil texture, structure, and chemistry were analyzed in detail, including granulometry, humus content, pH, CO_2, available N, P_2O_5, K_2O, exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), and total soluble salts. Pearson correlation analysis revealed very strong positive correlations between population abundance and sand ($r = +0.95$), clay ($r = +0.87$), humus ($r = +0.80$), mobile nitrogen ($r = +0.93$), and with exchangeable magnesium among key base cations ($r = +0.92$). A strong negative correlation was found with silt content ($r = -0.88$), indicating that excess silt may limit aeration. Correlations were computed at the cenopopulation level ($n = 9$), pairing abundance with co-located soil measurements from the 0-20 cm layer. The most favorable soil conditions for *E. yaroslavii* are loamy calcareous soils with 40-50% sand, 20-30% clay, slightly alkaline pH (7.4-7.9), humus ≥ 2.5%, and high base saturation with dominance of Ca^{2+} and Mg^{2+}. These findings suggest that population abundance is primarily determined by soil texture and organic matter, with magnesium acting as an important component of an overall balanced base-cation regime. Sites meeting these criteria should be prioritized for in situ conservation and habitat restoration, with recommended practices including organic amendment and liming to improve soil fertility and structure.

Keywords: Edaphic factors, *Euphorbia yaroslavii*, loamy soils, population ecology, salinity gradient

INTRODUCTION

Studying the factors that influence the distribution, structure, and abundance of rare and endemic plant species is a key challenge in ecology and conservation. In the face of global environmental change, habitat fragmentation, and anthropogenic pressures, understanding the ecological needs and population dynamics of these species is crucial for effective conservation strategies and their long-term survival (Kulymbet et al. 2023; Tastanbekova et al. 2025).

Euphorbia yaroslavii Poljakov, a rare and poorly studied herbaceous perennial from the Euphorbiaceae family, is a narrow endemic found in the semi-arid foothills of Southeastern Kazakhstan. Its above-ground rosette and inflorescence are short-lived, emerging in early spring and senescing by summer, while underground perennating organs ensure persistence. The species is confined to a few isolated localities in the Zailiyskiy Alatau mountain range, primarily occurring on stony slopes and piedmont terraces. Listed in Kazakhstan's Red Data Book, it faces high conservation concern due to its limited range, habitat specificity, and vulnerability to land-use changes and climate pressures. *Euphorbia yaroslavii's* fragmented populations, weak regeneration, and unbalanced age structure make it particularly susceptible to environmental disturbances, further exacerbated by habitat degradation and grazing (Red Data Book of Kazakhstan 2014).

Ecologically, *E. yaroslavii* displays a high specificity to edaphic and microclimatic conditions. It predominantly grows on fine-textured, carbonate-rich, or weakly saline soils that are generally low in fertility and organic matter. These substrates undergo seasonal extremes from rapid desiccation in summer to excessive surface moisture after spring snowmelt (Karabalayeva et al. 2025). As a result, the species has evolved adaptations to drought and nutrient limitation, yet its narrow ecological amplitude restricts its colonization potential even within favorable areas (Pachikin et al. 2014).

Soil quality - including texture, structure, chemical composition, and organic matter - directly influences seed germination, plant growth, and reproductive success (Amirov et al. 2023). In arid and semi-arid ecosystems, even small variations in nutrient availability can lead to substantial changes in vegetation cover, species composition, and population dynamics of endemic taxa (Osmonali et al. 2024a), for narrowly distributed species like *E. yaroslavii*, which exist near the limits of their physiological tolerance, soil chemical composition may be a decisive factor governing local abundance and vitality. Vegetation structure and community composition can also reflect habitat suitability (Tynybekov et al. 2024). Dense herbaceous cover retains soil moisture and moderates temperature fluctuations, promoting seedling establishment and adult survival (Osmonali et al. 2024b), whereas certain companion species may indicate restrictive soil conditions (Ding et al. 2025). Therefore, combining vegetation assessment with soil analysis provides a valuable framework for identifying edaphic filters shaping the population structure of threatened species.

Despite extensive research on plant ecological requirements in Europe and North America, studies on the interactions between soil properties and the population structure of Central Asian endemics remain limited. Investigations on *Euphorbia* species have mainly addressed growth physiology or reproduction of cultivated and widespread taxa (Kamel et al. 2025; Sakhawy et al. 2025). In contrast, *E. yaroslavii* occupies a narrow distribution range and highly specific habitats, emphasizing the need for focused ecological analysis to understand its niche specialization.

Recent studies highlight that soil texture, base saturation, salinity gradients, and exchangeable cations, particularly magnesium, are key factors in edaphic niche specialization in arid and semi-arid systems (Tongkoom et al. 2021; Jiang et al. 2022; Naorem et al. 2023; Aldassugurova et al. 2025). In dryland ecosystems, the sand-clay ratio, organic carbon, and salinity affect recruitment and biomass accumulation of steppe forbs (Muratbayeva et al. 2025). Loamy-calcareous soils in the Eurasian steppe provide essential rooting depth, microbial stability, and nutrient reserves (Głąb and Gondek 2025). Similarly, *Euphorbia margalidiana* Kuhbier & Lewej. and *Euphorbia schoenlandii* Pax depend on soil carbonate content and magnesium availability (Llorens et al. 2023; Jabar et al. 2024). However, the role of soil factors in the population dynamics of narrowly endemic *Euphorbia* species in Central Asia remains largely unexplored. This study aims to clarify these relationships and support site-specific conservation strategies.

The present study aims to identify the key edaphic and ecological factors that determine the population abundance and distribution of *E. yaroslavii* in the foothills of the Zailiyskiy Alatau. By integrating soil profiling, chemical characterization, and vegetation surveys, this research examines how variations in soil texture, nutrient composition, and base saturation shape the spatial structure of *E. yaroslavii* populations. The results are expected to contribute to species-specific conservation measures and improve understanding of edaphic filtering processes in arid mountain-steppe ecosystems.

MATERIALS AND METHODS

Study area

The study was carried out in three mountain gorges of the Zailiyskiy Alatau, Almaty Region, Southeastern Kazakhstan: Ushkonyr Gorge (population 1/P1) is located in Karasai District at elevations of 1,050-2,290 meters above sea level (masl) (mean ≈ 1,670 m). Shamalgan Gorge (population 2/P2) extends from 750 to 1,600 masl. (mean ≈ 1,175 m). Kaskelen Gorge (population 3/P3) cuts into the piedmont plain at 700-1,800 masl. (mean ≈ 1,250 m). All three gorges belong to the northwestern spur of the Tien Shan (Figure 1, Table 1).

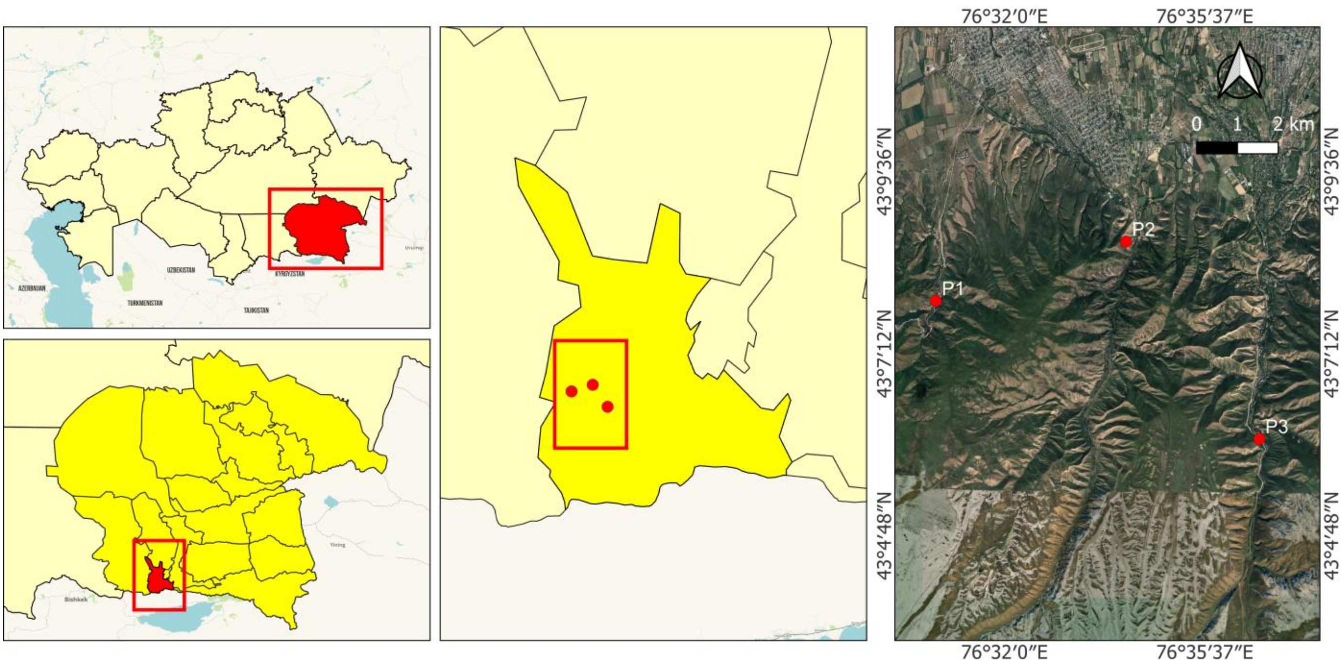


Figure 1. Map of the three studied populations of *Euphorbia yaroslavii*: Ushkonyr Gorge (P1), Shamalgan Gorge (P2), Kaskelen Gorge (P3) in Zailiyskiy Alatau, Southeastern Kazakhstan

Table 1. Geographical characteristics of *Euphorbia yaroslavii* populations

Population (P)	Location (mountain gorge, Zailiyskiy Alatau)	Elevation (masl ±SD)	Latitude (N)	Latitude (E)
P1	Zailiyskiy Alatau, Ushkonyr Gorge	1,276 ± 12	43.131590°	76.512721°
P2	Zailiyskiy Alatau, Shamalgan Gorge	1,171 ± 9	43.144616°	76.569955°
P3	Zailiyskiy Alatau, Kaskelen Gorge	1,315 ± 10	43.101270°	76.610102°

Note: Elevation values represent mean ± Standard Deviation (SD) calculated from GPS measurements (n = 5 per site)

The climate is sharply continental with pronounced altitudinal zonation. In the foothills (600-1300 masl), mean January temperature is -7.4°C, mean July temperature +23°C, and annual precipitation about 560 mm; in the mid-mountain belt (1,300-2,500 masl) January averages range from -11.3 to -4.3°C, July from +7 to +18°C, with 734-843 mm of precipitation; above 2,500 masl. Annual precipitation rises to 900-1300 mm, predominantly as snow (Kazhydromet 2024). Up to 65-70% of the annual rainfall occurs in the warm season (April-September). On the foothill slopes, gray soils (serozems) predominate; in the mid-mountain belt, mountain chestnut and mountain–chernozem soils with deeply humified profiles on loess and colluvial substrates develop; on south-facing exposures, thermoxeromorphic mountain–steppe and mountain–meadow soils are encountered (Balkybek et al. 2025).

Field work was performed during two consecutive seasons (May-June 2024 and May–June 2025). Reconnaissance visits in April documented vegetative emergence; abundance counts used in analyses were taken at peak flowering (late May-early June) to maximize detectability. The selection of these populations was made taking into account their distinct geographic positions within the Zailiyskiy Alatau, as well as pronounced differences in landscape, soil characteristics, and elevation, thereby encompassing the main ecological gradients of the species' range (Table 1).

Botanical analysis

Botanical methods were employed to investigate populations of *E. yaroslavii* and their relationships with abiotic environmental components. For each identified cenopopulation locus, a detailed botanical description was made using GPS navigation to record exact coordinates. Fieldwork was carried out by route reconnaissance: the study area was traversed on foot along pre-planned routes, enabling coverage of extensive terrain and documenting the species' distribution across varied ecological–cenotic conditions. Population structure was analyzed using modern plant population-biology approaches (Ydyrys et al. 2024).

At each cenopopulation locus (CP1-CP3 within each gorge), we established three belt transects of 50 m² each (total 150 m² per CP; 450 m² per gorge). Within each transect, all *E. yaroslavii* individuals were counted. The abundance metric for analysis was the total number of individuals per cenopopulation (sum across its three transects). Cenopopulations within a gorge were separated by ≥200-500 m and located on distinct slope facets, aspects or terrace positions to ensure ecological independence.

Herbarium processing of plant material followed standard protocols: collected specimens of *E. yaroslavii* and accompanying species were mounted on herbarium sheets with labels indicating the collection site, date, and collector's name. After fieldwork, samples were air-dried and examined in detail using a stereomicroscope. The procedures for collection, preservation, and preliminary processing of herbarium material conformed to accepted methodological guidelines (Kolesnikov 2015). Voucher specimens of *E. yaroslavii* were collected from all three study sites (Ushkonyr, Shamalgan, and Kaskelen Gorges, Zailiyskiy Alatau). The primary voucher is deposited in the Herbarium of the Institute of Botany and Phytointroduction (AA, Almaty, Kazakhstan).

The surveys were conducted outside the core zones of protected territories and complied with national regulations for research on endemic and Red Book-listed taxa. Species-level and taxonomic identifications were carried out in the laboratory using authoritative multi-volume keys and floristic manuals (Flora of Kazakhstan 1966). The community species list was cross-checked against up-to-date electronic databases. The schematic map was created using ArcGIS Desktop 10.4 (2024).

Soil analysis

Morphological soil descriptions were conducted on key plots hosting E. yaroslavii populations. Soil pits were excavated to characterize edaphic factors influencing the species' growth and abundance. Field diagnostics included horizon description, Munsell color assessment (Soil Survey Staff (USDA–NRCS) 2014), texture and root penetration evaluation, HCl carbonate testing, and moisture assessment, following standard guidelines (Korolyuk et al. 2012). Nine soil profiles were examined—three per site—and 52 soil samples were collected for chemical analysis.

Organic matter (humus) content was determined by the Tyurin spectrophotometric method following FAO (2021) guidelines. Total nitrogen was analyzed by titration using the Kjeldahl method in accordance with FAO (2025). Total phosphorus and potassium concentrations were measured spectrophotometrically using a Specord 210 Plus (Analytik Jena, Germany). Soil pH was measured potentiometrically with a pH meter I-160MI, Russia 2007 (ISO 10390. 2021). The CO_2 content was determined using a calcimeter to estimate carbonate concentration. Exchangeable Mg^{2+} was quantified by 1 M ammonium acetate extraction (pH 7.0) followed by AAS/ICP-OES; detection limit, QA/QC blanks and certified reference soils.

Particle-size distribution was determined according to USDA classification standards, with granulometric fractions defined as follows: sand (2.0-0.05 mm), silt (0.05-0.002 mm), and clay (<0.002 mm). The intermediate 0.005-0.001 mm fraction was apportioned 75% to silt and 25% to clay, following USDA methodology. The resulting percentage values were normalized to 100% and plotted on the USDA soil texture triangle for classification (USDA Natural Resources Conservation Service 2013). All analyses were carried out according to ISO 10390 (2005) standards. All sample was analyzed in four parallel replicates.

Pairing of botanical and soil data

We excavated one soil profile per cenopopulation (total n = 9), positioned within 5-10 m of the cenopopulation transects at the same micro-site (slope, aspect, surface cover) and on undisturbed ground. For correlation analyses, soil variables were taken from the surface 0-20 cm (A horizon). For parameters quantified by horizons, we computed depth-weighted means for 0-20 cm. This ensured a one-to-one pairing between each cenopopulation's abundance and its own co-located soil measurements.

Statistical analysis

The statistical unit was the cenopopulation (CP; n = 9). For each CP we analyzed the relationship between total abundance (sum across three 50 m² transects) and its paired soil properties (0–20 cm). Given the spatial separation among CPs, observations were considered independent. As a robustness check, we repeated partial correlations controlling for "gorge" (Ushkonyr, Shamalgan, Kaskelen) as a three-level factor; signs and magnitudes of the key associations remained unchanged.

To assess the relationships between *E. yaroslavii* abundance and abiotic environmental factors, Pearson's correlation analysis was performed. All statistical analyses were conducted in R-Studio, using base functions for Pearson correlations and *stats* for partial correlations. Figures were produced with *ggplot2*. This method evaluates the linear association between two quantitative variables (Zar 1999). The correlation coefficient (r) was calculated according to the following formula:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2}}$$

Where, x_i and y_i: values of the variables, $\bar{x}$ and $\bar{y}$: mean values

The following soil parameters were included in the analysis: humus content (%), available nitrogen (N), phosphorus (P_2O_5), potassium (K_2O) (mg/kg), pH, carbon dioxide (CO_2, %), total soluble salts, and soil texture (percentages of sand, silt, and clay).

Prior to correlation analysis, data were tested for normality using the Shapiro–Wilk test. Only variables exhibiting a normal distribution were included in the Pearson correlation. Correlations were considered statistically significant at $p < 0.05$. The resulting r-values were interpreted according to the conventional scale: weak ($r < 0.3$), moderate ($0.3 \leq r < 0.7$), and strong ($r \geq 0.7$).

RESULTS AND DISCUSSION

Morphological soil profiles within *Euphorbia yaroslavii* populations

P-1 (population 1). Ushkonyr Gorge. The soil profile has an average thickness of 100 cm and exhibits a well-developed structure. The parent material is composed of deluvial–proluvial loams. The combined humus horizon (A + B) is 42 cm thick. Humus content is 3.11% in the surface A horizon, decreasing to 1.70% in the B horizon (Table 2).

P-2 (population 2). Shamalgan Gorge. The soil profile has an average thickness of 80 cm and exhibits a well-developed structure. The parent material consists of deluvial–proluvial loams. The combined humus horizon (A + B) is 40 cm thick. Humus content is 3.79% in the surface A horizon, decreasing to 2.07% in the B horizon (Table 3).

P-3 (population 3). Kaskelen Gorge. The soil profile has an average thickness of 100 cm and exhibits a well-developed structure. The parent material consists of deluvial–proluvial loams. The combined humus horizon (A + B) is 48 cm thick. Humus content is 2.94% in the surface A_0 horizon, decreasing to 1.33% in the B horizon (Table 4).

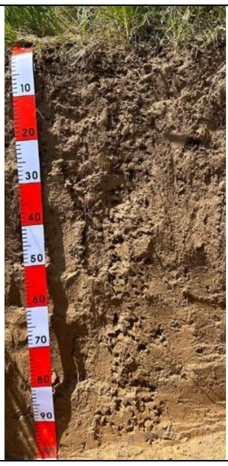
Table 2. P-1 Ushkonyr Gorge, Zailiyskiy Alatau, Southeastern Kazakhstan

Horizons	Depth, cm	Thickness, cm	Description
A	0-20	20	10YR 4/1, fresh, loose, loam, abundant roots, gravelly, nutty-granular structure, moderate effervescence, gradual color transition.
B	20-42	22	10YR 5/1, fresh, compacted, loam, coarse roots, granular–powdery structure, stony-gravelly, vigorous effervescence, gradual color transition.
BC	42-65	23	10YR 7/1, moist, compacted, loam, powdery-dusty texture, stony, vigorous effervescence, gradual color transition.
C	65-100	35	10YR 7/2, moist, compacted, loam, with inclusions of stones, carbonate accumulation, vigorous effervescence.

Table 3. P-2 Shamalgan Gorge, Zailiyskiy Alatau, Southeastern Kazakhstan

Horizons	Depth, cm	Thickness, cm	Description
A	0-17	17	10YR 5/1, dry, loose, loamy sand, nutty–granular, many roots, gravelly, no effervescence, clear color boundary.
B	17-40	23	10YR 5/2, fresh, dense, sandy loam, nutty–powdery structure, stony–gravelly, inclusions of stones, occasional roots present, no effervescence, gradual color transition.
C	40-80	40	10YR 4/1, moist, dense, loamy sand, powdery-dusty structure, stony, roots rare, weak effervescence.

Table 4. P-3 Kaskelen Gorge, Zailiyskiy Alatau, Southeastern Kazakhstan



Horizons	Depth, cm	Thickness, cm	Description
A_0	0-8	8	10YR 4/1, fresh, loose, loamy sand, nutty–granular, abundant fine roots, insect channels and burrows, plant residues, weak effervescence, gradual color transition.
A	8-20	12	10YR 5/1, fresh, moderately compacted, loam, nutty–granular, abundant fine roots, plant residues, vigorous effervescence, carbonate remnants, clear color boundary.
B	20-48	28	10YR 7/2, fresh, compacted, sandy loam, dusty-powdery, abundant roots, carbonate accumulation, vigorous effervescence, gradual color transition.
C_1	48-80	32	10YR 8/6, moist, compacted, loam, dusty-powdery, occasional roots, carbonate accumulation, vigorous effervescence, gradual color transition.
C_2	80-100	20	10YR 9/8, moist, compacted, loam, powdery-dusty, occasional roots, vigorous effervescence.

Soil chemistry

P-1 is characterized by a thick humus horizon (3.11%) and high exchangeable K in the 0–20 cm layer, but both P and K decline sharply with depth. At the same time, CO_2 concentration and pH steadily increase down the profile. P-2 exhibits the highest surface-layer phosphorus (34 mg/kg) and humus content (3.79%), slightly acidic pH constrains the growth of *E. yaroslavii*. P-3 has an upper layer rich in N (64-70 mg/kg) and K (500 mg/kg); however, humus and Ca decrease with depth, while Na and Mg accumulate in the subsoil.

The higher and more evenly distributed the humus, the better the soil's potential to maintain fertility and moisture regimes (Toktar et al. 2019). P-1 leads in organic matter, P-2 is more uniform, and P-3 is the most depleted.

In P-3, CO_2 rises sharply from 0.98% to 6.21%, and pH remains stably in the slightly alkaline range (7.49→7.94). P-2 shows low CO_2 (0.16-0.33%) and a more acidic reaction (pH 6.66-6.93). In P-1, CO_2 is moderate (3.59→7.68%) and pH is near neutral–alkaline (7.40→7.94). Exchangeable Ca^{2+} is high in all profiles (9.41-17.82 cmol(+)/kg); P-3 slightly surpasses the others in the surface layer, while P-1 and 2 are similar. All profiles are calcium-magnesium dominated, but P-3 exhibits a distinctly stronger magnesium component (Figure 2).

For each soil profile (population 1, population 2, and population 3), the mass proportions of the major cations Ca^{2+}, Mg^{2+}, and ($Na^{+} + K^{+}$) were determined. On the cation ternary diagram (Figure 2, left panel), P-3 samples (0-8, 8-20, 20-48, and 48-80 cm) plot closer to the Ca-Mg apex, indicating a dominance of calcium and magnesium, with the relative share of Na + K increasing with depth (48-80 cm). P-2 samples (0-17, 17-40, and 40-80 cm) shift toward the center of the triangle, reflecting a more balanced Ca^{2+} and Mg^{2+} ratio and moderate Na + K content. In P-1 (0-20, 20-42, 42-65, and 65-100 cm), there is a trend of decreasing Mg^{2+} and increasing Na + K in the mid-horizon (20-42 cm), after which the contribution of Ca^{2+} rises again in the deeper horizons.

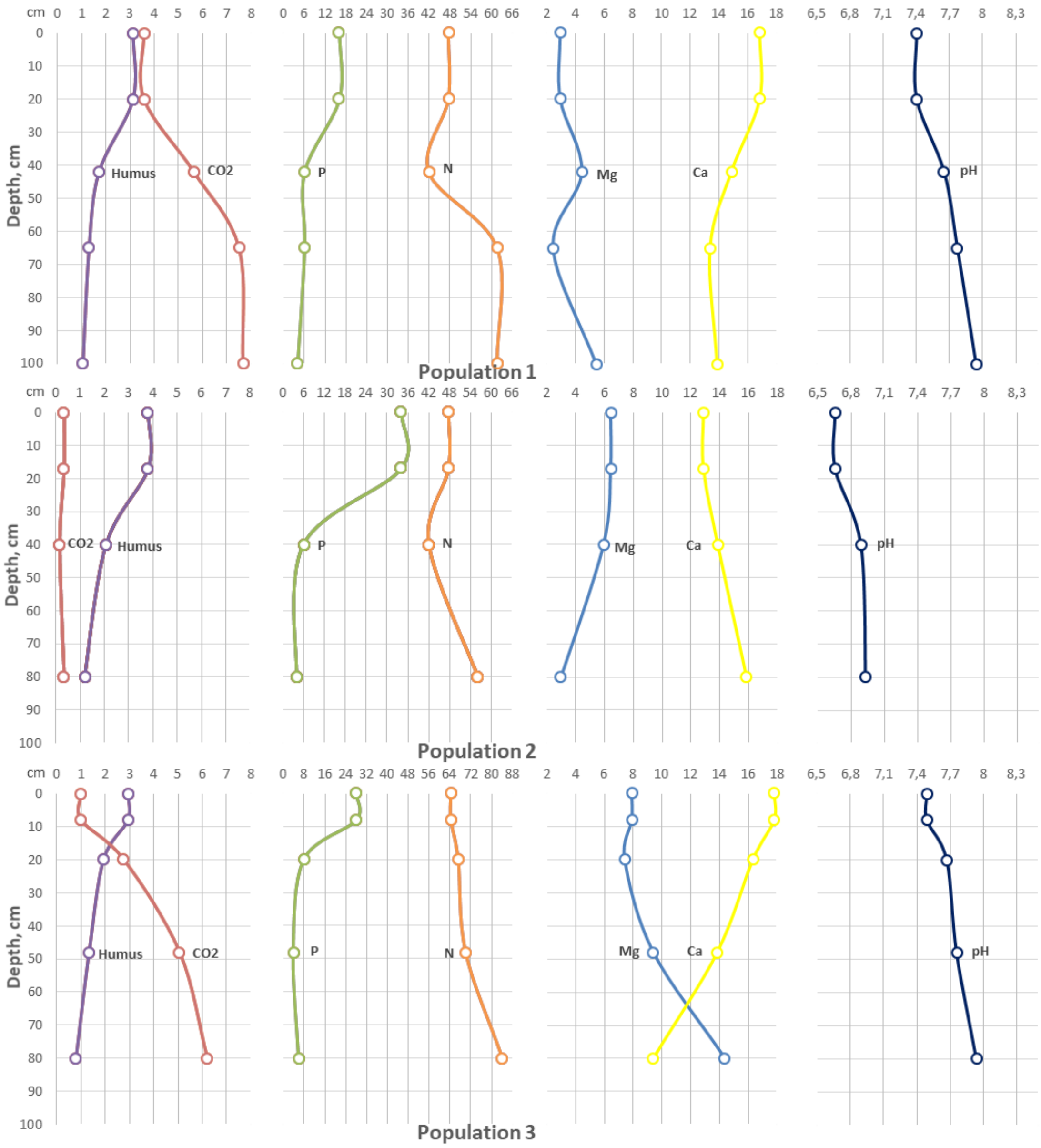


Figure 2. Soil chemical composition across three *Euphorbia yaroslavii* populations in the Zailiyskiy Alatau, Southeastern Kazakhstan: Ushkonyr Gorge (population 1), Shamalgan Gorge (population 2), and Kaskelen Gorge (population 3)

A similar ternary analysis of the main anions Cl^-, SO_4^{2-}, and HCO_3^- (Figure 2, right panel) showed that most samples are dominated by the sulfate–chloride complex ($SO_4^{2-} + Cl^-$), whereas bicarbonate varies markedly: at the surface of P-1 and P-3 its share is 32-34%, while in P-2 it falls to 7-10% in the deep horizons. Of particular note is the jump in SO_4^{2-} in the P-3 sample (20-48 cm) up to 63%, indicating a pronounced sulfate complex in the mid-horizon.

The Piper diagram of overall composition (Figure 3, central panel) illustrates the main bicarbonate–calcium–chloride (HCO_3^--Ca^{2+}-Cl^-) and sulfate–sodium (SO_4^{2-}-Na^+) facies. Samples from P-3 cluster in the Ca-Cl-HCO_3 field, characteristic of thin, calcareous soils, whereas P-2 and P-1 shift toward the Na-SO_4 corner along the lower margin of the diamond, indicating accumulation of sodium-sulfate salts under more humid or lowland conditions (Figure 3). Accordingly, these soils are classified as non-saline. In all profiles, total salt concentration does not exceed 0.13%, which falls within the non-saline category.

Soil texture

P-1 is loam throughout its depth. With sand contents of about 45-48% and silt around 15%, this profile exhibits high moisture-retention capacity. P-1 is the most balanced and homogeneous of the three. Sandy textures dominate P-2. Its upper (0-17 cm) and lower (40-80 cm) horizons classify as loamy sand, indicating high permeability and low water-holding capacity. The middle horizon (17-40 cm) is sandy loam, with a moderate increase in silt (~18%) and fine dust. Overall, P-2 retains a predominantly sandy character-especially in the upper and lower layers-consistent with its low moisture-holding potential.

P-3 exhibited a heterogeneous texture. The surface horizon (0-8 cm) is classified as loamy sand, dominated by sand

(>68%) with minimal silt (~8%). The subsurface horizons (8-20 cm and 48-80 cm) are classified as loam, with balanced proportions of sand, silt, and clay. The 20-48 cm interval is sandy loam, reflecting a slight predominance of sand. Thus, P-3 shows a transition from a lighter texture at the surface to a more structured loam in the deeper layers (Figure 4).

Phytocenotic structure of *Euphorbia yaroslavii* populations

Across the Zailiyskiy Alatau foothill gorges (Ushkonyr, Shamalgan, Kaskelen), *E. yaroslavii* is embedded in herb–grass–shrub steppe mosaics on calcareous loams rather than forming monodominant stands. The species typically co-occurs with grasses (*Poa stepposa* (Krylov) Roshev., *Bromus inermis* Leyss., *Agropyron cristatum* (L.) Gaertn.; locally *Stipa lessingiana* Trin. & Rupr., *Stipa capillata* L.), forbs (*Inula grandis* Schrenk ex Fisch. & C.A.Mey., *Iris albertii* Regel, *Ajania astigiata* (C.Winkl.) Poljakov, *Vicia crassa* L., *Achillea millefolium* L., *Origanum vulgare* L., *Chaerophyllum prescotti* DC., *Eremurus tianschanicus* Pazij & Vved. ex Pavlov), and shrubs (*Spiraea hypericifolia* L., *Rosa spinosissima* L., *Lonicera hispida* Pall. ex Schult., *Lonicera microphylla* Willd. ex Roem. & Schult.; locally *Caragana balchashensis* (Kasn. ex Kom.) Pojark.).

P1 Ushkonyr. CP1–CP3 represent herbaceous/grass–shrub assemblages with high forb diversity; *E. yaroslavii* occurs alongside *Euphorbia lamprocarpa* (Prokh.) Prokh. and the shrub layer of *Spiraea–Rosa–Lonicera* (individuals: 78, 48, 62).

P2 Shamalgan. Communities range from grass–herb–shrub to sedge-rich patches (*Carex taldycola* Meinsh., *Carex turkestanica* Regel); *E. yaroslavii* co-occurs with the same dominant grasses/forbs (15, 40, 38).

P3 Kaskelen. Herbaceous–shrub assemblages with *Inula*, *Vicia*, *Ajania*, *Iris* and shrubs including *Caragana*; *E. yaroslavii* present with *E. lamprocarpa* (18, 23, 15).

Taken together, *E. yaroslavii* is not isolated ecologically; it occupies patches within species-rich, calcareous steppe communities, with local abundance highest in well-drained, loamy herb–grass–shrub mosaics and lower in sedge-prone, finer-textured patches (Figure 5).

The Ushkonyr population (P-1) is characterized by the highest total abundance (Σ = 188 individuals) and the greatest species diversity (including grasses, forbs, and shrubs). The most favorable habitat for *E. yaroslavii* is CP1.

The Shamalgan population (P-2) comprises a total of 93 individuals. The highest abundance occurs in CP2 (sedge community), indicating a preference of *E. yaroslavii* for more humid, sedge-dominated microhabitats in this gorge.

The Kaskelen population (P-3) is relatively small (Σ = 56 individuals). Optimal conditions are found in the grass-shrub association (CP2), whereas the lowest abundance occurs in cenopopulation 3, where the cover is less grass-dominated.

Correlation analysis

To identify the ecological and soil-chemical factors determining *E. yaroslavii* population abundance, Pearson correlation coefficients were calculated between the total number of plants in each profile and various soil parameters.

The key factors and their correlations with abundance were: Humus content: r = +0.80. Soils with higher organic matter levels support larger populations, owing to enhanced nutrient availability, greater water-holding capacity, and improved aggregate stability-conditions that favor seed germination and seedling growth (Toktar et al. 2024).

Soil texture: Sand (%): r = +0.95. Clay (%): r = +0.87. These very strong positive correlations indicate that *E. yaroslavii* thrives in a loamy substrate that combines coarse (sand) and fine (clay) particles, thereby balancing soil aeration with moisture retention.

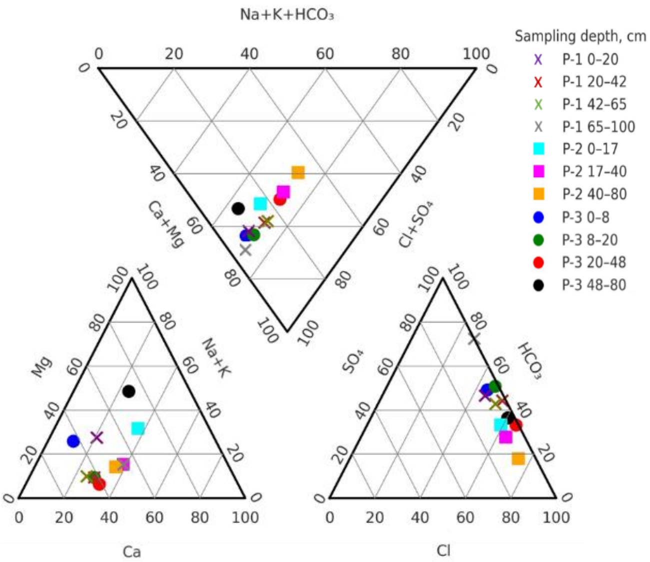


Figure 3. Piper diagrams the distribution of major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}) in soil samples collected from three study sites (P1-P3) at different soil depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm)

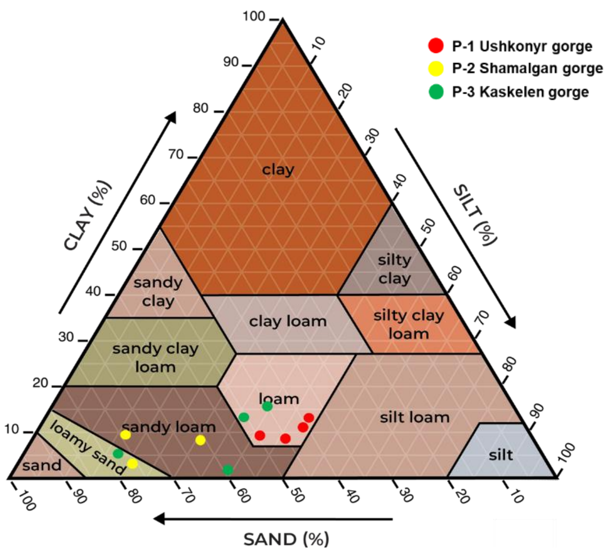


Figure 4. Soil texture classification based on particle size distribution for *Euphorbia yaroslavii* habitats. Each point represents a sample (n = 9 total) plotted within the USDA soil texture triangle, showing relative proportions of sand, silt, and clay

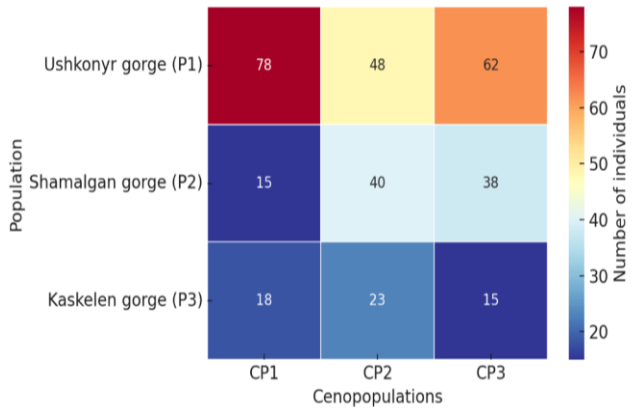


Figure 5. Heatmap showing the number of *Euphorbia yaroslavii* individuals across three cenopopulations (CP1-CP3) at each study site: Ushkonyr (P1), Shamalgan (P2), and Kaskelen (P3). Color gradient indicates abundance intensity (red = high, blue = low)

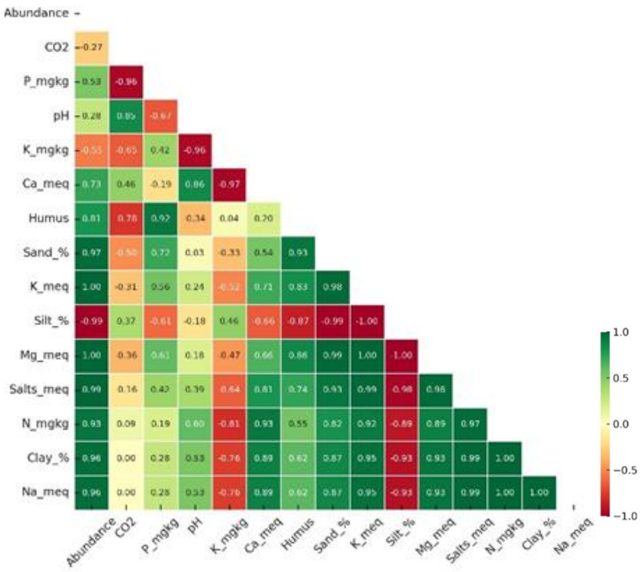


Figure 6. Pearson correlation matrix illustrating relationships between soil physicochemical parameters pH, humus, N, P, K, CO_2, texture fractions and *E. yaroslavii* abundance across all sites

Mobile nitrogen (N): r = +0.93 with population abundance. High reserves of mineral nitrogen directly stimulate the accumulation of vegetative biomass in *E. yaroslavii*.

Exchangeable magnesium and total base cation content: Mg^{2+} (meq/100 g): r = +0.92. Σ salts (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}): r = +0.94. Base cations - especially magnesium - are crucial for maintaining the structural integrity of cell walls and supporting photosynthesis; a high base saturation reinforces the soil matrix that underpins the species' deep rooting system.

Negative effect of silt: Silt % – population abundance: r = -0.88. Excessive silt reduces soil permeability and aeration, which impedes root respiration and water infiltration (Figure 6).

Correlation analysis demonstrated that *E. yaroslavii* prefers structurally balanced habitats rich in humus and base cations. Excessive silt content and low base saturation negatively impact population abundance. These findings will inform species-conservation planning and the design of restoration measures.

Co-variation analyses indicated that Mg^{2+} tended to increase in better-aerated loams (higher sand and clay, lower silt), consistent with deeper rooting and base saturation patterns (see Figure 6).

Conservation status, threats, and habitat vulnerability

E. yaroslavii is a narrow Kazakh endemic recorded at three discrete sites in the Zailiyskiy Alatau (Ushkonyr, Shamalgan, Kaskelen), indicating habitat fragmentation by roads, settlements, and recreation infrastructure. Populations occur on well-drained, calcareous loams; the species is not halophytic. Principal threats include trampling and soil disturbance from recreation/trail works, localized grazing and compaction, small-scale construction, and invasion by ruderal species. Our data provide a one-season snapshot, so a trend (decline and stability) cannot yet be inferred; we recommend annual monitoring of abundance and stage structure, and mapping of EOO and AOO. As of July 2025, the species is not assessed by the IUCN Red List, global category: not evaluated; nationally it is treated as of conservation concern (IUCN 2025). Priority actions: protect microhabitats with base-rich loams, limit trampling and grazing during peak phenology, control invasives, and consider ex situ seed banking.

Discussion

In this study, we identified the key soil factors determining the population abundance of *E. yaroslavii* in three mountain gorges of Kazakhstan. Pearson correlation analysis highlighted the paramount importance of soil textural, structural, and chemical properties, as well as organic matter and mineral nitrogen content, whereas phosphorus parameters proved to be statistically less significant.

From a niche-theory perspective, our results delineate the Grinnellian (abiotic) niche of *E. yaroslavii*: the species peaks on well-drained, calcareous loams (≈40-50% sand, 20-30% clay) with slightly alkaline pH (7-8), humus ≥ 2%, and high Mg-rich base saturation. These edaphic conditions act as environmental filters in arid foothills, supporting root aeration, stable water supply, and Mg-dependent photosynthetic efficiency, whereas silt-rich horizons likely exclude the species via reduced gas diffusion, surface crusting, and episodic waterlogging. In Hutchinson's n-dimensional niche terms, texture, pH, Ca-Mg status, organic matter, and low salinity jointly define the realized hypervolume of *E. yaroslavii.*

Ecologically, *E. yaroslavii* is a calciphilous meso-xerophyte, not a halophyte: soluble salts were low and halophytic traits were absent. Positive associations with pH and Ca^{2+}/Mg^{2+} reflect calcareous affinity; Mg - as a chlorophyll cofactor and enzyme activator - likely enhances carbon fixation and drought tolerance, explaining higher abundance on base-rich horizons. This pattern mirrors other *Euphorbia* endemics on calcareous substrates (e.g., *E. margalidiana*; Llorens et al. 2023) and parallels gypsumadapted congeners (*Euphorbia gypsicola* Rech.f. & Aellen, *Euphorbia bungei* Boiss.) with narrow edaphic specialization and reliance on Ca/Mg-enriched horizons (Palacio et al. 2022; Rabizadeh and Nasiri 2023). This view aligns with our recommendation to manage soils as base-rich but non-saline, with balanced macronutrients (N, P, K) and sufficient Mg rather than Mg alone.

The negative relationship between silt and abundance (r = -0.88) is consistent with previous observations that fine-textured, poorly aerated soils restrict root respiration and water infiltration, thereby suppressing plant establishment (Dexter et al. 2010; Głąb and Gondek 2025; Muratbayeva et al. 2025). Loamy soils, in contrast, provide optimal conditions for both gas diffusion and moisture retention- an advantage frequently reported for endemic or stress-sensitive taxa in semi-arid regions (Ramos et al. 2020).

The strong positive correlation with humus (r = +0.80) and mineral nitrogen (r = +0.93) underscores the role of organic matter in maintaining nutrient cycling and microbial activity. This relationship reflects the well-known coupling between soil organic carbon, CO_2 flux, and nitrogen mineralization (Six et al. 2000). Populations growing on humus-poor soils (e.g., P3, Kaskelen Gorge) exhibited lower regeneration and fewer individuals, suggesting that biogenic substrate enrichment supports demographic stability.

The positive correlation between soil pH, Ca^{2+}, and Mg^{2+} highlights the calcareous affinity of *E. yaroslavii*. This pattern agrees with evidence from Mediterranean and Central Asian *Euphorbia* species preferring alkaline, $CaCO_3$-rich substrates (Moore et al. 2014; Palacio et al. 2022). The particularly strong relationship with Mg (r = +0.92) supports the hypothesis of "Mg-favoritism" in eutrophic ephemeroids, where Mg^{2+} acts as a critical cofactor in chlorophyll synthesis and enzymatic activation (Marschner et al. 2012; Brady and Weil 2016; Ahmed et al. 2023). Magnesium enrichment may therefore underpin the higher photosynthetic efficiency and growth performance observed in *E. yaroslavii* populations inhabiting base-saturated soils.

This study integrates observations from two spring–early summer seasons (2024-2025), without evaluating other ecological variables such as microclimate or competition. Correlation-based results also indicate association rather than causation, which reduces, but does not eliminate, uncertainty in interannual dynamics. We therefore recommend long-term monitoring (≥5 years) to track abundance, recruitment, and soil–moisture–nutrient variability and to detect potential directional trends under ongoing climatic and land-use pressures.

In conclusion, our results fit within the broader framework of *Euphorbia* edaphic specialization, where substrate texture and cation composition define population structure and abundance. The species thrives in loamy calcareous soils with moderate sand and clay content, slightly alkaline pH, and high base saturation dominated by Ca^{2+} and Mg^{2+}. These edaphic conditions provide optimal aeration and nutrient balance, supporting growth and reproduction. These findings emphasize the importance of maintaining loamy, calcareous soils with adequate organic inputs and a balanced nutrient regime (N, P, K with sufficient Mg and trace elements) for the conservation and restoration of *E. yaroslavii* habitats.

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REFERENCES

Ahmed N, Zhang B, Bozdar B, Chachar S, Rai M, Li J, Li Y, Hayat F, Chachar Z, Tu P. 2023. The power of magnesium: Unlocking the potential for plant growth. Front Plant Sci 14: 1285512. DOI: 10.3389/fpls.2023.1285512.

Aldassugurova C, Ultanbekova G, Ametov A, Aksoy A, Kulymbet K, Akhmetova A, Nazarbekova S, Childibayeva A, Bazarbayeva T, Mukanova G, Baibotayeva A. 2025. Agrochemical compositions of soils and rhizosphere microorganisms of *Rosa potentilliflora* Chrshan. et M. Pop. in eastern and central part of Zailiyskiy Alatau. Ecol Process 14: 66. DOI: 10.1186/s13717-025-00634-9.

Amirov B, Seytmenbetova A, Kulymbet K, Tanirbergenov S. 2023. Modelling of fertilization on the photosynthetic and yield indicators of melon (*Cucumis melo* L.) under the saline soils of Southern Kazakhstan. Res Crop 24: 307-315. DOI: 10.31830/2348-7542.2023.ROC-945.

ArcGIS Desktop 10.4. 2024. Available online: https://desktop.arcgis.com/ (accessed on 26 September 2024).

Balkybek Y, Tynybekov B, Kulymbet K, Kurmanbay U, Umirbayeva Z, Nurakyn Z, Myltykbayeva A, Ydyrys A, Toktar M. 2025. Study of soil cover of *Veronica spuria* L. populations in Ile Alatau mountains, Kazakhstan. EQA-Intl J Environ Qual 66: 99-106. DOI: 10.6092/issn.2281-4485/20806.

Brady NC, Weil RR. 2016. The Nature and Properties of Soils (15th ed.). Pearson. Available online: https://www.pearson.com/ (accessed on 9 June 2025).

Dexter AR, Czyż EA, Goss MJ. 2010. Integrating soil physical properties as indicators of soil quality. In: Magdoff F, Weil RR (eds.). Soil Organic Matter in Sustainable Agriculture (2nd ed.). CRC Press, Boca Raton.

Ding Y, Liu Y, Dang Q, Akram Z, Arshad A, Zhu H, Zhang J, Han B, Turghun C. 2025. Study on the chemical composition and multidrug resistance reversal activity of *Euphorbia uralensis* (Euphorbiaceae). Intl J Mol Sci 26 (1): 412. DOI: 10.3390/ijms26010412.

FAO. 2021. Tyurin Spectrophotometric Method. Available online: https://openknowledge.fao.org/ (accessed on 3 January 2025).

FAO. 2025. Standard Operating Procedure for Soil Nitrogen Kjeldahl method. Available online: https://openknowledge.fao.org/ (accessed on 3 January 2025).

Flora of Kazakhstan. 1966. Alma-Ata, Volumes 1-9.

Głąb T, Gondek K. 2025. Enhancing Soil physical quality with diatomite amendments. Agronomy 15 (2): 424. DOI: 10.3390/agronomy15020424.

ISO 10390. 2021. Soil, Treated Biowaste and Sludge - Determination of pH. Geneva, Switzerland.

IUCN. 2025. The IUCN Red List of Threatened Species. Version 2025-2. https://www.iucnredlist.org. Accessed on 01 July 2025.

Jabar L, Siebert SJ, Pfab MF, Cilliers DP. 2024. Ecology, population biology and conservation status of *Euphorbia schoenlandii* Pax, an endemic to the Succulent Karoo, South Africa. S Afr J Bot 170: 48-60. DOI: 10.1016/j.sajb.2024.05.013.

Jiang LM, Sattar K, Lü GH, Hu D, Zhang J, Yang XD. 2022. Different contributions of plant diversity and soil properties to the community stability in the arid desert ecosystem. Front Plant Sci 25 (13): 969852. DOI: 10.3389/fpls.2022.969852.

Kamel AI, Badawy SA, Abdel-Mogib M, El-Rokh AR. 2025. Phytochemical, biological, DFT, and molecular docking evaluation of *Euphorbia paralias*. Sci Rep 15 (1): 17961. DOI: 10.1038/s41598-025-02420-1.

Karabalayeva D, Kurmanbayeva M, Kulymbet K, Kusmangazinov A, Zhumagul M, Anatoliy R, Saken M, Kuanyshbayeva M, Alzhanova B. 2025. Influence of soil characteristics on the distribution and evolution of *Trollius dschungaricus* Regel populations in the Northern Tien Shan, Kazakhstan. J Ecol Eng 26 (10): 450-459. DOI: 10.12911/22998993/207416.

Kazhydromet. 2024. Climatic data summary for Almaty Region. Hydrometeorological Service of the Republic of Kazakhstan. Available online: https://www.kazhydromet.kz/ (accessed on 23 May 2025).

Kolesnikov NI. 2015. Herbarium of Vascular Plants: Methodological Guidelines. St. Petersburg: V. L. Komarov Botanical Institute, Russian Academy of Sciences.

Korolyuk TV. 2012. Soil Interpretation of Space Images in the System of CPC Methods Digital Soil Cartography: Theoretical and Experimental Studies; Moscow, Russia 124-140. Available online: https://www.esoil.ru/publications/ (accessed on 3 October 2012).

Kulymbet K, Mukhitdinov N, Kubentayev S, Tynybayeva K, Tastanbekova A, Kurmanbayeva M, Gafforov Yu, Kaparbay R, Zhumagul M. 2023. The current state of the cenopopulations of *Adonis tianschanica* (Adolf) Lipsch. (Ranunculaceae) in Southeast Kazakhstan. Biodiversitas 24 (8): 4359-4372. DOI: 10.13057/biodiv/d240817.

Llorens L, Cortes L, Boira H. 2023. Deciphering the ecology of the threatened microendemic *Euphorbia margalidiana*. Front Plant Sci 14: 1155896. DOI: 10.3389/fpls.2023.1155896.

Marschner P. 2012. Marschner's Mineral Nutrition of Higher Plants (3rd ed.). Academic Press. 8. Available online: https://www.elsevier.com/books/marschners-mineral-nutrition-of-higher-plants/marschner/978-0-12-384905-2 (accessed on 11 June 2025).

Moore MJ, Poveda JFM, Douglas NA, Flores H. 2014. The ecology, evolution and assembly of gypsophile floras. In: Rajakaruna N, Boyd RS, Harris TB (eds.). Plant Ecology & Evolution in Harsh Environments. Nova Publisher, New York.

Muratbayeva A, Nurmahanova A, Kulymbet K, Myltykbayeva A, Akhmetova A, Abdullayeva B, Atabayeva S, Baitasheva G, Kyrbassova E, Omarova Z. 2025. Soil morphological and chemical characteristics in the habitats of the rare, endemic plant *Spiraeanthus schrenkianus* in Karatau Mountains, Kazakhstan. Braz J Biol 85: e295015. DOI: 10.1590/1519-6984.295015.

Naorem A, Jayaraman S, Dang YP, Dalal RC, Sinha NK, Rao CS, Patra AK. 2023. Soil constraints in an Arid Environment—Challenges, Prospects, and Implications. Agronomy 13 (1): 220. DOI: 10.3390/agronomy13010220.

Osmonali BB, Tokbergenova A, Taukebayev O, Zulpykharov K, Salmurzauly R, Smanov Z, Ussen S. 2024b. Weed species in plant communities as indicators of degradation of vegetation cover and fertile soil layer in desert regions. Biodiversitas 25 (12): 4930-4938. DOI: 10.13057/biodiv/d251230.

Osmonali BB, Vesselova PV, Kudabayeva G, Duisenbayev S, Taukebayev O, Zulpykhanov K, Ussen S, Abdiildanov DS. 2024a. Salt resistance of species of the Chenopodiaceae family (Amaranthaceae s.l.) in the desert part of the Syrdarya River Valley, Kazakhstan. Biodiversitas 25 (11): 4162-4170. DOI: 10.13057/biodiv/d251115.

Pachikin KM, Erokhina OG, Funakawa S. 2014. Soils of Kazakhstan, their distribution and mapping. Environ Eng Sci 519-533. DOI: 10.1007/978-3-319-01017-532.

Palacio S, Cera A, Escudero A, Luzuriaga AL, Sánchez AM, Mota JF, Pérez-Serrano Serrano M, Merlo ME, Martínez-Hernández F, Salmerón-Sánchez E, Mendoza-Fernández AJ, Pérez-García FJ, Montserrat-Martí G, Tejero P. 2022. Recent and ancient evolutionary events shaped plant elemental composition of edaphic endemics: A phylogeny-wide analysis of Iberian gypsum plants. New Phytol 235 (6): 2406-2423. DOI: 10.1111/nph.18309.

Rabizadeh F, Nasiri A. 2023. The adaptability of *Euphorbia gypsicola* and *Euphorbia bungei* in gypsum soils of west Semnan, Iran. Iran J Bot 29 (1): 23-35. DOI: 10.22092/ijb.2023.129428.

Ramos MA, Diniz FC, de Almeida HA, de Almeida GR, Pinto AS, Meave JA, Lopes SdF. 2020. The role of edaphic factors on plant species richness and diversity along altitudinal gradients in the Brazilian semi-arid region. J Trop Ecol 36 (5): 163-175. DOI: 10.1017/S0266467420000128.

Red Data Book of Kazakhstan. 2014. 2rd ed ArtPrintXXI. Astana, Kazakhstan.

Sakhawy M, Ateya AAE, Balah MA. 2025. Implications of *Euphorbia peplus* and *Euphorbia geniculata* allelopathy on some plant species and phytopathogenic fungi. BioResources 20 (3): 5633-5649. DOI: 10.15376/biores.20.3.5633-5649.

Six J, Paustian K, Elliott ET, Combrink C. 2000. Soil structure and organic matter I: Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci Soc Am J 64 (2): 681-689. DOI: 10.2136/sssaj2000.642681x.

Soil Survey Staff (USDA–NRCS). 2014. Field Book for Describing and Sampling Soils, version 3.0. U.S. Department of Agriculture, Natural Resources Conservation Service, Lincoln.

Tastanbekova A, Kulymbet K, Kurmanbayeva M, Höhn M, Zhumagul M, Abduraimov O, Issayev GI, Alshynbayev O, Toktar M, Smanov Z. 2025. Implications of population size, structure, and soil parameters for the conservation of *Allochrusa gypsophiloides* in Kazakhstan. Biodiversitas 26 (5): 2051-2064. DOI: 10.13057/biodiv/d260504.

Toktar M, Koshen BM, Shayakhmetova AS, Kushenov BM, Nurgaziev R. 2019. Dehumification of soils in the northern Kazakhstan region. 19th International Multidisciplinary Scientific GeoConference SGEM2019, Water Resources. 51 Alexander Malinov blvd, Sofia, Bulgaria. DOI: 10.5593/sgem2019/3.2/S13.015.

Toktar M, Zakiyeva A, Kantarbaeva EE, Akhmetov MB. 2024. Processes of humus loss in leached chernozem soils of the North Kazakhstan region. Pochvovedenie i agrokhimiya (2): 18-28. DOI: 10.51886/1999-740X_2024_2_18.

Tongkoom K, Marohn C, Piepho H.P, Cadisch G. 2021. Combining farmers' and scientists' tree species and soil fertility assessment for improved cropping decisions in swidden systems of Northern Thailand, Ecol Indic 127: 107719. DOI: 10.1016/j.ecolind.2021.107719.

Tynybekov B, Imanaliyeva M, Kuatbayev A, Satybaldiyeva G, Boribay E, Kulymbet K, Umirbayeva Z, Mamytova N, Bekbossyn N, Kurmanbay U, Sadyrova G, Toktar M, Nazarbekova S, Abdullayeva B, Nurmahanova A. 2024. Adaptation features of *Gentiana tianschanica* Rupr: Populations to environmental factors in Kazakhstan. Energy Environ 26: 1361. DOI: 10.30919/esee1361.

USDA Natural Resources Conservation Service. 2013. Soil Quality Indicators: Bulk Density. Available online: https://www.nrcs.usda.gov. (accessed on 10 June 2025).

Ydyrys A, Mukhitdinov N, Ivashchenko A, Ashirova Z, Massimzhan M, Imanova E, Parmanbekova M, Toktar M, Yeszhanov B, Ilesbek M, Askerbay G. 2024. Methodological guide for geobotanical research on rare, endemic, and medicinal plants: A case study of the Ranunculaceae family. ES Food Agrofor 18 (1340): 1-22. DOI: 10.30919/esfaf1340.

Zar JH. 1999. Biostatistical Analysis (4th ed.). Prentice Hall, Upper Saddle River, NJ.