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# Influence of soil characteristics on the distribution and evolution of *Trollius dschungaricus* Regel populations in the Northern Tien Shan, Kazakhstan

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## ABSTRACT

This study presents a comparative analysis of soil characteristics in three populations of the rare subalpine plant *Trollius dschungaricus* occurring in the Northern Tien Shan (Ketpen and Saty ridges). The aim was to identify the soil factors that influence the distribution and resilience of species under differing geo-ecological conditions. The examined soils are classified as mountain-meadow subalpine and sod-clayey subalpine types. A morphological description of the soil profile was conducted alongside chemical and particle-size analyses. The humus horizon thickness ranges from 32 to 40 cm, with humus content between 3.06 and 8.82%. The soil solution is mainly neutral to slightly alkaline (pH 7.0–8.0); available phosphorus and potassium fall within medium to high supply levels. The most humus-rich soils with the highest cation-exchange capacity are found on the Saty ridge, whereas the soils of the Ketpen ridge exhibit better drainage properties and a lower tendency toward compaction. All soils display weak carbonation, lack easily soluble salts, and show a propensity for surface horizon slaking under excessive moisture due to high silt and fine-dust fractions. These findings allow an assessment of the ecological capacity of the study sites and provide recommendations for conserving the *T. dschungaricus* habitats amid increasing anthropogenic pressure.

**Keywords:** *Trollius* L., population, Northern Tien Shan, humus, relief.

## INTRODUCTION

Contemporary studies of plant communities in high-mountain ecosystems play a vital role in biodiversity research and conservation efforts (Kubentayev et al., 2023; Myrzagaliyeva et al., 2024). The mountain regions of Central Asia are distinguished by harsh environmental conditions, including pronounced temperature fluctuations, intense solar radiation, and limited soil resources (Kulymbet et al., 2023; Balkybek et al., 2025). These factors give rise to unique plant assemblages that are specially adapted to extreme environmental stresses (Amirov et al., 2023). One of the rare and poorly studied members of the Ketpen ridge flora is *T. dschungaricus*, a perennial herb of the buttercup family (Ranunculaceae) (Kew Science, 2025). *T. dschungaricus* is a rare perennial species endemic to the mountainous regions of Central Asia (Sypabekkyzy et al., 2024). It occurs in subalpine and alpine meadows, preferring moist soils (Sun et al., 2023). The Ketpen ridge, part of the Kungey Alatau system, constitutes a key ecosystem for the habitat of this species. However, the ecological properties of the soils supporting its populations remain poorly understood (Tynybekov et al., 2024). This species is noted for its affinity to moist mountain meadows and river valleys, where specific soil conditions shape its distribution, abundance, and population viability. Despite its ecological importance, the soil characteristics of *T. dschungaricus* habitats on the Ketpen ridge have scarcely been investigated (Flora of China, 2001). Climate change and anthropogenic pressures are degrading mountain-meadow ecosystems, placing at risk those species adapted to a narrow range of environmental conditions. Examining the soil parameters of *T. dschungaricus* populations will deepen the authors' understanding of the ecological requirements of species and aid in selecting informed conservation measures (Alikhanova et al., 2024).

The mountainous area formed by the northern spurs of the Ketpen Range is deeply dissected by a meridionally oriented network of mountain streams that channel meltwater and rainfall toward the Ili depression (Pachikin et al., 2014).

The Saty ridge lies in the north-eastern sector of the Northern Tien Shan and is a key orographic element of the Kungei Alatau mountain system. Stretching in close proximity to the Kolsai Lakes, it forms part of the "Kolsai kolderi" UNESCO Biosphere Reserve. The region is distinguished by a high degree of ecosystem integrity, a unique alpine and subalpine flora, and pronounced altitudinal zonation (Sitpayeva et al., 2021).

As the mountain streams flow out onto the fore-mountain plain, they lose most of their discharge through infiltration into boulder-pebble deposits, while the remaining water is diverted for irrigation. Domestic water supply for settlements relies on these surface streams delivered through a network of canals. The water is only weakly mineralized and is considered to be of good drinking quality (Erst et al., 2019).

In the southern portion of the study area, which includes the mountain sector of the Ketpen Range and its northern slopes-chernozem, mountain dark-chestnut, and mountain light-chestnut soils predominate (Zhang et al., 2023). Soil formation here is shaped by several factors: a shallow soil profile, a high proportion of coarse skeletal material both at the surface and within the profile, and a drier climate (Rakhimova et al., 2017). These conditions produce the soils that are morphologically and genetically distinct from their counterparts in the central and western parts of Almaty Region, where pedogenesis occurs on thick loess deposits (Volynkin et al., 2023).

The aim of this study was to determine the soil characteristics of *T. dschungaricus* habitats on the Ketpen and Saty ridges.

## MATERIALS AND METHODS

### Study area

Field investigations were conducted in May-June 2024 under diverse ecological and cenotic conditions in the Ketpen and Saty ridges of the Northern Tien Shan (Figure 1). Three populations of *T. dschungaricus* were identified during the survey (Table 1). The selection of these three populations was based on their geographic distribution across distinct ridges (Ketpen and Saty), contrasting elevation levels (1990–2733 m a.s.l.), and varying ecological conditions. This sampling strategy was designed to capture the core environmental gradients within the known range of *T. dschungaricus* in the Northern Tien Shan and to ensure that the studied sites correctly reflect the habitat diversity of species.

The present study focused on the soil characteristics within the species distribution range. Special attention was devoted to describing and analyzing the prevailing soil conditions.

### Climate

*T. dschungaricus* occurs mainly within the subalpine and alpine belts, where distinctive micro-climatic conditions prevail. The local climate is markedly continental. Over the past six years the mean annual air temperature has been +8.0 °C, with monthly means of − 6.3 °C in January and +16.9 °C in July. Absolute extremes reach 36.0

**Table 1.** Geographic location of the studied *T. dschungaricus* populations

| Species name, population number | Geographic location | Coordinates |
|---|---|---|
| *T. dschungaricus,* Population-1 | Northern Tien-Shan, Ketpen ridge | N 43°33'51.19" E 80°33'45.42", 2733 m.a.s.l. |
| *T. dschungaricus,* Population-2 | Northern Tien-Shan, Ketpen ridge | N 43°34'58.01" E 80°33'56.32", 2453 m.a.s.l. |
| *T. dschungaricus,* Population-3 | Northern Tien-Shan, Saty ridge | N 42°99'07.9", E 78°38'58.54", 1990 m.a.s.l. |

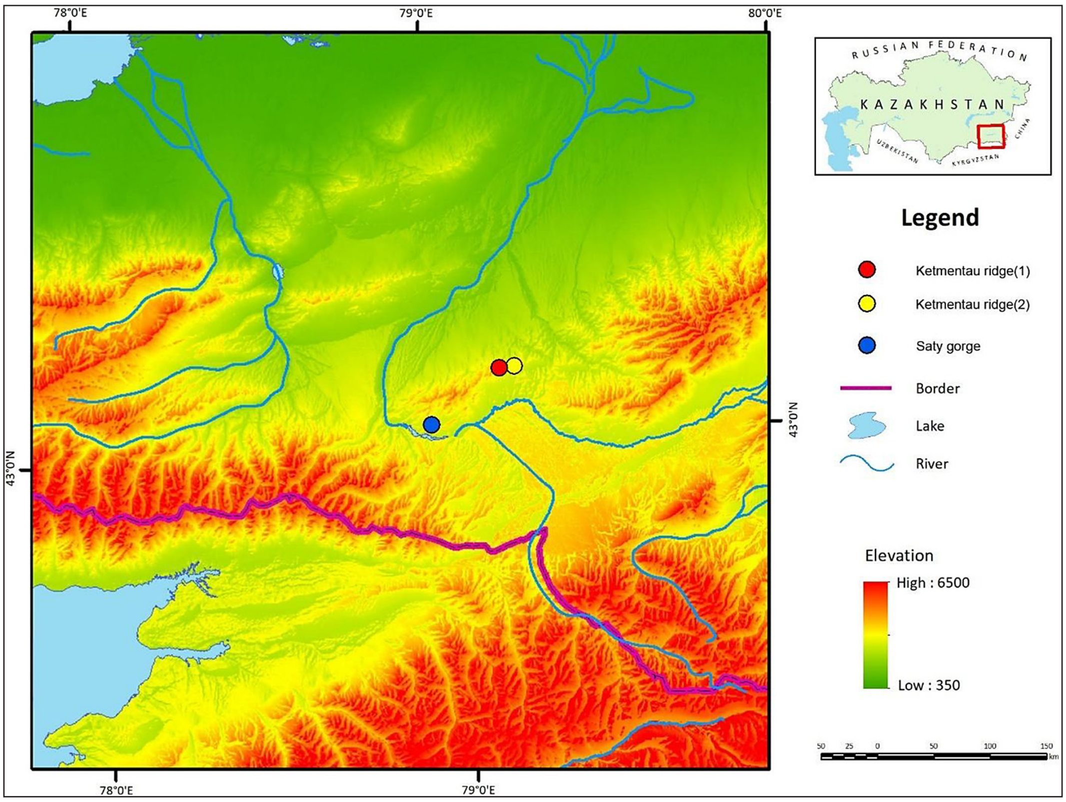


**Figure 1.** DEM-map of *T. dschungarus* populations

°C and −26.9 °C, respectively. The foothill zone enjoys an average frost-free period of 177 days. First frosts typically occur in early October, while the last spring frosts are recorded in late May. The growing season lasts about 216 days. Snow cover establishes in late October and disappears during the third ten-day period of April (Li et al., 2024).

According to the Podgornoye meteorological station (Kazhydromet, 2024), the long-term mean annual precipitation in the foothills amounts to 376.1 mm. This relatively modest total is due to the northern slopes of the Ketpen ridge being shielded from moist winds by the Dzungarian Alatau. Precipitation is highly seasonal, with maxima in spring and summer and minima in winter.

## Soil analysis

Soil profile excavation began with the investigation and selection of reference sites, taking into account relief, climatic parameters, and ground cover. During route-based field surveys, morphological methods were applied (Korolyuk et al., 2012), providing reliable, well-substantiated field diagnosis of soils and detailed description of their morphological properties. A total of nine soil profiles were excavated at the sites where the *T. dschungaricus* populations were found-three profiles in each locality. Forty-five soil samples were collected for chemical analysis, and every sample was analyzed in quadruplicate. The organic-matter content was determined by the Tyurin spectrophotometric method (FAO 2021). Total nitrogen was measured by titration using the Kjeldahl method (FAO 2025). Total phosphorus and potassium were quantified with a spectrophotometer (Specord 210 Plus, Germany). Soil pH was measured with a pH meter (I-160MI, 2007, Russia). The $CO_2$ (carbonate) content was assessed with a calcimeter. Particle-size distribution was analyzed following the N.A. Kachinsky method. Total soluble salts were determined with a flame photometer (Flapho4, Germany).

Population mapping was carried out in ArcGIS 10.4 (ArcGIS, 2024), and a digital elevation model (DEM) was generated from SRTM satellite imagery (2014).

## Statistical analysis

Descriptive statistical analysis was carried out to summarize the variability of soil parameters across the studied populations. For each soil sample, mean values, standard deviations, and value ranges were calculated. This approach ensured an accurate comparison of morphological and chemical soil characteristics among the three populations. All calculations were performed using R-studio (R-Studio Team, 2020)).

## RESULTS AND DISCUSSION

### Morphological description of soils

*Population 1 - Ketpen ridge*

The soil profile is of moderate depth (70 cm) and exhibits a well-developed structure. The parent material consists of deluvial–proluvial gravelly loams. The combined humus horizon (A + B) is 32 cm thick. Humus content is 7.18% in the surface $A_0$ layer, decreasing to 6.45% in $A_1$ and 3.19% in B. Soil type: mountain-meadow subalpine soil (Table 2). According to the analytical results, humus content is 7.18% in the $A_0$ horizon, decreases to 6.45% in the $A_1$ horizon, and falls to 3.19% in the B horizon. Total nitrogen (0.430%) and total phosphorus (0.31%) indicate a medium supply level. Available phosphorus is medium at 20.13 mg · 100 $g^{-1}$, while available potassium is elevated at 356.64 mg · 100 $g^{-1}$. Only weak effervescence with 10% HCl is observed in the BC horizon (1.69% $CO_2$ in carbonates). Carbonates are generally sparse, reaching a maximum of 2.36% in the C horizon. The soil-solution reaction is neutral to slightly alkaline (pH 7.0–8.0) from the surface through the entire profile. Easily soluble salts are absent throughout (Figure 2).

The A horizon is predominantly light loam, occasionally transitioning to medium loam. In the light-loam variants, the physical clay fraction (< 0.01 mm) constitutes 21.24–22.71%. Moderate amounts of gravel are observed in the middle horizons. According to N.A. Kachinsky's classification, soils containing more than 20% of the silt + fine-dust fraction are prone to slaking during rain and form a dense crust when they dry (Figure 3).

*Population 2 – Ketpen ridge*

The soils described here occur on the northern slopes of the Ketpen ridge. The parent material consists of gravelly loams of deluvial and proluvial origin. The water regime is predominantly leaching, with seasonal over-wetting. The profile is moderately differentiated into genetic horizons. The combined humus horizon (A + B) is 35 cm thick. Soil type: Mountain-meadow subalpine soil (Table 3).

According to the analytical data, humus content is 7.73% in the $A_0$ horizon, 5.46% in $A_1$, 3.06% in $B_1$, and 0.36 % in the BC horizon. Total nitrogen (0.114%) and total phosphorus (0.17%) indicate a medium supply level. Available phosphorus (26.13 mg per 100 g) is at a medium level, while available potassium (338.40 mg per 100 g) is at a high level. Weak effervescence with 10 % HCl is observed from the B horizon downward. The soil-solution reaction is neutral (pH 7.3–7.5) throughout the profile (Figure 2).

The cation-exchange capacity (CEC) in the $A_1$ horizon is 11.20 meq per 100 g, and in the B horizon 12.20 meq per 100 g, with sodium accounting for 1.34% of CEC. In the illuvial (B) horizon, exchangeable sodium represents 2.38% of the CEC, indicating a low exchangeable-sodium

**Table 2.** Soil type of Population 1 – Ketpen ridge

| Horizons | Depth, cm | Thickness, cm | Description |
|---|---|---|---|
| $A_0$ (litter (organic) horizon) | 0–7 | 7 | Dark-brown to black; fresh, loose, loamy, with a granular and lumpy structure; contains numerous plant remains; non-calcareous (no effervescence). The transition is clear in color |
| $A_1$ (humus horizon) | 7–17 | 10 | Dark brown, fresh, slightly compacted, loamy, granular and lumpy structure, many roots, well developed, not boiled. The transition is clear in color |
| B (illuvial horizon) | 17–32 | 15 | Brown; moist; compacted; weakly differentiated structure with noticeable clay accumulation; few roots; shows weak effervescence with dilute HCl. Boundary to the next horizon is gradual, distinguished mainly by color |
| BC (transitional horizon) | 32–42 | 10 | Brown; slightly moist; dense; loamy; powdery structure; contains gravel and slightly weathered rock fragments; few roots; shows weak effervescence with dilute HCl. Boundary to the underlying horizon is gradual, marked chiefly by color |
| C (parent-material horizon) | 42–70 | 28 | Light brown; slightly moist; dense; fine-grained and structureless; loamy. Roots are sparse. Stony–gravelly, only slightly decomposed material present. Exhibits moderate effervescence with dilute HCl |

**Table 3.** Soil type of Population 2 – Ketpen ridge

| Horizons | Depth, cm | Thickness, cm | Description |
|---|---|---|---|
| $A_0$ (litter (organic) horizon) | 0–5 | 5 | Black; fresh; loose; granular-cloddy structure; loam; slightly decomposed plant residues; abundant roots; non-calcareous (no effervescence). Boundary to the underlying horizon is clear, distinguished by color |
| $A_1$ (humus horizon) | 5–18 | 13 | Dark-gray; moist; slightly compacted; loam with a granular-cloddy structure; abundant roots; non-calcareous (no effervescence). Boundary to the underlying horizon is clear, distinguished by color |
| B (illuvial horizon) | 18–35 | 17 | Light brown; moist; compacted; loam with a weakly developed platy structure; slight migration of fine particles; contains gravel inclusions; shows weak effervescence with dilute HCl. Boundary to the underlying horizon is gradual, distinguished mainly by color |
| BC (transitional horizon) | 35–60 | 25 | Light brown; slightly moist; dense; powdery loam with a weakly differentiated, massive structure; transition to the parent material; stony-gravelly with large rock fragments; few roots; weak effervescence with dilute HCl. Boundary to the underlying material is gradual, distinguished mainly by color |
| C (parent-material horizon) | 60–80 | 20 | Light brown; slightly moist; very dense; loam; structureless; stony-gravelly; roots are scarce; exhibits moderate effervescence with dilute HCl |

status. Water-soluble salts are absent throughout the profile.

By texture, the A horizon soils are medium loam. In these medium-loam variants, the physical-clay fraction (< 0.01 mm) comprises 32.52%, while the combined silt and fine-dust fractions amount to 28.17%. Gravel occurs moderately in the mid-profile horizon. According to N.A. Kachinsky's classification, the soils containing more than 20% of the combined silt and fine-dust fractions are prone to slaking during rain and irrigation and form a dense crust upon drying (Figure 3).

### *Population 3 - Saty ridge*

The described soils occur in the northern part of the Saty ridge. The parent materials are eluvium and deluvium of crystalline schists and clayey loams. The terrain consists of moderately steep north- to northeast-facing slopes. These soils are characterized by a thick humus horizon and a well-developed structure.

The combined A + B humus horizon measures 40 cm in thickness. Soil type: Subalpine sod-clay soils (Table 4). According to the analytical data, humus content is 8.82% in the $A_0$ horizon, 6.53% in $A_1$, 3.06% in $B_1$, and 1.12% in the BC horizon. Total nitrogen (0.240%) and total phosphorus (0.11%) indicate a medium nutrient supply. Available phosphorus (22.38 mg per 100 g) is at a medium level, while available potassium (349.50 mg per 100 g) is at a high level. Weak effervescence with 10% HCl is observed from the BC horizon downward. The soil-solution reaction is neutral (pH 7.0–7.4) throughout the profile (Figure 2). Cation-exchange capacity (CEC) in the $A_1$ horizon is 15.30 meq per 100 g, and in the B horizon 15.20 meq per 100 g;

**Table 4.** Soil type of Population 3 – Saty ridge

| Horizons | Depth, cm | Thickness, cm | Description |
|---|---|---|---|
| $A_0$ (litter (organic) horizon) | 0–5 | 5 | Dark brown; fresh; loose; loam with a granular–cloddy structure; contains slightly decomposed plant residues; non-effervescent. Boundary to the underlying horizon is clear, distinguished by color |
| $A_1$ (humus horizon) | 5–20 | 15 | Dark gray with a brownish tint; moist; slightly compacted; loam; cloddy-granular structure; abundant roots; non-effervescent. Boundary to the underlying horizon is clear, distinguished by color |
| B (illuvial horizon) | 20–40 | 20 | Brownish-gray; moderately moist; blocky structure with signs of compaction; loam; non-effervescent. The boundary to the underlying horizon is gradual, distinguished chiefly by color |
| BC (transitional horizon) | 35–60 | 25 | Light brown; slightly moist; dense; powdery clay loam with a weakly differentiated, massive structure; transitions into the parent material with stone inclusions; few roots present; exhibits weak effervescence with dilute HCl. The boundary to the underlying horizon is gradual, distinguished by color |
| C (parent-material horizon) | 60–80 | 20 | Light brown; slightly moist; dense; clay loam; stony with schist fragments; few roots; exhibits moderate effervescence with 10 % HCl |

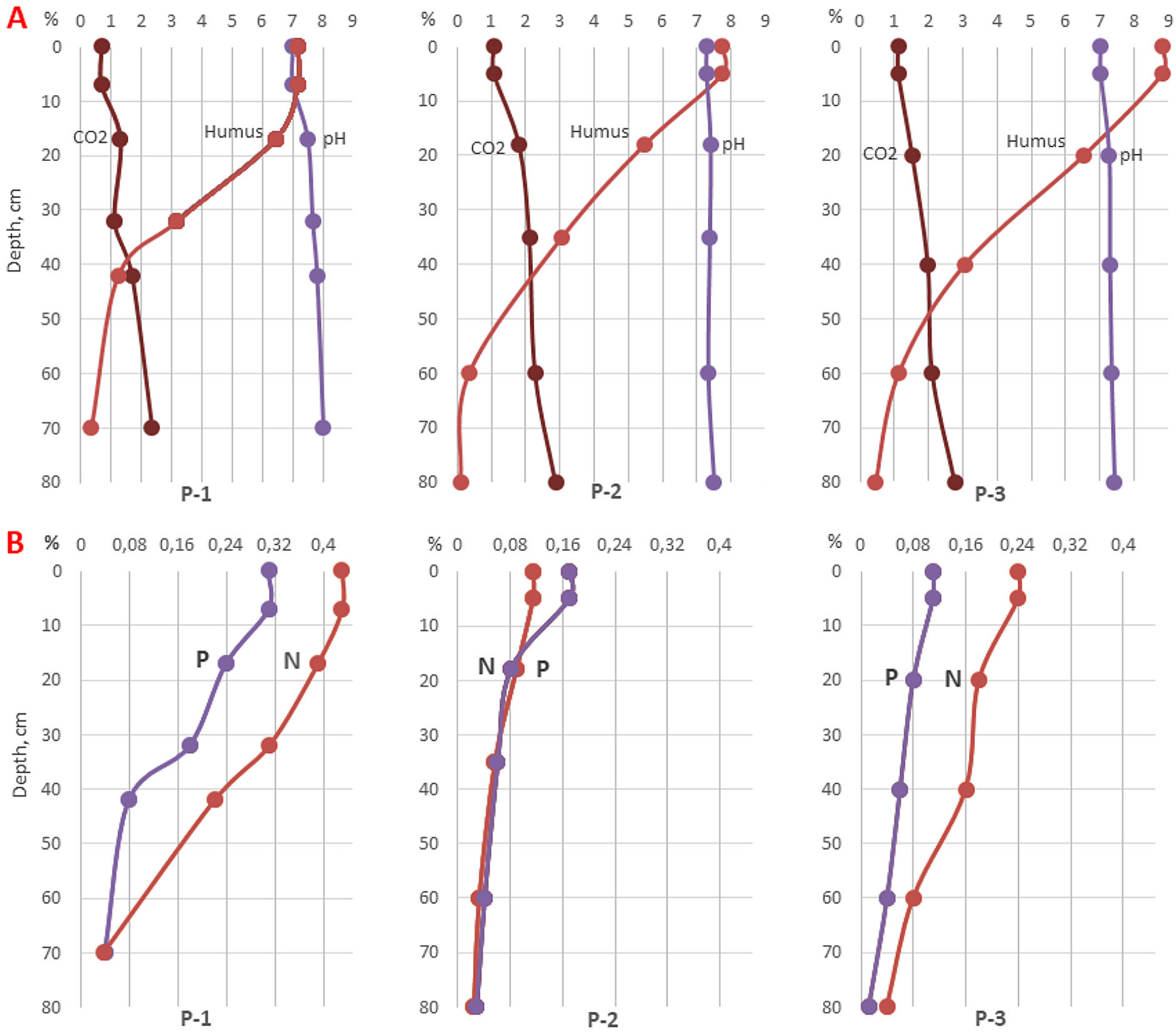


**Figure 2.** Analytical indicators of the soils in *Trollius dschungaricus* habitats: A – humus, $CO_2$ (%), pH; B – total N (nitrogen), total $P_2O_5$ (phosphorus) (%)

sodium comprises 1.97% of the CEC. In the illuvial horizon, exchangeable sodium accounts for 3.02% of the CEC, indicating a low exchangeable-sodium status. Water-soluble salts are absent throughout the profile.

By texture, the A horizon soils are medium loam. In these medium-loam variants, the physical-clay fraction (< 0.01 mm) constitutes 38.41%, while the combined silt and fine-dust fractions amount to 28.17% (Figure 3).

## Comparative analysis of the soils of all populations

All of the studied soils belong to subalpine types, differing primarily in their morphology and degree of profile development. The soils of Population 1 feature a medium texture (medium loam), which provides moderate water-holding capacity combined with good drainage. Although the humus content is only moderate, the total nitrogen and phosphorus levels are higher than in the other populations, reflecting elevated biological activity and fertility.

The soils of Population 2 exhibit a transitional type – they are mechanically heavier, with lower humus content and chemical parameters (notably phosphorus and potassium) at medium levels. Exchangeable sodium is low but higher than in Population 1. These soils are more prone to structural compaction and are less well-aerated.

The soils of Population 3 have the thickest humus horizons and the highest organic-matter content. Nutrient levels are within normal ranges, but their cation-exchange capacity and sodium percentage are markedly higher. These soils are heavier in texture and exhibit a high water-holding capacity.

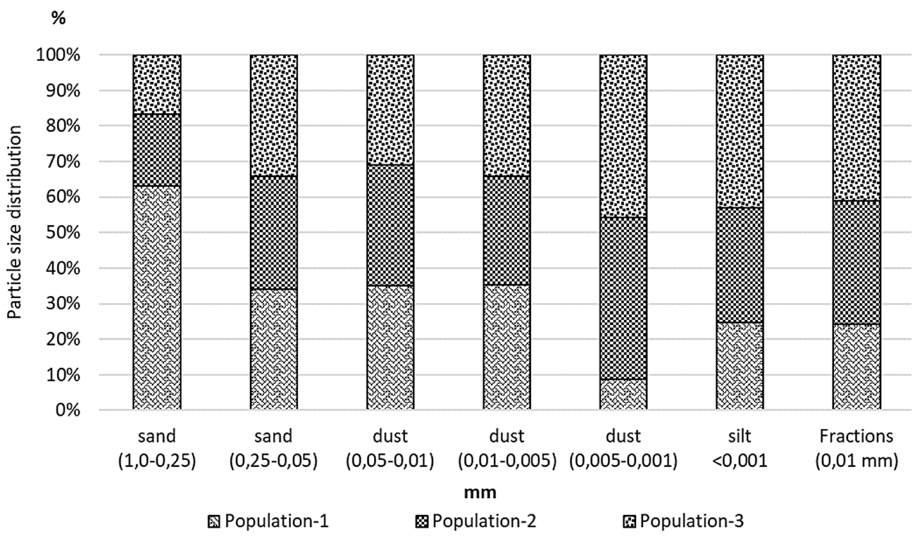


**Figure 3.** Soil texture distribution (sand, silt, clay) in studied populations

All three populations develop on different parent materials, which accounts for the observed variations in structure and composition. However, in every case there is a tendency toward slaking under excessive moisture due to the high silt and fine-dust content (> 20%). The soil reaction across all profiles is neutral to slightly alkaline; carbonates do not accumulate to harmful levels, and no signs of solonetz formation or salinization were detected.

## DISCUSSION

The conducted study focused on the comparative analysis of soils in three geographically distinct populations of *T. dschungaricus* in the Northern Tien Shan subalpine belt. The results revealed significant pedological differentiation, which is closely tied to the ecological requirements and distribution patterns of this rare species.

The soils across all three populations showed relatively high humus content, neutral to slightly alkaline pH, and absence of salinization. These parameters create favorable conditions for plant growth, particularly for mesophilous subalpine species. This is in line with findings by Tudi et al., (2022) and Tastanbekova et al., (2025), who reported that mountainous soils in the Tien Shan region often exhibit enhanced nutrient retention and buffering capacity due to organic inputs from dense vegetation and minimal anthropogenic disturbance. However, the variation in soil profile development, texture, and chemical composition among the studied sites suggests localized ecological specialization. For instance, the soils of Population 3 (Saty ridge) displayed the highest humus levels and the most developed profiles. These soils also had elevated CEC, indicating high nutrient-retention potential. Such characteristics are crucial for sustaining long-term plant growth and are often linked to increased microbial activity as well as improved soil structure. Dai et al., (2018) emphasized that CEC and humus content are reliable indicators of habitat quality in montane ecosystems, particularly for rare and endemic species. In contrast, Population 2, located on the northern slope of the Ketpen ridge, showed signs of lower nutrient availability, moderate horizon development, and heavier textures. These characteristics may negatively impact soil aeration and water infiltration, potentially limiting root respiration and nutrient uptake. Studies by Amin et al., (2023) have demonstrated that clay-rich soils with poor structure can suppress plant performance in subalpine zones, particularly under high precipitation or snowmelt conditions. The relatively balanced profile of Population 1, with medium texture and moderate nutrient status, suggests a transitional ecological zone. These soils may serve as ecotones that support both meadow and forest-edge vegetation, providing insights into the ecological amplitude of species. The higher levels of total nitrogen and phosphorus in these soils compared to other sites likely reflect better decomposition of organic material and stronger microbial activity, which is consistent with da Silva et al., (2020). Another important aspect highlighted in the conducted study is the absence of soluble salts and harmful carbonate accumulations. This indicates that the sites are free from chemical degradation, which is crucial for the survival of sensitive plant species. Nevertheless, the tendency of surface horizons to slake under excess moisture, due to high contents of fine dust and silt fractions (> 20%), could lead to soil crusting and hinder seedling emergence. This physical vulnerability, discussed by Kachinsky (1958) and later explored in highland ecosystems by Niu et al., (2021), underscores the importance of monitoring microerosion and compaction processes, especially in the context of increasing tourism and grazing pressure. The close relationship between *T. dschungaricus* occurrence and specific soil parameters - such as neutral pH, high organic matter, and medium texture - supports the ecological niche model proposed by Zhang et al., (2020) for other alpine and subalpine species. The collected data suggest that even subtle differences in soil morphology or parent material may influence population stability, recruitment rates, and overall resilience to environmental change. Furthermore, considering that all three populations develop under slightly different microclimatic and geomorphological conditions, the collected findings reinforce the concept of edaphic differentiation as a key driver of plant biodiversity in mountainous regions. These differences are often overlooked in conservation planning but should be considered when designating protected areas or developing site-specific restoration programs.

## CONCLUSIONS

This study presented a comparative assessment of soil morphological and chemical characteristics across three populations of *T. dschungaricus* in the subalpine belt of the Northern Tien Shan. While all studied soils fall within subalpine types, they exhibit distinct differences in horizon development, parent material, organic content, and nutrient status. Population 1 (Ketpen ridge) displayed the soils with balanced physical and chemical properties, including medium texture, elevated nitrogen and phosphorus levels, and favorable aeration. These conditions support the growth of mesophilous meadow vegetation and appear optimal for *T. dschungaricus* establishment. Population 2, also on the Ketpen ridge, showed heavier soil textures and moderately developed profiles with reduced nutrient availability. These characteristics may limit plant productivity under stress and require further investigation under dynamic climate scenarios. Population 3 (Saty ridge) had the most humus-rich and structurally developed soils with high cation-exchange capacity and moisture retention. However, their dense structure and high clay content may reduce aeration and increase the risk of compaction. Across all sites, the absence of salinization and the presence of neutral to slightly alkaline pH values confirm favorable chemical conditions for plant development. Nonetheless, the common tendency for surface horizons to slake and form crusts under moisture excess indicates a potential vulnerability in terms of seedling recruitment and soil stability.

Future research should focus on: long-term monitoring of soil-plant interactions, including seasonal dynamics; evaluating the impact of grazing, tourism, and land use on soil degradation in subalpine zones; studying belowground biomass and microbial communities to better understand the ecological amplitude of *T. dschungaricus*; developing the conservation strategies that integrate site-specific soil assessments and mitigate risks from climate and anthropogenic pressures. Such approaches are essential to ensure the conservation of this rare species and the long-term ecological stability of its subalpine habitats.

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