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Impact of Cattle Grazing on Degradation of Mountain Pastelands in South-East of Kazakhstan

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Abstract

This study examines the degradation of mountain pastures in Southeastern Kazakhstan, which is attributed to overgrazing and other human activities. Soil degradation progresses more slowly than vegetation changes, but its effects are severe, with a reduction in silty and dusty fractions to 30% and an increase in sandy fractions, which lowers the water retention and makes the soil more vulnerable to erosion. As a result, key pasture grasses, such as cereals (Poaceae) and legumes (Fabaceae), are being replaced by inedible and toxic plants with deep root systems. Pasture productivity varies seasonally, with a total biomass yield at 0.42±0.05 t/ha in spring, peaking at 1.28±0.40 t/ha in summer, and declining to 0.36±0.007 t/ha in autumn, while the edible portion follows a similar pattern, ranging from 0.31±0.01 t/ha in spring to 0.97±0.28 t/ha in summer and 0.28±0.021 t/ha in autumn. The proportion of weeds and poisonous plants remains high throughout the year (22–25%), indicating a progressive transformation of the plant community under grazing pressure. Field studies confirm significant shifts in vegetation, with nutritious forage species being replaced by unpalatable and invasive plants. These changes threaten biodiversity and pasture sustainability, emphasizing the urgent need for rotational grazing and sustainable management practices to restore degraded pastures and ensure a long-term productivity for livestock farming in Kazakhstan.

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1. Introduction

Large natural areas in many countries worldwide are currently utilized as natural pastures.[1-2] Human interaction with ecosystems leads to continuous alterations in spatial patterns and resource availability, impacting both landscapes and socio-ecological systems.[3-5] Pasture degradation represents one of the most significant land use challenges in the region.[6-13] Pastoral activities have reshaped the landscape into a mosaic of plant communities, each supporting varying levels of biodiversity and delivering distinct ecosystem services.[14] Kazakhstan has a significant agricultural potential due to its vast natural pastures and low population density. The livestock sector has a large and historically established livestock sector. The country's livestock structure is dominated by sheep farming, as well as cattle and horse breeding. Camel breeding is practiced in desert and semi-desert regions. The efficient use of pastures with good soil conditions can reduce feed costs and increase the overall profitability of livestock farming. Thus, the condition and quality of the soil play a key role in the successful management of livestock farming.

Vast mountainous territories of Southeastern Kazakhstan are used as natural pastures. Cattle grazing is one of the historically established forms of human impact on ecosystems throughout Kazakhstan. The object of our study is the territory of mountain pastures in Southeastern Kazakhstan, which occupies approximately 22% of the region's total area.[15] The preservation of pasture ecosystems in Southeastern

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Kazakhstan has become an increasingly urgent issue due to the high degree of degradation. Unsustainable pasture utilization, including excessive forage harvesting and inadequate monitoring of vegetation conditions, has resulted in pasture depletion and a decline in productivity. Consequently, these factors have had adverse effects on livestock farming and the regional economy.[16] The pasture ecosystems of Southeastern Kazakhstan are rich in biodiversity, featuring rare and endangered plant and animal species. Degradation of the studied areas threatens the loss of biodiversity and disruption of the ecological balance of the region The strong impact and influence of grazing on pasture degradation is becoming increasingly relevant for countries in Europe, South and North America, as well as for Central Asia and Kazakhstan, becoming an important problem in land use.[17]

Unregulated load and intensive grazing of livestock when the number of animals exceeds the permissible norm for a certain area leads to the depletion of the soil. This makes it difficult for seeds to germinate and plants to grow, and results in the loss of vegetation cover, which makes the soil more susceptible to erosion and leads to the loss of the topsoil and deterioration of its quality, a reduction in biodiversity, reducing species diversity and changing the composition of plant and insect communities.[18] Livestock grazing can bias plant communities towards annual or invasive species, while moderate grazing promotes diversity in grassland ecosystems.[19] Degraded pastures become less productive, which in the long term can reduce the possibilities for livestock farming. To reduce the pressure on pastures, it is necessary to use a rotational grazing system that reduces the pressure on pastures, increases the productivity of pastures where pastures are given time to recover taking into account local conditions, and improves biodiversity and the sustainability of the region's ecosystem.[20] When the grazing load norm is exceeded and the pasture rotation system is absent or not observed, it leads to the development of negative consequences that affect all components of the agricultural landscape.

Pasture degradation processes in Southeastern Kazakhstan occur unevenly and spontaneously across the entire region. Kazakhstan ranks sixth globally in terms of grassland resources, with pasturelands covering 189.0 million ha, historically serving as a key driver of the national economy by providing essential forage resources for livestock farming.[21] According to the agency of the Republic of Kazakhstan, 27.1 million ha of pastures are classified as moderately to severely degraded. In terms of zonal distribution, pasture ecosystem degradation is most pronounced in the flatlands, where over 95% of all degraded pastures are located, particularly within desert and semi-desert zones, which account for 16.1 million ha, or 60% of their total area.[22] In Southeastern Kazakhstan, pasture ecosystems are fundamental to livestock farming, a crucial sector of the agricultural sector. However, in recent years, an increased grazing pressure has disrupted the natural equilibrium, further exacerbating the degradation and transformation processes, particularly in the region's arid ecosystems, which are inherently vulnerable to environmental stressors.

These processes have a negative impact on the successful development of the livestock sector of agriculture and on the living standard of the population living in these regions. Identifying the causes of degradation of pasture areas requires analysis and research of effective measures for rational use, taking into account the characteristics of mountain pastures. According to the Ministry of Agriculture of the Republic of Kazakhstan for 2022, the total area of the country was 272.5 million hectares, including pastures of 183.4 million hectares, which account for 67% of the total territory. In other words, pastures comprise two-thirds of Kazakhstan. Natural pastures serve as the primary source of forage for livestock in Kazakhstan. Considering the extensive coverage of pastureland, these ecosystems also play a significant role as a climate-regulating factor in the country.[23] In 2023, the total value of agricultural production in Kazakhstan amounted to $76,251.509 million, with livestock products accounting for ₸30,125.104 million, representing 39.5% of the total agricultural output. Effective pasture management and the improvement of degraded pastures play a crucial role in mitigating greenhouse gas emissions, particularly in terms of carbon storage and sequestration.[24]

The purpose of this study is to assess the current state of pastures in Southeastern Kazakhstan, examine the impact of overgrazing on their productivity, vegetation, and soil quality, and propose sustainable management and restoration practices to conserve biodiversity and ensure the long-term sustainability of these ecosystems.

2. Materials and methods

2.1 Study sites and experimental design

The highland meadows of Southeastern Kazakhstan are vital for cattle husbandry in the Almaty region. The research was carried out in Southeastern Kazakhstan's mountainous North Tien Shan province, the Ile Alatau on the Assy plateau (Fig. S1A), Enbekshikazakh district (Fig. S1B), and the Ketpen ridge (Kegen, Raimbek, and Uygur districts) (Fig. S1C). Field and expeditionary work was carried out throughout the grazing period in the spring in May, in the summer in July, and in the fall at the beginning of October. We covered the territories of four districts, of which three districts (Kegen, Raimbek, and Uygur) belong to the Ketpen ridge and one district (Enbekshikazakh) belongs to the Ile Alatau. Below are the data on the total area of the districts and the area of pastures studied on which cattle is currently grazing (pastures dominated by the Poaceae family and other species of herbaceous plants, for example, forbs from the families: *Fabaceae, Asteraceae, Lamiaceae* and *ect*.) (Table 1).

2.2 Determining the pasture load

Pasture monitoring encompasses a scientifically based and coordinated system of measures designed to optimize the

Table 1: Physical and geographical characteristics of the research areas.

Study sites (Area, thousand ha)	Enbekshikazakh		Kegen		Raimbek		Uygyr	
	Total area	Tasture	Total area	Pasture	Total area	Pasture	Total area	Pasture
	780.7	530.9	675.5	472.6	1420.0	442.5	876.6	386.6
Coordinate	43°14′364″N, 77°53′533″E		43°10′444″N, 80° 01′438″E		43°13′143″N, 80° 05′211″E		43°26′637″N, 80° 01′438″E	
Soils	Subalpine meadow heavily turfed		Mountain dark chestnut		Subalpine meadow heavily turfed		Subalpine meadow heavily turfed	
Elevation in metres above sea level (m a.s.l.)	2667		2249		2297		2755	
Altitudinal zonation	Subalpine		Mountain-steppe		Subalpine		Subalpine	
Biogeographic region	Ketpen ridge		Ketpen ridge		Ketpen ridge		Ile-Alatau ridge	

effective use of pastures for livestock farming development. The load of the pasture period was determined in the studied areas based on the number of livestock per ha of pasture. The calculation is made using the formula given in Eq. (1):

$$L = \frac{P}{(A \times D)} \quad (1)$$

where L represents the livestock load per ha (heads), P denotes the productivity of pasture per ha (for the corresponding period) in terms of green mass (kg), A refers to the daily pasture feed consumption per head of cattle (kg), and D indicates the duration of pasture utilization (day).

During field expeditionary research, permanent transects were established by driving pegs with corresponding numbers (0, 50, and 100 m, *etc*.) every 50 m along a cord stretched along the centerline of the transect. On grassy highland and mountain-steppe pastures, transects were laid out 2 m wide and 150-200 m long. On large-shrub pastures, it was about 4 × 300 m^2 (400-500 m) in size. For homogeneous pastures, one transect was laid out. When studying the impact of cattle grazing on natural pastures, transects up to 3-5 km long were constructed, considering pasture areas located at different distances from the livestock point (50 m, 100 m, 1 km, and 2 km, *etc*.). Stationary observation sites were marked along the transect with numbered pegs. At these sites, the yield of pasture grasses was recorded, the composition of the vegetation cover was described, *etc*. The monitoring work included the collection and systematization of source materials for pasture mapping. The calculation of the pasture load was conducted based on the number of animals released per hectare during the entire grazing period, expressed in conventional heads per hectare per season, and served as an indicator of anthropogenic load.[25]

2.3 Determination of pasture productivity

To determine the soil moisture, a thermostat-weight method was used to collect soil samples in the field. To determine the soil moisture using this method, laboratory scales, a drying cabinet, a soil auger, and weighing bottles were used. The sampling locations were recorded using a GPS navigator, and the sample number and depth were recorded. The collected soil samples were weighed, and the results were recorded in a log. After that, the soil samples were dried in a drying cabinet at 105 °C. Depending on the soil moisture, the drying time was 6 h. The weighing bottles containing dry soil were then cooled for 10-15 min and weighed.[26] Soil moisture was calculated using the formula depicted in Eq. (2):

$$W = \frac{Me \times 100}{Mn} \quad (2)$$

where W is the soil moisture, Me is the mass of water evaporated from the soil sample during drying, and Mn is the mass of the soil sample after drying.

2.4 Methodology of geobotanical research

During the geobotanical survey of natural forage pastures, the following were identified: the composition and structure of the vegetation cover in relation to habitat conditions; areas and features of the territorial distribution of pastures; and seasonal use patterns and productivity. During the field period, a reconnaissance survey of the territory was conducted, including geobotanical mapping of the pastures. During the study, a description of the vegetation, soil, and ecological state of the natural pastures, as well as herbage productivity, was carried out. The description of the vegetation was made on sites of approximately 100 m² in size. For floristically poor and sparse groups, larger sites were selected. When pasture types were named by vegetation, the dominant plant was listed

first. Samples of all plant species were included in the description form. All species of a given description point were included in the list of plants. The dry mass weight per 1 m^2 was recorded after sorting, drying, and weighing the mown crop.

The average height of the vegetation cover, as a whole and by tiers, was determined by the height of the predominant part of the plants. Soil characteristics were carried out based on soil survey materials by comparing geobotanical and soil contours. Plants were collected for the herbarium throughout the field period. Recommendations for the rational use and improvement of degraded pastures in the studied areas were provided. The abundance of species in phytocenoses was determined using the Drude abundance scale. The species composition of plants in plant communities was determined using the relevant botanical guides, such as the flora of the Union of Soviet Socialist Republics (USSR), the flora of Kazakhstan, the guide to plants of Central Asia, and the illustrated guide to plants of Kazakhstan. Species and generic names of plant species are given according to the Plants of the World Online (POWO) database, as well as according to Cherepanov and Abdulina.[27,28] The structure of families is presented according to the system developed by Takhtadzhyan. The collection and processing of herbarium material were carried out using the generally accepted method of Skvortsov.[29,30]

2.5 Determination of soil moisture

Pasture yield was determined using a 1 m² plot laid loosely (not randomly) at 4 locations (points) of the pasture plot. The grass on the meters was cut at a height of 3 cm from the soil surface. The cut samples from each meter were weighed separately in grams. The results were then summed up and divided by 4. The average yield in grams was obtained, and then it was multiplied by 10,000 (m²/ha) to obtain the pasture yield in/ha. Soil samples were collected during the dry season at most sites using a stratified random procedure.[31]

2.6 Laboratory analysis

All chemical analyses of the soil were conducted at the U. Uspanov Kazakh Research Institute of Soil Science and Agrochemistry.

3. Results and discussion

3.1 Botanical features and geographical location

As a result of field research on natural and economic use, the studied mountainous regions of Southeastern Kazakhstan are divided into the following vertical zones, or belts (Table 2).

The soil and vegetation cover of the mountainous terrain have their own characteristics. Their formation in the mountains is subject to the law of vertical zonality, but the proximity of deserts and the continental climate determines, even on one ridge, at one altitude, depending on the exposure and steepness of the slope, the development of sharply different soils and vegetation.[32] The high-mountain meadow zone is located at an altitude of 2600-2700 to 3800 m above sea level. At an altitude of 2400-2600 to 2800-3200 m, there are subalpine mountain meadow and peaty soils, on which tall-grass subalpine cereal-forb meadows (*Alchemilla sibirica*, *A. scalaris*, *Gentiana algida*, *G. kaufmanniana*, *Aster alpinus*, *Erigeron aurantiacus*, *Festuca ovina*, *F. kryloviana*, *Kobresia capilliformis*, *K. humilis*, *K. stenocarpa*, *Dichodon*

Table 2: Classification of vertical zonality of the studied areas of Southeastern Kazakhstan.

Macrorelief	Altitudinal zonation	Plant communities	Height (m)
Mountains	Highlands	Alpine meadows	3300-3800
		Subalpine meadows	3200-2700
	Middle mountains	Coniferous forests	3100-2700
		Mixed forests	1800-2700
		Meadow forests, chernozem (black soils)	1200-1800
	Foothill-steppe lowlands	Foothill-steppe, dark chestnut soil	1000-1200
		Foothill-dry steppe, light chestnut soil	850-1000
Foothills	Foothill semi-desert	Grass-wormwood, *Artemisia sublessingiana*, common serozem	550-850
	Desert	Forbs-wormwood, *Artemisia terrae-albae*, light serozem	Above 550

cerastoides, *Trisetum spicatum*, *Poa alpina*, *Helictotrichon tianschanicum*, *Juniperus sabina*, and others) exist. Even higher, up to 3800 m, there are low-grass alpine meadows (*Eritrichium villosum*, *Primula algida*, *Myosotis sylvatica*, *Phlomoides oreophila*, and others), sedge-kobresia meadows (wastelands).

The mid-mountain region, located at altitudes of 1200-1400 to 2400-2700 m above sea level, is characterized by rich, leached, and degraded mountain chernozems and mountain forest-meadow soils. Forb-grass meadow-steppes with vegetation such as *Dactylis glomerata*, *Brachypodium sylvaticum*, *Geranium collinum*, *Archangelica brevicaulis*), forests of fruit trees (*Malus sieversii*, *Armeniaca vulgaris*, *Crataegus chlorocarpa Populus tremula*), bushes (*Cotoneaster suavis*, *C. neo-antoninae*, *Spiraea lasiocarpa*, *Berberis sphaerocarpa*, *Lonicera altmannii*, *L. microphylla*, *L. stenantha, Rosa beggeriana, R. laxa*, *R.alberti* and others) extend to a height of 1600-1700 m. In the higher regions, up to 2400-2700 m, there are meadow-forest vegetation spruce forests (*Picea schrenkiana* with *Populus tremula*, *Sorbus tianschanica*, *Padus avium and Salix Iliensis*, *S. karelinii*, *S. hastata*), as well as tall grass meadows (*Ligularia macrophylla*, *Dactylis glomerata*, *Brachypodium pinnatum*, and others). Chernozem-like mountain-meadow soils predominate here. Low mountains (at an altitude of 700-800 to 1000-1200 m above sea level) are a zone of dark chestnut and chernozem (low-humus and medium-humus) soils. Up to 800-1000 m, ehere are sod-grass steppes (fescue-feather grass) with forbs and steppe shrubs (*Cerasus tianschanica*, *Spiraea hypericifolia*, *Cotoneaster megalocarpus, Rosa pimpinellifolia*). Above are rich grass-cereal meadow steppes with shrubs such as *Elytrigia repens*, *Bromopsis inermis*, *Poa trivialis*, *P. annua*, *Euphorbia tianschanica*, *E. latifolia*, *Glycyrrhiza glabra*, and others (Fig. S2).

The formation of the vegetation cover of natural mountain pastures is influenced by various factors: terrain (steepness, length, slope exposure), soil cover (water permeability, erosion resistance, fertility level, genetic characteristics of soils); intensity and nature of precipitation, as well as significant influence of human economic activity (grazing, fires, deforestation, and recreational factors). Preventing soil erosion on slopes is crucial for maintaining the forage productivity of mountain pastures.

Modeled by slope or soil type, site geometry (*i.e.*, fragmentation, size, slope) can also influence soil erosion by controlling runoff and erosional processes.[33] Soil erosion is one of the most significant processes contributing to land degradation, particularly in mountainous areas.[34] Active processes of soil washing and leaching are directly dependent on the steepness of the slopes. The soils become poorer, and their permeability increases. It has been calculated that with a doubling of the slope steepness, the size of erosion per unit area increases by a factor of 2.5.[35] The shape and length of the slope greatly influence soil erosion. It can be assumed that when the length of the slope doubles, soil loss per unit area increases by one and a half times. Erosion processes are especially destructive on the convex slopes.[36] Slopes facing south and west suffer more from erosion than slopes facing north and east. Depending on the slope gradient, its water-thermal regime and vegetation cover change. In the studied mountain areas of Southeastern Kazakhstan, the southern slopes (with a steepness of 10 to 55°) receive 12-14 times more solar radiation in winter and 1.1-1.2 times more in summer than the northern slopes.

On the southern slopes, the snow cover is unstable, 50% of the wintertime, the soil surface is exposed and, therefore, freezes more deeply. The greatest danger of erosion occurs when the surface soil has thawed, but the frozen layer below limits and even prevents the movement of water into the depths. On the southern slopes, the snow melts a month earlier, so grazing begins here earlier than on the northern slopes. Rainfall significantly contributes to the manifestation of soil erosion on slopes.[37] To determine the erosive properties of rain, it is necessary to consider the intensity, duration, total amount of precipitation, and its distribution throughout the season. With an increase in absolute heights in tors, the amount of precipitation increases. In the studied areas, annual precipitation ranges from 180-220 mm in the foothill-desert zone, 300-600 mm in the low mountains, 840-900 mm in the midlands, and 900-1000 mm in the highlands. Most of this precipitation falls during the summer pasture period, and often, the rains are of a torrential nature. In mountainous areas, erosion is caused by meltwater runoff. Therefore, the height of the snow cover at the beginning of the snowmelt period is of great importance here.[38]

According to our observations, the average height in the mid-mountains ranges from 700-800 mm, while in the highlands, it is 900 -1000 mm. We have explored the Assy plateau, which is one of the largest mountain pastures of the Ile-Alatau, located at an altitude of 2200-2800 m. The landscape of the mountain pasture is characterized by a great biological diversity and highly productive plant communities. The main life forms are perennial and annual grasses, subshrubs, and shrubs. In polydominant meadow communities, according to the richness of the species composition, cereal long-rhizome mesophilic grasses predominate: *Phleum paniculatum*, *Elytrigia repens*, *Hordeum vulgare*, *Festuca pratensis*, *Bromus inermis*, *Alopecurus pratensis*, *Phleum phleoides*, *Poa pratensis*. There are meadow herbs: *Achillea millefolium*, *Medicago falcata*, *Sanguisorba officinalis*, *Lathyrus pratensis*, *Inula Britannica, Trifolium repens*, and species of genera: *Potentilla*, *Geranium*, *Myosotis*, *Alchemilla*, *Astragalus*, and others. The total projected soil cover by plants is quite high, reaching 95-100% (Fig. S3).

The assessment of anthropogenic factors influencing the degradation of pasture ecosystems in Southeastern Kazakhstan was conducted in the Almaty region, encompassing the Enbekshikazakh, Uyghyr, Kegen, and Raimbek districts. Table 3 shows that the largest percentage of the pasture area falls in two districts: Kegen (70% of

pastures) and Enbekshikazakh (68%). In the Uygyr district, the share of pastures is 44%, and the smallest percentage of pastures falls on the Raimbek district - 31%.

To assess the impact of grazing on pasture degradation in Southeastern Kazakhstan, an analysis was conducted on the population dynamics of large livestock (cattle, horses, and camels) and small ruminants (sheep and goats) (Table 4). The extent of pasture degradation resulting from grazing is influenced not only by the density of livestock per unit area but also by the duration of the grazing period. Prolonged grazing exerts a detrimental effect on both soil stability and vegetation cover, accelerating degradation processes within pasture ecosystems. The physical properties of the soil are partially restored during the 21-week period after the soil damage.[39] To determine the livestock load, it is necessary to consider that sheep, cows, horses, and camels do not consume the same amount of feed per day to sustain their lives and produce products. Animal species differ in their preferences for different plants, the order in which they select the species, and the height at which they cut the plant they eat.

Cattle prefer taller grasses and other plants, horses choose shorter cereal plants, and sheep prefer vegetative parts. Goats are less selective than other farm ruminants regarding the types of plants they eat.[40] The proportions of change in feed consumption are not linear with the change in the animal's weight. The smaller the animal, the more feed it needs per unit of its weight. Therefore, it is necessary to convert the existing livestock into a single standard unit. To convert the existing livestock into a standard unit, it was accepted to consider sheep and goats equal to one conventional sheep. For cows, five conventional sheep were adopted, for horses, six, and for camels, eight conventional heads of sheep.

To determine the grazing load, the available livestock must be divided by the area of pastures. Data on the dynamics of the grazing load in the study area are illustrated in Table 5 and Fig. S4.

Table 3: The share of pastures in the land use structure of the study area.

Districts	Area (thousand ha)		Share of pastures %
	Total area	Pasture area	
Enbekshikazakh	780.7	530.9	68
Kegen	675.5	472.6	70
Raimbek	1420.0	442.5	31
Uygyr	876.6	386.6	44

Table 4: Livestock populations in Enbekshikazakh, Kegen, Raimbek, and Uygyr districts (2020-2024).

Districts	Pasture area (thousand ha)	Year				
		2020	2021	2022	2023	2024
Enbekshikazakh	530.9	813645	830416	857047	890869	567799
Kegen	472.6	618916	627753	652930	665623	513008
Raimbek	442.5	698096	724002	777744	799709	453125
Uygyr	386.6	634563	646341	649097	630088	484512

Table 5: Load on pastures during grazing in the studied areas.

Districts	Year				
	2020	2021	2022	2023	2024
Enbekshikazakh	1.53	1.56	1.61	1.68	1.07
Kegen	1.31	1.33	1.38	1.41	1.09
Raimbek	1.58	1.64	1.76	1.81	1.02
Uygyr	1.64	1.67	1.68	1.63	1.25

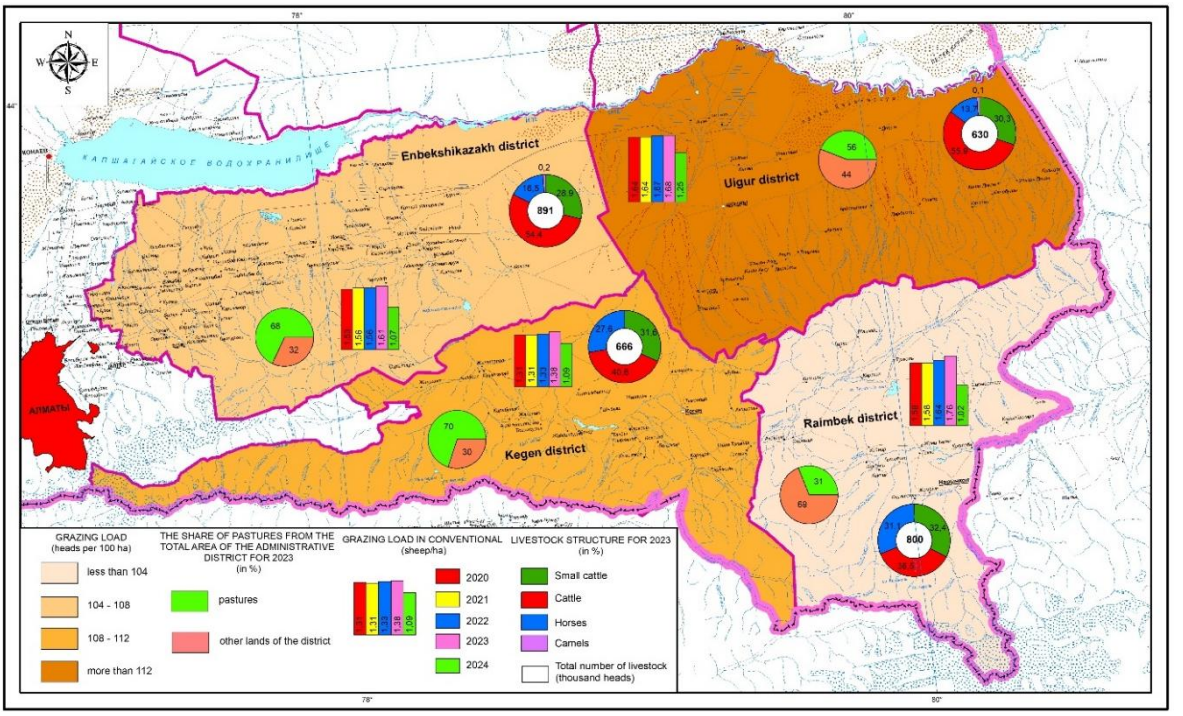


Fig. 1: The grazing load of animals on the pastures of the study areas.

Fig. S4 illustrates that in 2024, the grazing load on the pastures in the study area significantly is decreased due to a reduction in livestock numbers. Overall, the lowest grazing pressure was observed in the Raimbek district, whereas the highest was recorded in the Uygyr district (Fig. 1).

3.2 Soils

Soil is the basis for vegetation and one of the primary parameters for producing feed for agriculture. Soil plays a crucial role in the formation and heterogeneity of habitats and thus, can lead to changes in vegetation structure and plant diversity.[41] The importance of soil as pasture for livestock farming is very high. Soil influences the growth of grass and other plants that serve as feed for livestock. Good soil provides the necessary nutrients, which contribute to the growth of high-quality vegetation. Healthy soil supports a diversity of microorganisms and other organisms, and contributes to the sustainability of the pasture ecosystem. This, in turn, helps in the fight against diseases and pests. Good soil structure ensures effective drainage and permeability, preventing waterlogging and promoting better water absorption by plants. Sustainable pasture management practices can help increase the soil's carbon content. Soils can act as a carbon store, which is important in the fight against climate change. Stopping the degradation of pastures and converting them to arable land will help preserve carbon reserves in the soil.[42] Fertile soils ensure the high productivity of pastures, allowing livestock farms to produce more meat, milk, and other products.

3.2.1 Chemical properties of the soils studied

Humus is a crucial component that maintains the health and productivity of pastures, which in turn impacts the efficiency of livestock farming. This is especially important for pastures that are susceptible to erosion due to livestock trampling. Humus plays a crucial role in maintaining the fertility of pasture soils, contributing to the formation of soil aggregates and enhancing its structure. This, in turn, increases the air permeability and water-holding capacity of the soil, which is important for the growth of grasses and other plants. The presence of humus in the soil helps reduce erosion by binding soil particles and preventing them from being washed away.[43] In the study area, we described the alpine mountain-meadow (Assy pasture, Ile Alatau) and subalpine mountain-meadow sod soils (Shalkudusu pasture, Ketpen ridge) (Fig. S5).

As illustrated in Fig. S5, the profile description of horizon A (0-15 cm) reveals a sod layer with a black coloration, loose composition, and granular structure. This horizon is interwoven with both thick and thin root systems and exhibits a loamy texture. The transition is abrupt, with underlying bedrock appearing as large boulders. Characteristic features of mountain meadow soddy soils include low thickness, strong sodding, good structure and high humus content. Chemical analyses of the alpine mountain meadow soddy soil of the Assy plateau of the Ile-Alatau Alatau showed that the humus content was more than 14%, the pH value was acidic - 5. The absorption capacity is about 33 meq per 100 g of soil. Among the absorbed cations, calcium predominates (Ca-68%). According to the granulometric composition, the studied mountain-meadow sod soil is medium loamy fine sandy. The upper sod horizons have a high moisture capacity. Despite the high mechanical strength of the turf, its structure is expressed relatively weakly. As a result of the fastening of lumps by thin roots, fractions >5 mm and microaggregate separateness predominate, and there are a few granular fractions. Due to

low biodegradability, high humidity, and low temperature throughout the year, the processes of humification-mineralization of plant residues proceed very slowly (Table 6). A study of the subalpine mountain meadow soil of the high-mountain pasture Shalkudusu of the Ketpen ridge (Fig. S5B) showed that the horizon A1 (0-14 cm): black with brownish peaty layers of sod, moist, firmly sodded, intertwined with fibrous roots of cereal grasses, slightly compacted, powdery, loamy, the transition is gradual. Horizon A2 (14-37 cm): brownish-black, moist, medium loam with a large number of roots, compacted, powdery-granular structure, inclusions of gruss, crushed stone, stones, gradual transition. Horizon B (37-68 cm): brownish-black, moist, compacted, lumpy-granular structure, fewer roots, heavy loamy, with gravel and crushed stone; occasional stones. Horizon C (68-100 cm): yellowish-brown, wet, dense, structureless, heavy, loamy with an admixture of gravel, crushed stone, and stones. Table 6 presents data on the chemical composition of the subalpine mountain meadow soil from the Shalkudusu pasture on the Ketpen ridge. Subalpine mountain meadow soils have a high humus content (14.3%) in the upper horizon, which drops sharply to 7.9% below. The total nitrogen content is very high, at 0.68%. Soils that have an acidic reaction and strong base unsaturation, but saturated soils with a neutral reaction are also found. The absorption capacity is high (33.3% meq/100 g). Calcium predominates in the composition of absorbed bases (more than 80% of the capacity), which, along with a large amount of organic matter, determines the good granular structure of the soil. This determines their high water permeability, reducing the development of erosion processes. However, the destruction of the sod leads to soil washouts and erosions. Table 7 provides data on the granulometric composition of subalpine mountain meadow soils.

The graph shows the correlations between different soil fractions. The color scale indicates the strength of the relationship between the fractions: the brighter the blue color,

Table 6: Granulometric composition of the studied alpine mountain-meadow sod soil pasture Assy, Ile-Alatau.

Soil	Depth (cm)	Fraction content (% of absolute dry soil)						
		Fraction size (mm)						
		sand			dust		silt	Fraction
		1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001	<0.01
Alpine mountain meadow turf	0-15	38.9	14.7	22.5	9.3	10.2	4.2	23.8

Table 7: Granulometric composition of the studied subalpine mountain meadow soils of the Shalkudysu pasture, Ketpen ridge.

Soil	Depth (cm)	Fraction content (% of absolute dry soil)								
		Fraction size (mm)								
		3	3-1	1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001	<0.01
Subalpine mountain meadow soil	0-14	6.4	4.9	0.7	8.1	41.3	14.6	17.8	12.6	45.0
	14-37	15.7	4.6	1.5	7.7	32.4	15.4	19.8	18.6	53.8
	37-68	25.4	14.8	2.3	10.7	27.7	11.6	16.3	16.6	44.5



Fig. 2: Correlation matrix of soil fractions.

the stronger the positive correlation, while the yellow shades represent a negative correlation. Fig. 2 illustrates a strong positive correlation between larger particle fractions, such as 3 mm and 1-0.25 mm. This means that as the content of the larger fraction increases, the content of smaller particles in these ranges also increases. For example, the 3 mm and 3-1 mm fractions have a correlation of 0.86, indicating a close relationship between them. On the other hand, there is a very strong negative correlation between larger fractions, such as 3 mm and 0.05-0.01 mm (-0.98). This indicates that as the larger particles increase, the smaller fractions decrease. Similar negative correlations are also observed between 3-1 mm and 0.05-0.01 mm fractions. Fractions with smaller particles, such as 0.01-0.005 mm and 0.005-0.001 mm, exhibit a strong positive correlation (0.92), which may indicate similar distribution patterns for these particles in the soil.

Overall, the graph shows that fractions with larger particles and smaller particles exhibit opposite trends, and changes in one fraction may be associated with changes in others. This can help in understanding soil properties, such as permeability or water retention capacity. Table 7 shows that the granulometric composition of the subalpine mountain meadow soil is heavy, loamy, silty-dusty. The coarse dust fraction (0.05-0.01 mm) predominates in the soil profile, and the silt fraction (<0.001 mm) increases in the lower horizons (16.6-18.6%).

Due to the high biogeneity of mountain-meadow subalpine soils, more humic acids are formed in them, but due to the unsaturation of these soils with bases, most of the humic acids are represented by mobile forms (Table 8). Thus, the analysis of the granulometric and microaggregate composition of soils of degraded pastures shows that the sum of dusty and silty fractions decreases, and the sum of sandy fractions increases. According to the chemical analysis of the granulometric and microaggregate composition, the dispersion factor changes insignificantly, the structure coefficient has negative indicators, and the soil erosion resistance is close to zero. The inability of the soil to resist erosion results in a further reduction of the finest particles and an increase in the fractions of coarse and medium sand. An increase in the sand fraction's content reduces the soil's water-holding capacity, resulting in a decrease in the moisture available to plants. An increase in the content of sand fractions in the soil leads to a decrease of up to 40% of cereals (*Poaceae*) and legumes (*Fabaceae*) with fibrous root systems (*Dactylis glomerata, Helictotrichon pubescens, Festuca kryloviana, Alopecurus pratensis, Trifolium pratense, Trifolium repens*) eaten by animals and leads to an increase in plants with a taproot system (from 5 to 20%), i.e., the introduction of inedible weeds and poisonous plants of the families *Polygonaceae, Ranunculaceae, Urticaceae, Asteraceae, Polygonum aviculare, Aconitum leucostomum, A. soongaricum, Urtica cannabina, Echinops chantavicus*. All these lead to a decrease in pasture productivity. Additionally, the decrease in yield is attributed to a decline in the soil's content of mobile forms of plant nutrients, including nitrogen, phosphorus, and potassium.

The graph displays soil parameters, including their mean values, standard deviations, and ranges, for various soil characteristics (Fig. 3). The mean value represents the central tendency of each parameter at different depths. For example, the humus content in the soil averages 8.06%, indicating a stable level of organic matter. The nitrogen percentage in the soil is relatively low at 0.48%, which may suggest the need for nitrogen fertilizers. The carbon-to-nitrogen ratio (C:N) is 10:7, which is typical for soil with moderate levels of carbon and nitrogen. The standard deviation shows the variation of each parameter. For example, humus has a standard deviation of 5.21%, indicating significant fluctuations in its content within the soil. The nitrogen percentage has a standard deviation of 0.20%, indicating its stability. The pH level has a low standard deviation of 0.58%, reflecting the stability of soil acidity.

The range shows the difference between the maximum and

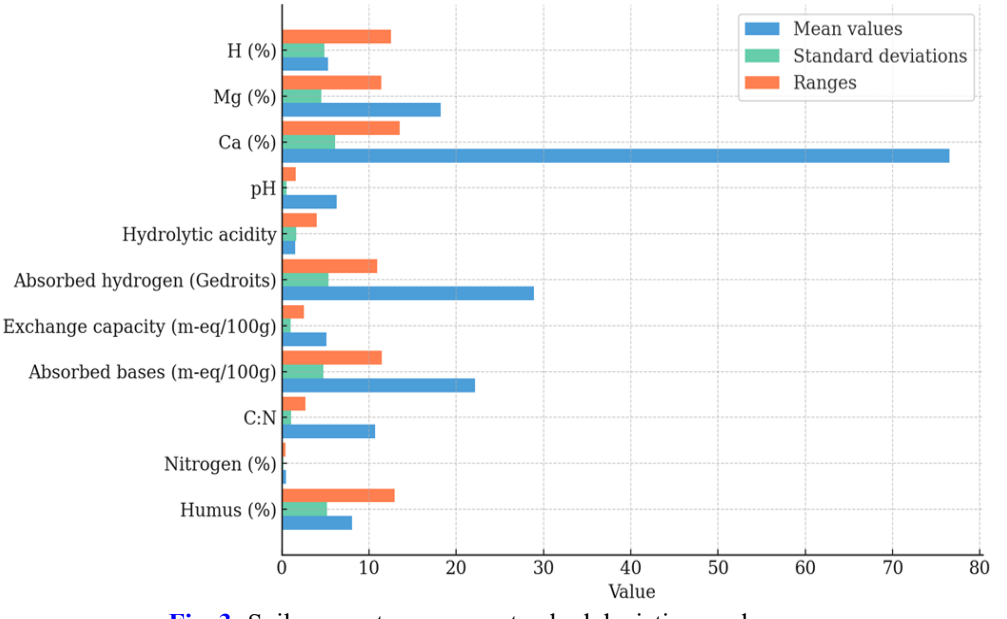


Fig. 3: Soil parameters: mean, standard deviation, and range.

Table 8: Content of gross humus, nitrogen, absorbed bases, and hydrogen in the studied soils.

Profile	Depth (cm)	Humus(%)	Nitrogen (%)	C: N	Absorbed bases (meq/100 g) Ca	Mg	Exchange capacity (meq/100 g)	Absorbed hydrogen according to Gedroits	Hydrolytic acidity	pH	Absorbed cations (%) Ca	Mg	H
Alpine mountain meadow sod soil	0-15	14.39	-	-	22.17	5.65	32.27	4.45	13.35	5.0	68.7	17.5	13.8
Subalpine mountain meadow soil	0-14	14.30	0.67	12.1	27.38	4.78	33.31	1.15	6.49	6.1	82.2	14.3	3.5
	14-37	7.91	0.43	10.6	19.11	3.54	23.74	1.09	-	6.3	80.5	14.9	4.6
	37-68	4.35	-	-	-	-	-	-	-	6.5	-	-	-
Alpine mountain meadow sod soil	0-21	10.5	0.6	10.7	26.19	6.1	32.71	0.42	-	6.6	80.0	18.7	1.3
	21-40	3.52	0.22	9.4	15.92	5.75	22.38	0.71	-	6.5	71.1	25.7	3.2
	40-68	1.48	-	-	-	-	-	-	-	6.6	-	-	-

minimum values for each parameter. For example, the humus content ranges from 1.48% to 12.91%, indicating significant variations in its content at different depths. The nitrogen percentage has a range of 0.45%, also indicating some variation in this parameter. The carbon-to-nitrogen ratio (C:N) ranges from 2.7, indicating variations in this ratio with depth.

Overall, the graph indicates that soil parameters, including humus, nitrogen percentage, and pH, exhibit significant fluctuations with depth. This is crucial for understanding soil stability and identifying which parameters may require further attention to enhance soil quality. High standard deviations for certain parameters, such as humus and hydrolytic acidity, indicate that these parameters may vary with soil depth. The ranges indicate the extent, to which these parameters can vary. This helps assess soil fertility at different levels.

The artificially maintained number of domestic animals by humans can use up the resources of pastures to the point of exhaustion, which leads to a significant transformation in the plant community, changing its entire floristic composition, that is, to the replacement of natural species of the plant community with weedy, poorly eaten and inedible plant species. At the same time, changes in the vegetation cover can be so profound that such plant communities become practically unsuitable for agricultural use. Weeds in pastures reduce the quality and yield of forage, impair animal productivity, and increase management costs associated with

Table 9: Total biomass of pasture plants determined in the field.

Season	Number of points	Weight (g/m^2) Wet weight	Dry weight	Vegetation
Spring	1	167.9	47	*Fabaceae -5; Poaceae - 6; Asteraceae -10; Cyperaceae - 3; Gentianaceae - 2; Ranunculaceae -3; Boraginaceae - 2; Rosaceae -2: Polygonaceae -2; Alliaceae -1; Valerianaceae -1; Crassulaceae -1; Brassicaceae - 3.*
	2	159.3	43	*Fabaceae -2; Poaceae - 10; Asteraceae -7; Cyperaceae - 3; Boraginaceae -2; Rosaceae -2: Polygonaceae - 2; Valerianaceae - 1; Crassulaceae -1; Brassicaceae - 3; Scrophularia-ceae -1; Campanulaceae - 1; Geraniaceae -2; Urticaceae -2; Saxifragaceae -2; Primulaceae -2; Lamiaceae -3.*

Season	Number of points	Weight (g/m^2)		Vegetation
		Wet weight	Dry weight	
	3	124.1	36	*Fabaceae -2; Poaceae- 310; Asteraceae -8; Boraginaceae -2; Polygonaceae - 2; Brassicaceae -3; Scrophulariaceae - 1; Campanu-laceae -1; Geraniaceae -2; Urticaceae -2.*
Summer	4	346.5	149	*Fabaceae -8; Poaceae - 13; Asteraceae -12; Cyperaceae - 1; Boraginaceae -2; Rosaceae -5: Polygonaceae - 4; Valerianaceae -1; Crassulaceae -1; Brassicaceaee -3; Scrophula-riaceae -1; Campanulaceae -1; Geraniaceae – 3; Urticaceae -2; Saxifragaceae -4; Primulaceae -2; Lamiaceae -5; Convolvulaceae -1.*
	6	190.9	84	*Caprifoliaceae -4; Berberidaceae -2; Fabaceae -6 видов; Poaceae - 9; Asteraceae -12; Boraginaceae -2; Rosaceae - 3: Polygonaceae -3; Brassicaceae -5; Scrophulariaceae -3; Geraniaceae -3; Urticaceae -2; Lamiaceae -4.*
	8	170.5	75	*Cupressaceae -3; Fabaceae -4; Poaceae- 9; Asteraceae -7; Boraginaceae -3; Rosaceae -7: Polygonaceae - 4; Valerianaceae -1; Crassulaceae - 2; Brassicaceae -7; Scrophula-riaceae -3; Campanulaceae -1; Geraniaceae -4; Urticaceae -1; Primulaceae -2; Lamiaceae -4.*
	10	213.3	96	*Fabaceae -5; Poaceae - 11; Asteraceae -9; Boraginaceae - 4; Rosaceae -5: Polygonaceae - 6; Valerianaceae -1; Crassula-ceae -2; Brassicaceae -7; Scrophulariaceae -3; Campanulaceae -1; Geraniaceae -4; Urticaceae -1; Primulaceae -2; Lamiaceae-4.*
	5	392.9	165	*Fabaceae -5; Poaceae - 11; Asteraceae -9; Boraginaceae - 4; Rosaceae -5: Polygonaceae -6; Valerianaceae -1; Crassulaceae -2; Brassicaceae -7; Scrophulariaceae -3; Campanulaceae -1; Geraniuaceae -4; Urticaceae -1; Primulaceae -2; Lamiaceae -4.*
	7	356.8	157	*Fabaceae -5; Poaceae - 11; Asteraceae -9; Boraginaceae - 4; Rosaceae -5: Polygonaceae -6; Valerianaceae -1; Crassulaceae -2; Brassicaceae -7; Scrophulariaceae -3; Campanu-laceae -1; Geraniaceae -4; Urticaceae -1; Primulaceae -2; Lamiaceae -4.*
	9	371.1	167	*Fabaceae -4; Poaceae- 9; Asteraceae-10; Boraginaceae - 3; Rosaceae -5: Polygonaceae -6; Crassulaceae -2; Brassicaceae -7; Scrophula-riaceae -3; Campanulaceae -1; Geraniaceae -4; Urticaceae -1; Primulaceae -2; Lamiaceae-4.*
Autumn	11	67.9	36	*Fabaceae -3; Poaceae- 10; Asteraceae -8; Boraginaceae - 3; Rosaceae -6: Polygonaceae -3; Valerianaceae -1; Crassulaceae -3; Brassica-ceae -7; Scrophulariaceae -3; Campanulaceae -1; Geraniaceae- 4; Urticaceae -2; Lamiaceae -6.*
	12	64.8	35	*Fabaceae -3; Poaceae- 7; Asteraceae -6; Boraginaceae -3; Rosaceae -4: Polygonaceae -5; Brassicaceae -5; Scrophulariaceae -2; Campanulaceae -1; Geraniaceae -2; Urticaceae -2; Primulaceae-2; Lamiaceae -5.*

pasture restoration.[44] As our studies have shown, accounting for the total harvest does not give a real idea of the forage value of lands, since due to the large proportion of uneatable weed plants, the total yield of vegetation on degraded pastures cannot match or even exceed good areas not affected by degression (Table 9).

Vegetation in the study area, which comprises four districts, varies depending on vertical zonality. We present a grouping of changes in belts and plant communities according to vertical zonality in the study area. According to this grouping, our research was conducted in the mountainous zone of the mid-mountain belt, characterized by plant communities of subalpine meadows and turf grasses, as well as coniferous and mixed forests (Table 9).

As a result of our research, the plants were divided into the following groups: 1. well eaten; 2. moderately eaten; 3. slightly and not eaten species. The first group of well-eaten plants mainly includes representatives of the families Fabaceae, Poaceae, Asteraceae, Cyperaceae, Juncaceae, and others. Weakly and uneatable plant species (weeds and poisonous) include representatives of the following families: Ranunculaceae (*Aconitum leucostomum, A. soongaricum, A. rotundifolium*, *Ranunculus longicaulis*), Chenopodiaceae, Urticaceae, some representatives of the family Asteraceae (*Conyza canadensis, L. narynensis*, *Xanthium strumarium, Arctium tomentosum*, *A. lappa, Ligularia .macroylla*, *Cirsium vulgare*, *Onopordon acanthium*, *Acroptilon australe, Centaurea kasakorum*, *Sonchus oleraceus*, *Cousinia umbrosa*, Peganaceae *(Peganum harmala*) some representatives Fabaceae, Alliaceae (Table 10).

Table 10: Number of plant species eaten in the study areas.

Plant belt	Number of points	Plant species palatability		
		Well eaten	Below satisfactory	Inedible or eaten occasionally
Spruce forests and woodlands of the Ketpen ridge: dwarf pine-spruce (*Picea schrenkiana, Junipers pseudosabina J. sibirica with Caragana jubata*) - in the Ketpen ridge forests and woodlands, with an undergrowth of *Sorbus tianschanica, Salix iliensis, Rosa alberti, Lonicera Altmannii*; grass and moss communities; deciduous-spruce (*Picea schrenkiana, Acer semenovii, Populus tremula*) forests and woodlands.	6	9	15	7
	10	8	6	5
	7	7	24	10
	9	5	21	7
	8	7	42	5
	12	9	44	7
Forb-feather grass and fescue-feather grass forb-bunchgrass and bunchgrass-grass with shrubs in combination with shrub thickets in Ile-Alatau: Forb-bunchgrass (*Stipa zalesskii, S. kirghisorum, Helictotrichon pubescens, H. desertorum, Stachys officinalis, Phlomoides pratensis, Medicago falcata, Origanum vulgare, Iris brevituba*) and bunchgrass (*Festuca valesiaca, Stipa capillata, S. lessingiana, Bothriochloa ischaemum, Ajania fastigiata*) in combination with roses (*Rosa platyacantha, R. pimpinellifolia, Cotoneaster multiflorus, C. melanocarpus, Spiraea lasiocarpa*) and with caraganas (*Caragana pleiophylla, C. pruinosa*).	1	3	7	5
	2	4	11	6
	3	10	45	9
	4	11	21	8
	5	4	13	3
	11	4	14	5

Table 11: Productivity of the edible part of the grass stand of the studied pastures in the spring period (g/m^2).

Number of points	Weight, g/m^2	
	Wet weight	Dry weight
Average value	107.7±3.96	33.3±1.89
Range	9.6	4.0

Table 11 shows that the average wet weight is 107.7 g/m² with a standard deviation of 3.96 g/m², indicating that the wet weight fluctuates by approximately 3.96 g/m² from the mean. The average dry weight is 33.3 g/m² with a standard deviation of 1.89 g/m², suggesting that the dry weight exhibits less variation compared to the wet weight. The wet weight range is 9.6 g/m², demonstrating that the moisture content of the samples varies within this span. For the dry weight, the range is 4.0 g/m², which also confirms a lower variability in this parameter. The wet weight shows a greater variability than the dry weight, meaning that the moisture content in the samples fluctuates more than the dry matter content.

Table 12: Yield of the edible part of the grass stand of the studied pastures in the summer period (g/m^2).

Number of points	Weight (g/m^2)	
	Wet weight	Dry weight
Average value	215.0±61.22	96.6±26.21
Range	141.8	61.0

The data show values for the wet and dry weights of the samples, including mean values, standard deviations, and ranges. The average wet weight is 215.0 g/m² with a standard deviation of 61.22 g/m², indicating significant fluctuations in the wet weight of the samples (Table 12). The moisture content varies by 61.22 g/m² from the mean, which may be related to differences in storage conditions or sample composition. The average dry weight is 96.6 g/m² with a standard deviation of 26.21 g/m². This shows that the dry weight is less variable compared to the wet weight. The dry matter content is more stable, indicating that the composition of the samples remains relatively unchanged. The range of wet weight is 141.8 g/m², indicating significant differences in moisture content between the samples. This could be due to differences in characteristics or storage conditions. The range of dry weight is 61 g/m², indicating variability, but to a lesser extent than that of the wet weight. This suggests that the dry matter content in the samples is more uniform. The wet weight exhibits a greater variation, indicating more significant changes in moisture content between points. The moisture content varies significantly, while the dry matter content remains stable. This could be useful for further calculations, such as assessing the moisture content in materials.

In autumn, the yield, as shown in Table 13, reveals that the average wet weight is 53.8 g/m² with a deviation of ± 6.65 g/m², indicating a noticeable variability in wet weight across the samples. The range of wet weight values is 9.4 g/m², further confirming a broader variation in this parameter. In contrast, the dry weight has an average value of 29.5 g/m² with a smaller deviation of ±2.12 g/m², suggesting that the changes in dry weight are less pronounced. The dry weight range is only 3.0 g/m², highlighting a lower variation among the samples. Consequently, the wet weight exhibits a greater variability compared to the dry weight, suggesting that the moisture content in the samples fluctuates more significantly than the dry matter content.

Table 13: Productivity of the edible part of the grass stand of well and moderately edible plant species of the studied pastures in the autumn period (g/m^2).

Number of points	Weight (g/m^2)	
	Wet weight	Dry weight
Average value:	53.8±6.65	29.5±2.12
Range	9.4	3.0

3.3 Assessment of pasture degradation in the study areas

The development of degradation processes in the mountainous areas of the Northern Tien Shan, including the Ketpen Ridge, Shalkudusu pasture, and the Ile Alatau on the Assy Plateau, was assessed using GIS technologies (Fig. S6). The territory under study, in botanical and geographical terms, belongs to the Dzungarian-Northern Tien Shan group of zonality types, the Ile Alatau-Northern Zhetisu zonality type, and the Kungey-Terskey-Ketpen zonality type.[45] As a result of the research, an assessment was made of the change in the yield and structure of the grass stand and soil under the influence of the degree and methods of grazing. The yield of the grass stand was assessed according to 4 degrees of degradation: highly productive, productive, low-productive, and unproductive. Changes in the structure and transformation of the grass stand were assessed by four degrees of transformation: unchanged, moderately changed, strongly changed, and broken. Each of these degrees was assessed based on the content in the grass stand, where plant species were thinning out due to overgrazing and increasing in abundance, as well as the penetration of new species (Table 14).

According to Table 14, according to the dynamics of degradation, the studied pastures were classified as moderately and intensely degraded pastures, since the content of weeds and poisonous invasive species in the composition of the grass stand with a moderate transformation of the grass stand is from 5 to 20%, and with an intense degree from 20-40%, this in turn indicates that the state of our studied pastures is in a state of intense and moderate degradation in terms of the transformation of the grass stand. With moderate pasture

Table 14: The degree of ecological condition of the studied agricultural lands.

Degree of ecological condition of agricultural lands	Degradation of pasture grassland		Trails (%)	Soil erosion and deflation destruction of humus horizon (%)
	Productivity average-long-term (%)	Composition of grass stand		
Tense	13.6	a) Thinning species (readily eaten) up to 40% b) Increasing in abundance up to 40% c) Penetrating species (weeds and poisonous) up to 20 units.	15-25	10-25
Crisis	25.6	a) Thinning species (readily eaten) up to 20% b) increasing in abundance up to 50% c) penetrating species (weeds and poisonous) up to 40 units	25-50	25-50
Destructive	Less than 25	a) Thinning species (readily eaten) less than 10% b) Increasing in abundance up to 40% c) Penetrating species (weeds and poisonous) more than 60 units.	More than 50	More than 50

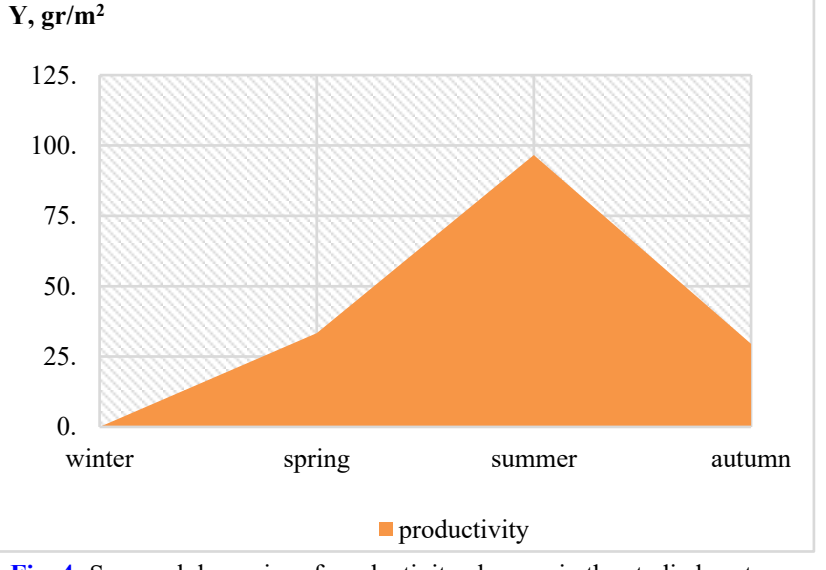


Fig. 4: Seasonal dynamics of productivity changes in the studied pastures.

Table 15: Dynamics of seasonal changes in pasture productivity in the studied areas.

Season pasture period	Productivity (t/ha)		Content of weeds and poisonous plants (%)
	Total biomass	Edible part	
Spring	0.42±0.05	0.31±0.01	25.33±10.26
Summer	1.28±0.40	0.97±0.28	23.57±4.86
Autumn	0.36±0.007	0.28±0.021	22.0±7.78

degradation, pasture productivity can decrease by 25%. With intense pasture degradation, the reduction in the edible portion of the grass stand can reach up to 50% (Table 14).

Fig. 4 illustrates the seasonal dynamics of pasture productivity, exhibiting a gradual increase in yield from winter to mid-summer, followed by a sharp decrease in autumn.

In spring, the average productivity of total biomass is 0.42 t/ha, with a deviation of only ±0.05. This indicates stable results with minimal differences between the samples. The edible part is almost unchanged at 0.31 with a deviation of ±0.01. However, the content of weeds and poisonous plants is higher during this season, reaching 25.33% with a significant variation (±10.26%). In summer, productivity is at its peak. The average total biomass is 1.28 t/ha, with a noticeable variability (±0.40). The edible part also fluctuates, averaging 0.97 t/ha with a deviation of ± 0.28. As for weeds and poisonous plants, their content is slightly lower than in spring at 23.57%, with a deviation of ±4.86%, indicating a more stable situation. In autumn, productivity decreases to its lowest values. The average total biomass is 0.36 t/ha with a very small deviation of ±0.007, showing almost identical results between the samples. The edible part is slightly lower than in spring at 0.28 t/ha with a deviation of ±0.021. The content of weeds and poisonous plants averages 22%, with a deviation of ±7.78%, indicating a moderate variability (Table 15). Thus, the productivity is the highest in summer but shows significant variability. In the spring, productivity is lower but more stable, with a higher weed content. In autumn, productivity is at its lowest, but the results remain consistent as the growing season comes to a close.

Fig. 3 illustrates that the studied area, encompassing a total of 366543.9 ha of mountain pastures across four regions (Enbekshikazakh, Uygyr, Kegen, and Raimbek) in Southeastern Kazakhstan, experiences varying degrees of degradation. The extent and intensity of degradation were assessed based on the condition of the vegetation cover, specifically the proportion of edible and non-edible plant components (Table 16).

The results of this study clearly demonstrate that pasture degradation in Southeastern Kazakhstan is a significant issue driven by overgrazing and changing ecological conditions. Seasonal variations in productivity were evident, with the highest biomass recorded during the summer (12.76±4.07 t/ha) and the lowest in autumn (3.55±0.07 t/ha). This highlights the vulnerability of pastures to overgrazing during periods of peak productivity, which accelerates their degradation. A key observation was the transformation of vegetation cover. The dominance of native grasses, such as those in the Fabaceae and Poaceae families, decreased significantly in degraded areas, while invasive weeds and poisonous plants increased.[46] This change negatively impacts forage quality and livestock nutrition, ultimately reducing the agricultural productivity in the region. These findings are consistent with prior studies conducted in Central Asia, where overgrazing has been shown to trigger soil erosion, nutrient depletion, and biodiversity loss. The soil analysis further revealed critical issues. In areas such as Shalkudusu and Assy pastures, an increase in sandy soil fractions was observed, leading to a lower water retention and reduced fertility. This directly affects the ability of pastures to sustain vegetation, particularly edible species with fibrous root systems, and encourages the spread of inedible weeds with taproots.[47] To address these challenges, it is evident that current grazing practices require reconsideration. Unregulated livestock grazing not only depletes soil and vegetation but alsothreatens the sustainability of livestock farming. Introducing rotational grazing systems could allow pastures time to recover while optimizing livestock density per ha could reduce pressure on already fragile ecosystems.[48] This study has its limitations. The focus was primarily on specific regions, and it did not account for the potential impact of long-term climate change, which could exacerbate the pasture degradation.[49] Future research should aim to incorporate climatic data and test restoration techniques, such as reseeding with native grass species and enhancing soil quality using organic amendments.

Addressing pasture degradation requires an integrated approach. This involves regulating grazing intensity, restoring degraded lands through reseeding, and

Table 16: The intensity degree of degradation of the studied pastures.

Degree of pasture degradation	Intensity of degradation degree	Area (ha)
Stressful	Strong	50530.4
	Medium	54666.1
	Weak	67913.3
Moderate	Strong	56294.6
	Medium	101702.6
	Weak	35436.8
Total:		366543.9

continuouslymonitoring pasture conditions.[50] Such efforts will not only enhance the pasture productivity but also ensure the preservation of biodiversity and ecosystem stability for future generations. The study identified the interrelationship between vegetation cover, biomass reserves, and soil characteristics. Changes in vegetation cover and pasture degradation processes have a direct impact on soil structure. Nutrient-rich and structurally stable soils enhance the plant diversity and biomass productivity.[51]

However, in soils affected by erosion and depletion, vegetation cover becomes sparse, beneficial grasses decrease, and the prevalence of weeds increases. The biomass reserves of pasture plants undergo seasonal fluctuations, leading to a decline in productivity due to an excessive grazing pressure. Moreover, increased grazing intensity leads to soil compaction, reduced moisture retention capacity, and a decline in biological productivity. These factors contribute to changes in plant composition, particularly the loss of rare and nutritious species.[52]

In the future, the introduction of rotational grazing systems will be essential for restoring pastures. Degraded lands should be replanted with local plant species. Proper livestock distribution can help minimize the pasture degradation.[53] Improving soil quality requires the use of organic fertilizers and implementing anti-erosion measures. Enhancing moisture retention can be achieved through the introduction of specialized technologies. Continuous monitoring is necessary to preserve the biodiversity of pasture ecosystems.

Educational programs for local communities and farmers should be organized. Government policies should support a sustainable pasture management. Strengthening scientific research and monitoring pastures through remote sensing technologies is critical. The selection of plant species adapted to climate change can help maintain ecological stability. From an economic perspective, proper pasture management can enhance livestock productivity and increase farmers' incomes. Strengthening partnerships between governmental and scientific institutions, farmers, and international organizations is essential for ensuring the sustainable use of pastures. These measures will contribute to maintaining long-term pasture productivity and ensuring ecological sustainability.

4. Conclusion

Pasture degradation in Southeastern Kazakhstan is a pressing issue caused by overgrazing and changing environmental conditions. This study identified clear seasonal variations in pasture productivity, with the highest biomass recorded in summer and the lowest in autumn. These changes underscore the substantial impact of grazing intensity and climatic factors on the sustainability of pasture ecosystems. The replacement of native grasses with invasive weeds and poisonous plants significantly reduces forage quality, directly impacting the livestock productivity. The findings also revealed that soil degradation, including reduced fertility and moisture retention, is a major contributing factor. In areas with increased sandy soil fractions, the ability of pastures to sustain vegetation declines, further accelerating the degradation.

To address this issue, sustainable grazing practices must be prioritized. Implementing rotational grazing, reseeding pastures with native plant species, and improving soil quality are crucial steps for restoring and maintaining pasture ecosystems. Additionally, regular monitoring of pasture conditions using advanced technologies can help prevent further damage and ensure an effective resource management. Combating pasture degradation is vital not only for preserving biodiversity and ecosystem health but also for ensuring the long-term sustainability of livestock farming in the region. Immediate and coordinated action will help protect these vital ecosystems for future generations.

Looking ahead, several key strategies can enhance the resilience of pasture ecosystems. Developing climate-adaptive grazing methods and integrating precision agriculture technologies will optimize pasture usage. Investments in research on drought-resistant forage crops and soil restoration techniques will further support pasture sustainability. Additionally, promoting community-driven pasture management programs will ensure local engagement and accountability in the conservation of resources. Strengthening partnerships between farmers, scientists, and policymakers will facilitate the implementation of long-term solutions. The adoption of these measures will improve the sustainability of pasture ecosystems, securing their ecological and economic benefits for the future.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

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