

RESEARCH ARTICLE

Monitoring of the *Saiga* Population: Balancing Nature and Agriculture

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Abstract: The rapid recovery of the Saiga population (*Saiga tatarica*) in Kazakhstan represents a significant conservation success; however, it has simultaneously generated complex ecological and socio-economic challenges in steppe ecosystems. This study evaluates the relationships between Saiga population density and pasture ecosystem condition and identifies ecological thresholds relevant to balancing biodiversity conservation and sustainable agricultural land use. The research is based on an integrated interdisciplinary approach combining field surveys, soil physicochemical and microbiological analyses, geospatial technologies (GIS and remote sensing), and multivariate statistical methods. Vegetation parameters, soil quality indicators, and microbial activity were analyzed in relation to Saiga population density across representative steppe ecosystems during the 2021–2023 growing seasons. The results demonstrate a nonlinear association between grazing pressure and ecosystem condition. Moderate population densities within the empirical management range of 10–20 individuals km⁻² were associated with relatively stable vegetation and soil biological functioning, whereas higher population densities and grazing pressure were associated with reduced plant biomass, declining vegetation cover, deterioration of soil properties, and lower microbial activity. During the monitoring period, vegetation cover in intensively grazed areas declined from 81.3±4.2% in 2021 to 68.9±5.1% in 2023, while mean NDVI changed from 0.64 in 2021 to 0.58 in 2022 and 0.60 in 2023. A conceptual ecosystem framework linking Saiga density, vegetation, soil, rhizosphere microbiome, and ecosystem productivity is proposed. Because the study uses an observational design, the identified relationships are interpreted as associations rather than experimentally demonstrated causal mechanisms. The findings support adaptive pasture management based on ecological zoning, remote sensing, monitoring of vegetation and soil indicators, and regulation of grazing pressure.

Keywords: *Saiga* Population, Population Monitoring, Steppe Ecosystems, Pasture Degradation, Soil Fertility, Rhizosphere Microbiome, Agroecosystems, Sustainable Land Use

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Introduction

The increasing demand for food production is placing new requirements on modern agricultural systems, which must simultaneously maintain high productivity and minimize their impact on natural ecosystems. Climate variability, deterioration

of soil resources, and inefficient utilization of agricultural inputs are among the major factors limiting the long-term sustainability of crop production. These challenges have stimulated growing interest in technological and biological approaches that can improve plant performance, enhance the efficient use of resources, and strengthen crop resilience under adverse environmental conditions. In recent years, considerable attention has been devoted to the integration of plant physiology, biotechnology, and sustainable agricultural practices. Research carried out in Kazakhstan has provided evidence of the potential of locally available biological and mineral resources for improving plant adaptation to environmental stresses. In particular, the application of natural mineral materials during seed priming has been associated with enhanced antioxidant protection and greater salt tolerance in barley seedlings [1]. Studies of medicinal and endemic plant species have likewise demonstrated the value of Kazakhstan's native flora as a source of biologically active resources with potential applications in biotechnology and sustainable production systems [2,3].

The sustainability of agricultural landscapes, however, cannot be considered independently of the condition of surrounding natural ecosystems. Increasing climatic variability and anthropogenic disturbance can alter vegetation structure, resource availability, and ecological interactions, thereby affecting both agricultural productivity and biodiversity. This is particularly important in Kazakhstan, where extensive steppe ecosystems represent a major component of the country's natural landscapes and support a wide range of species adapted to semi-arid environmental conditions. One of the most ecologically significant herbivores of these ecosystems is the *Saiga tatarica*. The status and dynamics of saiga populations are closely associated with the availability and condition of vegetation resources across steppe habitats. Changes in population density may therefore be linked to variations in pasture productivity, vegetation biomass, and environmental conditions. For this reason, assessment of saiga population dynamics together with indicators of vegetation productivity can provide valuable information for understanding changes occurring within steppe ecosystems and for developing scientifically based approaches to their sustainable management.

The recovery of the *Saiga* population is the result of effective conservation measures; however, its rapid growth has led to the emergence of a new set of ecological and socio-economic challenges. In the steppe regions of Western Kazakhstan, pressure on pasture ecosystems has intensified, resulting in vegetation degradation, reduced forage productivity, and increased soil erosion processes. Natural pastures of Kazakhstan constitute the ecological and economic foundation of extensive livestock production systems and simultaneously represent the principal habitat and migration environment for *Saiga* populations. Under arid climatic conditions, these ecosystems are characterized by limited regenerative capacity and high sensitivity to disturbances associated with overgrazing and climatic fluctuations [4, 5]. In recent years, increasing concentrations of *Saiga* herds within localized migration corridors and grazing territories have significantly intensified pasture loads, particularly in regions where livestock farming is also highly developed [6,7]. As a result, competition for forage resources between wildlife and agricultural systems has become one of the key environmental management problems in the steppe zone of Kazakhstan.

The soils of these regions are predominantly chestnut soils formed under conditions of insufficient moisture and characterized by moderate humus content and limited nutrient reserves [8, 9]. These soils are highly sensitive to disturbances in vegetation cover and structural integrity, making them particularly vulnerable to excessive grazing pressure [10, 11].

Reduction of plant biomass caused by intensive grazing weakens soil protection against deflation and erosion, accelerates moisture loss, and negatively affects biological processes responsible for maintaining soil fertility. The increasing population of *Saiga* intensifies competition with livestock for forage resources, especially under conditions of limited water availability typical of arid environments [4]. An additional contributing factor is land-use transformation associated with agricultural expansion, infrastructure development, and the reduction of natural migration routes, which leads to uneven spatial distribution of grazing pressure and concentration of animals in ecologically vulnerable territories. From an ecological perspective, high densities of large herbivores may lead to reduced plant biomass, disruption of soil structure, and acceleration of degradation processes [12]. At the same time, moderate grazing pressure can perform important ecological functions by stimulating nutrient cycling, supporting vegetation heterogeneity, and maintaining dynamic ecological equilibrium within steppe ecosystems [13].

Therefore, the ecological impact of *Saiga* populations is nonlinear and depends on the balance between population density, carrying capacity of pastures, and environmental conditions. Biological processes in soils, including rhizosphere microbiome activity and enzymatic processes, play a crucial role in maintaining soil fertility and ecosystem stability [14, 15].

The rhizosphere microbiome is a fundamental component of soil systems, ensuring nutrient cycling and plant–soil interactions [16, 17]. A reduction in vegetation cover caused by intensive grazing can disrupt these processes and lead to a decline in soil biological activity, deterioration of soil structure, and decreased ecosystem resilience.

At the same time, the *Saiga* performs important ecological functions, including the redistribution of organic matter, seed dispersal, and maintenance of biological diversity in steppe ecosystems. This highlights the necessity of developing compromise solutions aimed at ensuring the sustainable coexistence of wildlife and agriculture. Thus, a complex ecological and socio-economic conflict has emerged in Kazakhstan, requiring the development of scientifically grounded approaches to monitoring and managing *Saiga* populations while taking into account the condition of agroecosystems, pasture productivity, soil fertility, and ecosystem sustainability. Despite the substantial body of research on the role of large herbivores in steppe ecosystems, several unresolved scientific issues remain, particularly in the context of Kazakhstan. Recent studies in soil ecology and microbiology confirm the critical importance of biodiversity and the microbiome in maintaining ecosystem stability [14, 15, 18]. However, most existing studies are generalized and do not adequately consider the specific environmental conditions of arid steppe regions in Central Asia, nor the integrated interactions among *Saiga* populations, pasture vegetation, soil properties, microbiological activity, and agricultural productivity.

In particular, there is a lack of comprehensive studies integrating the impact of *Saiga* populations on key agroecosystem components - vegetation cover, soil properties, microbial activity, and pasture productivity - within a unified conceptual framework. Furthermore, quantitative criteria for determining the optimal population density of large herbivores that ensures a balance between their ecological function and agricultural sustainability remain insufficiently developed. Specifically, scientifically justified threshold values for *Saiga* density that distinguish between stable and degraded ecosystem states are lacking. Therefore, a clear research gap exists in the absence of an integrated approach to assessing the impact of *Saiga* on agroecosystems, considering the interactions between biotic and abiotic components, as well as in the limited development of mechanisms for determining optimal ecological balance. In this context, the aim of this study is to develop a scientifically grounded approach for assessing the impact of the *Saiga* population on agroecosystems in the steppe zone of Kazakhstan and to determine the optimal population range that ensures a balance between biodiversity conservation and sustainable agricultural production.

To achieve this aim, the following objectives were formulated: to conduct a comprehensive assessment of pasture conditions under different *Saiga* population densities; to evaluate the impact of grazing pressure on agrochemical soil properties and biological activity; to investigate changes in the rhizosphere microbiome under varying grazing intensities; to establish quantitative relationships between *Saiga* population density and agroecosystem productivity; to develop an integrated model of interaction «*Saiga* – pasture – soil – microbiome – productivity»; to determine threshold population densities at which the ecosystem shifts to a degraded state. The proposed solution to the identified problem is based on the implementation of an integrated ecosystem approach that considers the interactions between biotic and abiotic components and is grounded in the principles of adaptive management. This approach involves a transition from traditional wildlife population regulation to systemic agroecosystem management, in which the *Saiga* population is considered a key component of the ecological system. Within this framework, it is proposed to apply quantitatively defined population thresholds, implement spatial zoning and ecological migration corridors, utilize remote sensing and geoinformation technologies for monitoring pasture conditions, and integrate ecological and economic management mechanisms, including compensation and incentive-based approaches. Thus, the solution to the problem lies not only in regulating the *Saiga* population, but also in the development of a scientifically grounded management system that ensures the sustainable coexistence of wildlife and agriculture in the steppe ecosystems of Kazakhstan.

The findings of this study provide a scientific basis for developing evidence-based policies aimed at balancing biodiversity conservation and agricultural sustainability in Kazakhstan. The rapid growth of the *Saiga* population requires a transition from reactive measures to a proactive, adaptive management framework grounded in quantitative ecological thresholds and spatial planning. First, policy measures should focus on establishing science-based population thresholds. The results suggest that maintaining *Saiga* density below the empirically defined risk level of approximately 20 individuals/km² may help preserve ecosystem functions and minimize the risk of pasture degradation. Regulatory mechanisms, including adaptive quota systems and region-specific population control, should be implemented based on continuous monitoring data. Second, spatial land-use planning must become a central component of wildlife management. The designation of ecological migration corridors and buffer zones will reduce the overlap between *Saiga* habitats and agricultural lands, thereby minimizing economic losses. Integrating wildlife movement patterns into regional land-use policies is essential for reducing human - wildlife conflict. Third, sustainable pasture management practices should be promoted. This includes the implementation of rotational grazing

systems, restoration of degraded lands, and regulation of grazing pressure based on real-time vegetation indices. These measures will enhance the resilience of agroecosystems under increasing environmental stress. Fourth, economic instruments are required to ensure social acceptance of conservation policies. The introduction of compensation schemes and insurance mechanisms for farmers affected by wildlife damage can mitigate economic risks and foster cooperation between stakeholders. Fifth, the integration of digital technologies is crucial for effective decision-making. The use of GIS, remote sensing (NDVI/EVI), and artificial intelligence enables real-time monitoring of ecosystem conditions and supports predictive modeling of *Saiga* population dynamics. Figure 1 presents the proposed adaptive management framework. It combines ecological monitoring, spatial planning, and economic measures to support *Saiga* conservation and sustainable agriculture. The ecological relationships underlying this framework are illustrated in Figure 2. The model links *Saiga* density with vegetation, soil condition, microbial activity, and pasture productivity. These links represent hypothesized pathways rather than proven causal relationships.

Overall, the proposed policy framework emphasizes an integrated approach combining ecological, economic, and technological tools. Such a strategy enables the transition from conflict-driven management to sustainable coexistence between wildlife and agricultural systems.

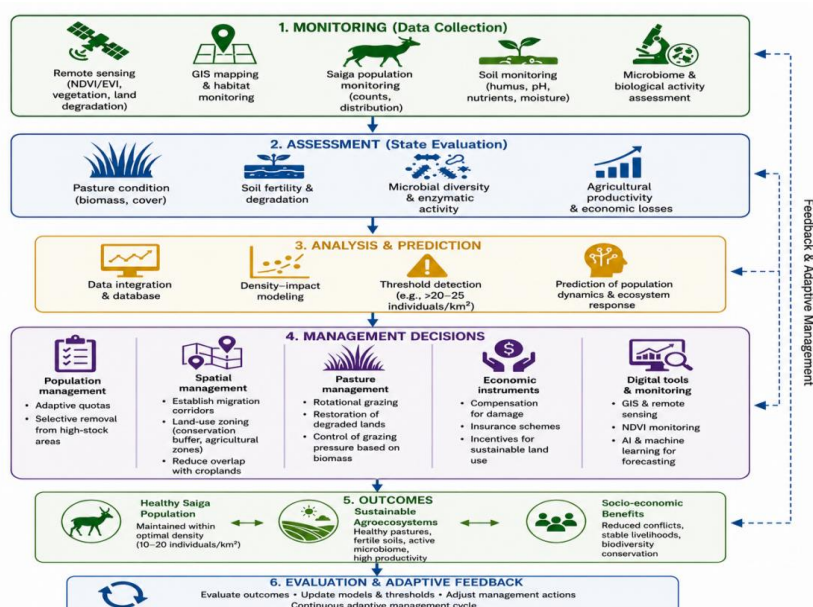


Fig. 1: Conceptual framework for adaptive management of the *Saiga* population aimed at balancing ecosystem sustainability and agricultural productivity

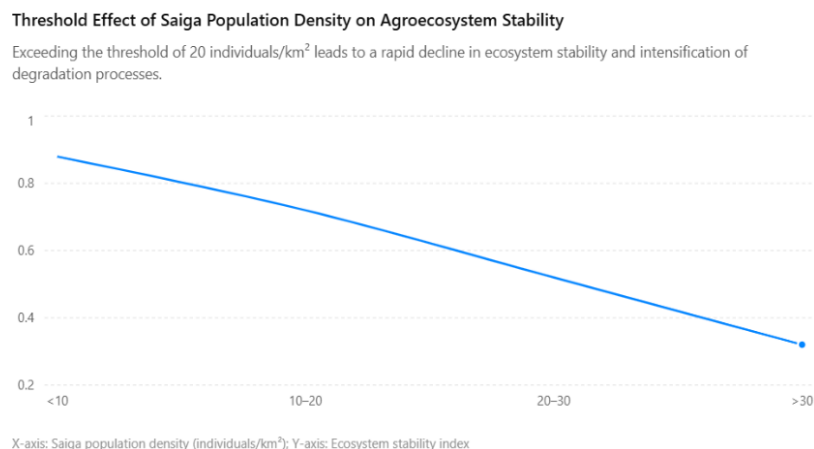


Fig. 2: Conceptual model of cascading agroecosystem degradation under increasing *Saiga* population density

Materials and Methods

The study was conducted during the 2021–2023 growing seasons in the steppe zone of the West Kazakhstan Region, Republic of Kazakhstan, within the principal migration corridor of the Ural *Saiga* (*Saiga tatarica*) population. The study area is characterized by an arid continental climate with low and highly variable annual precipitation, elevated summer temperatures, and pronounced interannual climatic variability, all of which influence vegetation productivity, soil processes, and pasture ecosystem dynamics. Five representative study sites were selected on the basis of long-term monitoring data describing Saiga migration routes and grazing intensity. The selected sites included Zhanibek District (S1), Bokeyorda District (S2), Kaztalov District (S3), Akzhaik District (S4), and Syrym District (S5). Site selection was based on four principal criteria:

- (i) Long-term occurrence of *Saiga* herds
- (ii) Representation of the dominant regional soil types, namely dark chestnut and light chestnut soils
- (iii) Contrasting gradients of grazing intensity
- (iv) Comparable climatic conditions and land-use patterns among the study locations

Within each study site, three grazing intensity categories were established according to the average density of *Saiga* individuals. Areas with fewer than 10 individuals km⁻² were classified as having low grazing intensity, while densities of 10–20 individuals km⁻² represented moderate grazing intensity. Densities within the 20–25 individuals km⁻² range were interpreted as an empirical risk-indicator zone, whereas densities above 25 individuals km⁻² were considered indicative of high grazing pressure.

Ten permanent sampling plots measuring 50 × 50 m were established within each grazing category, resulting in a total of 150 sampling plots distributed across the five study sites. Soil sampling was conducted simultaneously with vegetation surveys during the peak growing season. Composite soil samples were collected from the 0–20 cm soil layer by combining three subsamples obtained within a 5 m radius around the center of each sampling plot. The collected soil samples were air-dried, homogenized, and analyzed for their physicochemical and biological characteristics using internationally recognized laboratory protocols. The measured soil properties included soil organic matter content, soil pH, total nitrogen concentration, available phosphorus content, dehydrogenase activity, urease activity, and basal soil respiration, providing a comprehensive assessment of soil fertility and microbial functioning under different grazing intensities.

Vegetation assessments were carried out concurrently with soil sampling. Within each permanent plot, five randomly positioned quadrats of 1 m² were surveyed to determine plant species composition, percentage vegetation cover, aboveground biomass, and dominant plant species. Aboveground biomass was estimated by harvesting all plant material within each quadrat, followed by drying at constant temperature until constant weight was achieved. Rhizosphere microbial communities were investigated using both culture-dependent and molecular approaches. Culturable microorganisms were quantified as colony-forming units per gram of dry soil, whereas bacterial community composition was characterized through high-throughput sequencing of 16S rRNA gene fragments. Sequence quality control, taxonomic assignment, and diversity analyses were performed using the QIIME2 bioinformatics pipeline. Microbial diversity was evaluated using the Shannon diversity index, Simpson diversity index, and Chao1 richness estimator. Spatial analyses were conducted using Geographic Information Systems (GIS) integrated with Sentinel-2 multispectral satellite imagery at a spatial resolution of 10 m. Vegetation dynamics were quantified using the Normalized Difference Vegetation Index (NDVI), which served as an indicator of vegetation productivity, spatial degradation patterns, and temporal changes in aboveground biomass throughout the study period. Overlay analysis was subsequently employed to integrate satellite-derived vegetation indices with Saiga distribution data and land-use information, enabling the identification of spatial relationships between grazing intensity, vegetation condition, and ecosystem responses.

Scenario modelling framework. Future ecosystem scenarios were generated using an evidence-based, threshold-oriented ecological assessment framework integrating field observations collected during 2021–2023, remote sensing indicators, and ecological threshold values identified from the observed data. The objective of the framework was to compare plausible ecosystem trajectories under different levels of Saiga population density and grazing pressure. The scenarios are intended as a decision-support framework rather than deterministic long-term population forecasts.

The modelling framework was based on five key ecological indicators identified as the principal drivers of ecosystem stability: *Saiga* population density (individuals km⁻²); normalized difference vegetation index (NDVI); aboveground forage biomass (c ha⁻¹); soil humus content (%); soil microbial activity (microbial biomass and enzymatic activity).

Each indicator was standardized to a dimensionless scale ranging from 0 to 1 using min–max normalization:

$$Xi = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (1)$$

Where: X_i is the normalized indicator, X is the observed value, and $X_{\min}$ and $X_{\max}$ represent the minimum and maximum values recorded during the study.

To evaluate overall ecosystem functioning, an integrated ecosystem stability index (I_{ES}) was calculated as

$$I_{ES} = \frac{NDVI + Biomass + Humus + Microbial\ Activity}{4} \quad (2)$$

Where: Each component contributed equally to the composite indicator.

Population density was evaluated across a range from 10 to more than 35 individuals km⁻² while maintaining environmental conditions within the range observed during the 2021–2023 monitoring period. At each density level, vegetation productivity, soil quality, microbial activity, and forage production were assessed using empirical relationships derived from field observations and correlation analysis. Rather than applying formal threshold detection or breakpoint analysis, an empirical risk-indicator assessment was conducted using the 20–25 individuals km⁻² range as a reference for increasing ecological risk. This range was identified based on the observed responses of vegetation and other ecosystem components to increasing population density. Densities within and above this range were associated with the onset of more pronounced vegetation degradation, while densities exceeding 30 individuals km⁻² were associated with stronger reductions in aboveground biomass, soil fertility, microbial activity, and pasture productivity. Accordingly, the 20–25 individuals km⁻² range was used as an empirical risk-indicator range for scenario classification and management interpretation, rather than as a statistically estimated ecological threshold. These indicators should therefore be interpreted as context-specific empirical values reflecting the conditions observed during the 2021–2023 monitoring period.

Three management scenarios were subsequently defined:

Scenario I: Sustainable Coexistence, representing relatively stable ecosystem functioning under moderate grazing pressure

Scenario II: Transitional Pressure, representing increasing ecological stress and elevated degradation risk

Scenario III: Ecological Degradation, representing sustained high grazing pressure and a high-risk ecosystem trajectory

The scenarios are used to compare management alternatives and should not be interpreted as deterministic forecasts.

Statistical analyses were performed using IBM SPSS Statistics version 26.0 and the R statistical environment (vegan package). Prior to hypothesis testing, data normality was assessed using the Shapiro–Wilk test. Differences among grazing intensity categories were evaluated by one-way analysis of variance (ANOVA), followed by Tukey's Honestly Significant Difference (HSD) post hoc test. Relationships among soil, vegetation, and microbial variables were examined using Pearson correlation analysis and multiple linear regression models. Multivariate variation in environmental and biological characteristics was explored through Principal Component Analysis (PCA), whereas differences in microbial community composition among grazing treatments were assessed using Permutational Multivariate Analysis of Variance (PERMANOVA). In addition, Generalized Linear Models (GLMs) were applied to quantify the influence of grazing intensity and environmental variables on vegetation productivity, soil properties, and microbial diversity. Collectively, these analytical approaches enabled a comprehensive evaluation of the ecological impacts of *Saiga* grazing across multiple spatial and temporal scales. Statistical significance was set at $p \leq 0.05$.

Results

The analysis revealed a strong and consistent relationship between the density of the *Saiga* population and the condition of pasture ecosystems. Increasing *Saiga* density was associated with a progressive decline in vegetation cover and aboveground biomass. The quantitative characteristics of this relationship are presented in Table 1.

Table 1: Effect of *Saiga* density on pasture condition

No	<i>Saiga</i> density (ind./km ²)	Vegetation cover (%)	Biomass (centners/ha)	Degree of degradation
1	5–10	75–85	18–22	Low
2	10–20	60–70	14–18	Moderate
3	20–30	45–55	10–14	High
4	>30	30–40	6–10	Critical

The results demonstrate a clear threshold effect: when *Saiga* density exceeds 20 individuals/km², pasture degradation accelerates sharply. This indicates that grazing pressure becomes a limiting factor for vegetation stability beyond this threshold. The analysis revealed a strong and consistent relationship between the density of the *Saiga* population and the condition of pasture ecosystems. Increasing *Saiga* density was associated with a progressive decline in vegetation cover and aboveground biomass.

Vegetation dynamics during the 2021–2023 monitoring period. The analysis of vegetation cover and productivity revealed clear interannual and grazing-related variation (Table 2).

Table 2: Temporal dynamics of vegetation indicators during the 2021–2023 monitoring period

No	Year	Vegetation cover (%)	NDVI	Aboveground biomass change	Vegetation response
1	2021	81.3±4.2	0.64	0% (baseline)	Reference year
2	2022	72.6±4.8	0.58	—	Decline in vegetation condition
3	2023	68.9±5.1	0.60	≈ -24% vs. 2022	Partial NDVI recovery; biomass remained reduced

Remote sensing analysis of Sentinel-2 imagery was combined with field measurements of vegetation cover and aboveground biomass to assess changes in pasture condition during 2021–2023. Mean NDVI declined from 0.64 in 2021 to 0.58 in 2022, followed by a partial recovery to 0.60 in 2023 (Figure 3).

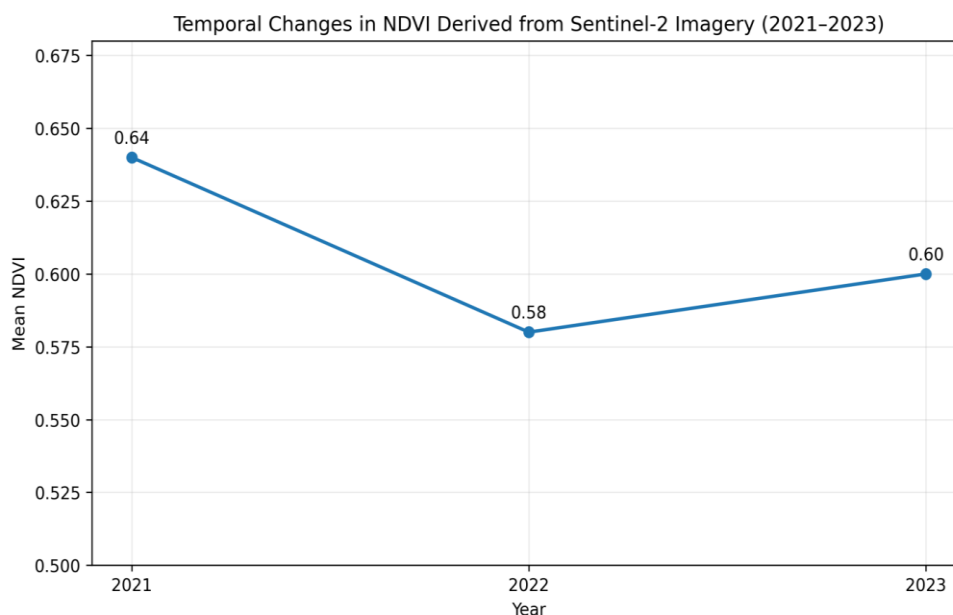


Fig. 3: Temporal changes in NDVI derived from sentinel-2 imagery during 2021–2023

A similar pattern was observed in field measurements. In intensively grazed areas, vegetation cover decreased from 81.3±4.2% in 2021 to 72.6±4.8% in 2022 and 68.9±5.1% in 2023, accompanied by an approximately 24% reduction in aboveground biomass. Areas with lower grazing pressure maintained comparatively more stable vegetation conditions (Figure 4).

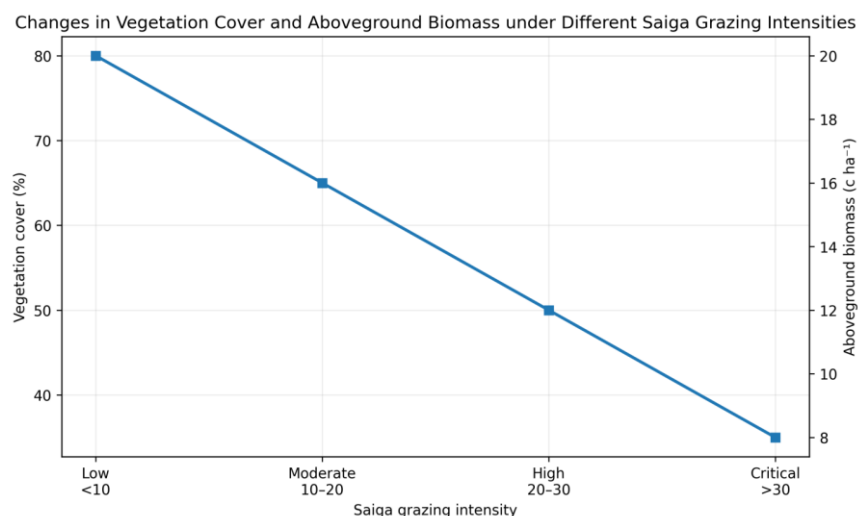


Fig. 4: Changes in Vegetation Cover and Aboveground Biomass under Different Saiga Grazing Intensities

The correspondence between NDVI and field observations indicates a decline in vegetation condition under higher grazing pressure. The partial recovery of NDVI in 2023 suggests that interannual climatic variability also influenced vegetation productivity. However, areas repeatedly exposed to high grazing pressure remained in poorer condition than minimally grazed reference areas. Given the observational design, these temporal changes cannot be attributed exclusively to *Saiga* grazing, as climatic and other environmental factors may also have contributed to the observed variation.

Changes in plant community composition. Grazing intensity significantly influenced floristic composition. Intensively grazed areas exhibited a decline in perennial bunchgrasses, particularly *Stipa capillata* and *Festuca valesiaca*, which are highly sensitive to continuous grazing pressure. At the same time, an increase in grazing-tolerant and disturbance-adapted species was observed, including *Artemisia lerchiana*, *Poa bulbosa*, and several annual forbs. This shift indicates a transition from relatively stable steppe communities toward more disturbance-tolerant vegetation states. These observations are interpreted as an association with grazing pressure rather than direct experimental evidence of causality.

To assess the impact of grazing pressure on soil quality, key agrochemical indicators were analyzed across different load levels. The results are summarized in Table 3.

Table 3: Agrochemical Soil Indicators under Different Grazing Pressure

№	Indicator	Low pressure	Moderate pressure	High pressure
1	Humus (%)	3.2–3.8	2.6–3.1	2.1–2.5
2	pH	7.3–7.6	7.6–7.9	7.9–8.2
3	Nitrogen (mg/kg)	50–60	40–50	30–40
4	Phosphorus (mg/kg)	15–20	10–15	8–12

An increase in grazing intensity leads to a systematic deterioration of soil properties. Humus content decreases by approximately 20–30% under high pressure, while soil alkalinity increases. These changes indicate a decline in soil fertility and resilience. The influence of vegetation degradation on soil biological processes was assessed through microbiological and enzymatic indicators. The results are presented in Table 4.

Table 4: Soil Biological Activity

№	Indicator	Low pressure	High pressure
1	Microbial biomass (mg/kg)	350–420	180–250
2	Dehydrogenase (mg TPF/kg)	4.5–5.6	2.0–3.0
3	Urease (mg NH ₃ /kg)	22–30	10–18
4	Respiration (mg CO ₂ /kg/day)	30–40	15–22

Soil biological activity was lower under high grazing pressure, with approximately twofold differences in some microbial indicators between low- and high-pressure sites. These results are consistent with reduced vegetation inputs and altered soil conditions under intensive grazing; however, because the study is observational, they should be interpreted as statistically associated changes rather than proof that vegetation degradation directly suppresses microbial processes.

Soil physicochemical and biological responses. Soil properties exhibited significant variation along the grazing gradient. In high-density grazing zones, reductions in soil organic matter and nutrient availability were observed, accompanied by decreased enzymatic activity. Dehydrogenase and urease activities declined in heavily grazed sites, indicating lower microbial metabolic activity and altered nutrient cycling. Soil respiration rates also decreased in degraded zones, reflecting lower biological activity. Microbial community dynamics. Microbial diversity indices (Shannon, Simpson, Chao1) showed a consistent decline with increasing grazing intensity. High grazing pressure was associated with reduced microbial richness and altered community structure. Sequencing-based analysis indicated that microbial communities in heavily grazed areas were less diverse and relatively enriched in stress-tolerant taxa. Integrated relationships among ecosystem components were examined. Correlation analysis revealed significant associations between Saiga population density and ecosystem variables. Grazing intensity was negatively associated with vegetation biomass, while vegetation cover was positively associated with soil organic matter. Microbial activity also showed positive associations with vegetation productivity. Principal Component Analysis (PCA) indicated separation among low, moderate, and high grazing-intensity zones. These results support an ecosystem-level conceptual framework but do not establish the direction or causality of the observed relationships.

The effect of Saiga population density on pasture productivity was evaluated, with results summarized in Table 5.

Table 5: Productivity of Forage Lands

No	Load level	Yield (centners/ha)	Losses (%)
1	Low	20–25	0–10
2	Moderate	15–20	15–25
3	High	10–14	30–45
4	Critical	6–10	50–60

Pasture productivity declines significantly with increasing grazing pressure, with yield losses reaching 50–60% under critical conditions, highlighting the economic implications of overpopulation. The integrated analysis allowed the development of a conceptual model describing the cascade effect of Saiga impact (Figure 5).

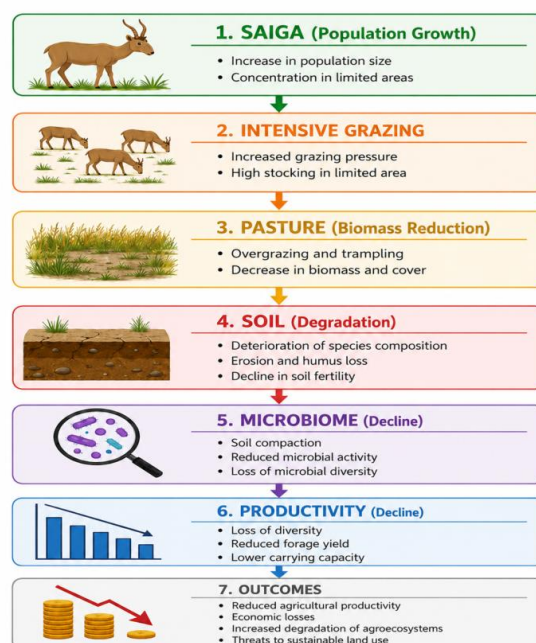


Fig. 5: Conceptual model of the impact of the Saiga population on agroecosystems

The results indicate that the impact follows a cascade mechanism: grazing pressure leads to vegetation degradation, which in turn causes deterioration of soil properties and suppression of the microbiome, ultimately resulting in reduced productivity.

Correlation analysis confirmed strong relationships: biomass–humus: $r = 0.72$; microbiome–enzymes: $r = 0.81$; grazing pressure yield: $r = -0.76$. An integrated assessment of ecosystem stability was conducted to determine the optimal balance between *Saiga* population density and agroecosystem condition. The results are presented in Table 6.

The optimal ecological balance is achieved at 10–20 individuals/km², where ecosystem functions remain stable without signs of degradation. When the population density exceeded approximately 20 individuals km⁻², lower vegetation condition and greater ecosystem stress were observed.

To quantify ecosystem resilience, an integral index (I_{balance}) was calculated. The results are shown in Table 7.

A sharp decline in ecosystem stability occurs when *Saiga* density exceeds 20 individuals/km², confirming the threshold nature of degradation. The results indicate that exceeding a population density threshold of 20 individuals/km² leads to a rapid decline in ecosystem stability. To evaluate the dual role of the *Saiga* population, a comparative analysis of its positive and negative ecological effects was conducted. The results are presented in Table 8.

The results demonstrate that while *Saiga* contributes positively to ecosystem functioning under moderate densities, negative effects dominate once the ecological threshold is exceeded, leading to degradation processes. Based on the analysis, critical threshold values for population regulation were identified. These are summarized in Table 9.

Table 6: *Saiga* population balance and ecosystem condition

№	Density (ind./km ²)	Ecological state	Pasture condition	Soil fertility	Yield
1	<10	Stable	Good	High	High
2	10–20	Optimal	Stable	Moderate	Stable
3	20–30	Stressed	Degrading	Reduced	Decreased
4	>30	Critical	Destroyed	Low	Low

Table 7: Ecosystem stability index

№	Load level	Density	Index (0–1)	Interpretation
1	Low	<10	0.80–0.90	Stable
2	Optimal	10–20	0.65–0.80	Balanced
3	High	20–30	0.45–0.65	Degradation risk
4	Critical	>30	<0.45	System collapse

Table 8: Ecological balance of *Saiga* impact

№	Impact factor	Positive effect	Negative effect
1	Vegetation	Regeneration, seed dispersal	Biomass reduction, trampling
2	Soil	Redistribution of organic matter	Erosion, humus depletion
3	Microbiome	Stimulation of activity	Suppression under high pressure
4	Pastures	Natural regulation	Degradation under overgrazing
5	Agriculture	Minimal impact	Yield reduction

Table 9: Threshold levels for population regulation

№	Indicator	Threshold value	Consequence
1	<i>Saiga</i> density	20 ind./km ²	Onset of degradation
2	Plant biomass	<12 c/ha	Risk of pasture loss
3	Humus content	<2.5%	Decline in soil fertility
4	Microbial activity	<250 mg/kg	Suppression of biological processes
5	Yield	<12 c/ha	Economic losses

These indicators can be used as practical thresholds for adaptive management, allowing early detection of ecosystem degradation and timely intervention. To assess possible management strategies, ecosystem trajectories were compared using the threshold-based framework described in the Materials and Methods section. The analysis incorporated observed relationships among Saiga density, vegetation productivity, soil quality, microbial activity, and pasture yield. Three management scenarios were generated according to increasing population pressure and corresponding ecological responses (Table 10).

The simulation results indicate that maintaining Saiga density within the range of 10–20 individuals km⁻² preserves ecosystem stability and forage productivity. Increasing population density beyond approximately 20 individuals km⁻² results in progressive declines in vegetation biomass and soil quality, while densities exceeding 35 individuals km⁻² are associated with ecosystem collapse characterized by severe pasture degradation and substantial yield losses. The economic consequences of increasing grazing pressure were evaluated and are presented in Table 11.

Economic losses increase significantly with grazing intensity, highlighting the direct link between ecological degradation and agricultural productivity decline.

Model validation and uncertainty. The ecological thresholds used in the scenario framework were compared with field observations collected during the 2021–2023 monitoring period. The predicted direction of change in vegetation condition, soil fertility, microbial activity and pasture productivity was consistent with the observed ecological gradient. This comparison supports the use of the framework for identifying relative ecological risk zones and comparing alternative management trajectories; it does not constitute independent predictive validation or demonstrate causal mechanisms. The model should therefore be regarded as a decision-support framework requiring further validation with longer-term and spatially explicit datasets.

Model uncertainty and limitations. The proposed scenarios represent ecological projections based on observed threshold responses rather than deterministic predictions. Several sources of uncertainty should be acknowledged, including interannual climatic variability, fluctuations in migration routes, spatial heterogeneity of vegetation, limitations of satellite-derived NDVI, and the relatively short monitoring period. Furthermore, the model assumes stable land-use practices and does not explicitly account for extreme droughts, disease outbreaks, or anthropogenic disturbances. Therefore, future scenarios should be interpreted as plausible ecological trajectories and updated as additional long-term monitoring data become available.

A set of key indicators for monitoring ecosystem stability was identified (Table 12).

Table 10: Scenario analysis of Saiga population management

No	Scenario	Saiga density (ind./km ²)	Ecosystem state	Yield (%)	Degradation risk
1	Optimal	10–20	Stable	85–100	Low
2	Controlled growth	20–25	Stressed	70–85	Medium
3	Uncontrolled growth	25–35	Degrading	50–70	High
4	Overpopulation	>35	Collapsed	<50	Critical

Table 11: Economic loss assessment

No	Scenario	Saiga density (ind./km ²)	Ecosystem state	Degradation risk
1	Sustainable coexistence	10–20	Relatively stable	Low
2	Transitional pressure	20–30	Stressed	Moderate–High
3	Ecological degradation	>30	Degrading/high-risk	High

Table 12: Monitoring indicators of ecosystem balance

No	Indicator	Normal	Risk threshold	Critical level
1	Saiga density (ind./km ²)	10–20	20–25	>25
2	Biomass (c/ha)	>18	12–18	<12
3	Humus (%)	>3.0	2.5–3.0	<2.5
4	NDVI	>0.6	0.4–0.6	<0.4
5	Microbial activity	High	Moderate	Low

These indicators provide a quantitative framework for real-time monitoring and can serve as early warning signals of ecosystem degradation.

The effectiveness of different management strategies was evaluated (Table 13).

Table 13: Effectiveness of Management Measures

No	Measure	Load reduction (%)	Pasture recovery	Economic effect
1	Quotas	20–30	Moderate	Moderate
2	Migration corridors	30–40	High	High
3	Pasture rotation	25–35	High	Moderate
4	Compensation	-	-	High (social effect)
5	GIS-based monitoring	15–25	Indirect	High

Spatial management (migration corridors) and sustainable pasture practices demonstrate the highest ecological effectiveness, while economic instruments enhance stakeholder acceptance. The findings demonstrate that the impact of the Saiga population on agroecosystems is dual and threshold-dependent: at densities of 10–20 individuals/km², the ecosystem remains stable; beyond the threshold, a cascade degradation process is initiated: pasture → soil → microbiome → productivity; at critical levels (>30 individuals/km²), ecosystem collapse occurs.

Thus, the key factor for sustainable land use is maintaining an ecologically justified population balance of *Saiga*. The visualization of the spatial distribution and migration dynamics of the *Saiga* population represents an important component in the analysis of steppe ecosystem sustainability in Kazakhstan. In the context of increasing population size and growing anthropogenic pressure on natural resources, the study of spatio-temporal movement patterns has become particularly relevant.

The presented map is based on the integration of scientific data, field observations, and modern geoinformation approaches. It reflects key aspects of *Saiga* spatial organization, including seasonal migration routes, population density distribution, and major habitat zones. The primary purpose of this visualization is to identify areas of potential ecological risk associated with animal concentration and grazing pressure. The map allows for the assessment of interactions between *Saiga* population dynamics and agroecosystem conditions and serves as a tool for supporting evidence-based decision-making in sustainable land management. Thus, the map contributes to a deeper understanding of the interactions between wildlife and agricultural landscapes and provides a foundation for developing adaptive ecosystem management strategies in the steppe regions of Kazakhstan.

The presented map illustrates the spatial distribution, seasonal migration routes, and population density of the Saiga population across the territory of Kazakhstan. The map integrates multiple ecological and geospatial layers, providing a comprehensive overview of the species' movement patterns and habitat use. The visualization clearly demonstrates the seasonal dynamics of *Saiga* migration. During spring (March–May), *Saiga* populations move toward calving areas and spring pastures. In summer (June–August), the animals disperse across northern and central steppe regions characterized by higher vegetation productivity. In autumn (September–November), reverse migration occurs, while in winter (December–February), *Saiga* shift toward southern and more sheltered areas with milder climatic conditions. These migration routes are represented by directional arrows, reflecting the cyclical and adaptive nature of *Saiga* movement.

In addition, the map presents the spatial variation in population density, expressed in individuals per square kilometer. Areas of low density are shown in lighter tones, whereas zones of higher concentration are highlighted in yellow, orange, and red gradients. The highest population densities are observed in western and central regions of Kazakhstan, including Atyrau, Aktobe, and Kyzylorda areas, indicating zones of potential ecological pressure (Figure 6).

Furthermore, the visualization highlights major migration corridors of both regional and international significance, which are essential for maintaining ecological connectivity, genetic exchange, and long-term population resilience.

The map also identifies key seasonal habitats, including calving areas, as well as spring, summer, autumn, and winter pastures. These zones reflect the spatial organization of the *Saiga* life cycle and underline the importance of habitat heterogeneity for maintaining population stability. The main migration of Saigas occurs from Western Kazakhstan (Figure 7).

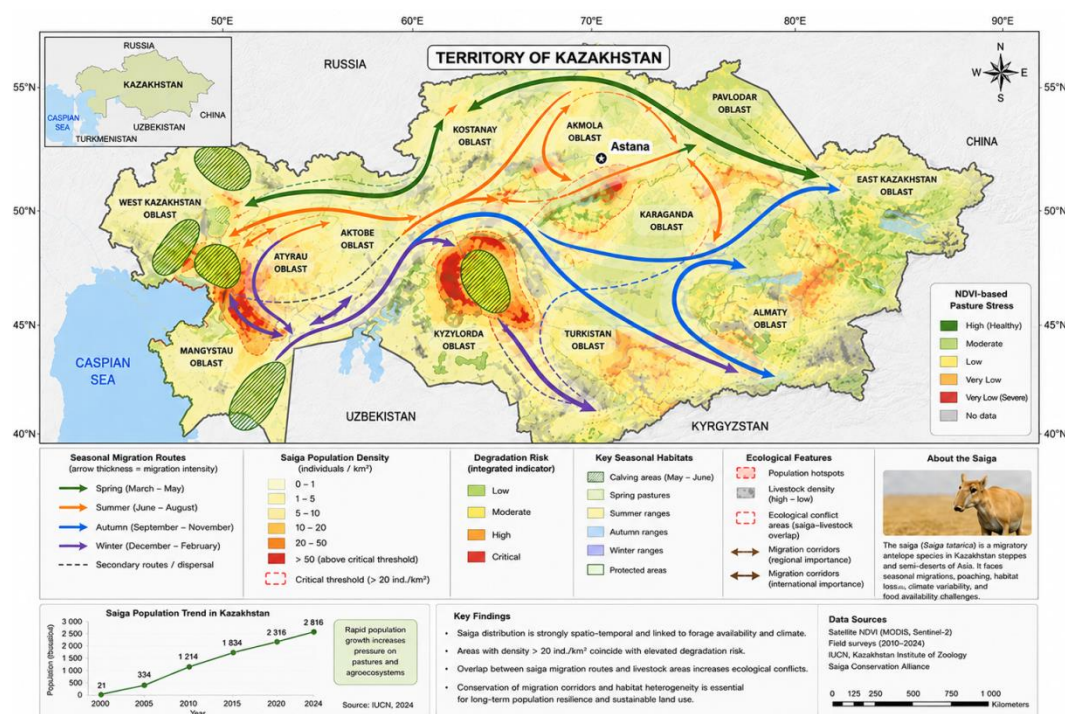


Fig. 6: Spatial distribution, seasonal migration routes, population density and degradation risk of the *Saiga* population in Kazakhstan



Fig. 7: Spatial distribution of *Saiga* migration routes and ecological landscape zones in West Kazakhstan Region

From a scientific perspective, the map demonstrates that *Saiga* distribution exhibits a pronounced spatio-temporal structure, closely linked to climatic conditions, forage availability, and seasonal environmental variability. Notably, areas of high population density frequently overlap with key pasture zones, which may lead to localized overgrazing and increased pressure on agroecosystems under conditions of population growth. Overall, this map serves as an important analytical tool

for understanding *Saiga* population dynamics and provides a foundation for developing adaptive management strategies aimed at balancing biodiversity conservation and sustainable land use in Kazakhstan.

Empirical risk-indicator assessment of ecosystem degradation. The results indicate a nonlinear relationship between *Saiga* population density and ecosystem condition. An empirically defined risk-indicator range of approximately 20–25 individuals km⁻² was associated with the onset of more pronounced changes in vegetation and soil biological properties. At densities below this range, ecosystem indicators generally remained comparatively stable, whereas increasing densities within and above the risk-indicator range were associated with greater reductions in vegetation productivity, soil fertility, and microbial activity. Densities exceeding 30 individuals km⁻² were associated with more pronounced deterioration across multiple ecosystem components. These findings support the use of the 20–25 individuals km⁻² range as an empirical risk indicator for management and scenario classification rather than as a statistically estimated ecological threshold.

Discussion

The results indicate that the current increase in the *Saiga* population in the steppe regions of Kazakhstan is associated with complex and multidimensional changes in agroecosystem condition. Previous studies have primarily examined *Saiga* population dynamics, reproductive characteristics, forage availability, and pasture use, providing an important ecological basis for understanding the current population recovery [13, 19–22]. More recent research has also demonstrated that changes in *Saiga* abundance and forage vegetation can influence natural pastures and create management challenges in the steppe zone of Western Kazakhstan [6, 7, 23]. The present study extends these earlier observations by examining *Saiga* population density together with vegetation, soil, microbiological, and productivity indicators within an integrated agroecosystem framework.

The observed relationships were nonlinear and depended on population density, spatial distribution of migration routes, grazing pressure, climatic variability, and the resistance of natural landscapes to disturbance. At moderate population densities (10–20 individuals/km²), *Saiga* grazing was associated with vegetation heterogeneity, organic-matter redistribution, and maintenance of biological activity in soils. This observation is consistent with the broader ecological concept that moderate herbivore disturbance can contribute to spatial heterogeneity and nutrient redistribution, whereas increasing grazing pressure may exceed the regenerative capacity of vegetation. Earlier studies in Kazakhstan emphasized the importance of forage vegetation for *Saiga* distribution and pasture use [23] demonstrated that increasing *Saiga* abundance can have measurable effects on pasture ecosystems. The present findings add a belowground dimension to these observations by showing that changes in vegetation condition were accompanied by changes in soil biological functioning.

At higher population densities (>20 individuals/km²), areas with greater *Saiga* concentration were characterized by lower vegetation cover, reduced aboveground biomass, changes in soil properties, and lower microbial activity. This pattern is broadly consistent with previous research demonstrating that increasing grazing intensity can modify vegetation structure and ecosystem functioning. The results are also compatible with the findings of [23], who emphasized the importance of forage vegetation dynamics for *Saiga* use of natural pastures in Western Kazakhstan. However, the present study goes beyond vegetation-based assessment by integrating plant biomass with soil fertility, microbial activity, and pasture productivity. Thus, the observed response should be interpreted as a coordinated aboveground–belowground ecosystem response rather than as an isolated decline in forage resources.

The density-dependent response observed in the present study is also relevant to the earlier ecological literature on *Saiga* management. [20] emphasized that *Saiga* population dynamics and habitat conditions are closely interconnected, while more recent studies have highlighted the consequences of increasing *Saiga* abundance for pasture systems and human *Saiga* interactions [6, 7]. The present results suggest that the ecological consequences of population recovery may become more pronounced when local concentrations increase, particularly in areas where migration routes and grazing pressure are spatially concentrated. This finding supports the need to distinguish between total regional population size and local population density when evaluating ecosystem pressure.

An important result of the present study is the identification of approximately 20 individuals/km² as an empirical risk level associated with the onset of more pronounced vegetation and ecosystem degradation. Previous studies have demonstrated density-dependent relationships between herbivore pressure, forage availability, and pasture condition, but the present study integrates multiple ecological indicators to identify a density range useful for scenario classification and management interpretation [6, 23]. Importantly, the value of approximately 20 individuals/km² was derived from the observed ecological

responses presented in the relevant tables and was not obtained through formal statistical breakpoint analysis or an independently calibrated mechanistic population model. Therefore, this value should be interpreted as an empirical management indicator or empirical risk level rather than as a statistically estimated or universal ecological threshold. Its applicability should be independently validated under different climatic conditions, landscape types, and longer monitoring periods.

Particular importance should be given to the observed changes in soil microbiological processes. Lower dehydrogenase and urease activity, as well as reduced soil respiration, were associated with increasing grazing pressure. Previous research has established that soil microbial communities and enzyme activities are sensitive indicators of changes in soil functioning and environmental disturbance [14, 15, 24, 25]. Studies of grazing systems have further demonstrated that grazing intensity can alter soil microbial communities and rhizosphere processes [17, 18]. The present results are consistent with these observations, but provide additional evidence for the simultaneous response of microbial activity, vegetation biomass, soil properties, and pasture productivity under increasing *Saiga* pressure.

The observed reduction in microbial activity is particularly important because soil microorganisms contribute to nutrient cycling, organic-matter transformation, and maintenance of soil functioning [14, 15]. Soil enzyme activities can provide sensitive indicators of changes in biochemical functioning because enzymes regulate key processes involved in decomposition and nutrient availability [24, 25]. In the present study, the association between grazing pressure and lower dehydrogenase and urease activity therefore suggests that increasing *Saiga* concentration may be accompanied by changes in belowground biological functioning. However, direct causal pathways were not experimentally evaluated, and these relationships should consequently be interpreted as ecosystem-level associations rather than experimentally demonstrated mechanisms.

The rhizosphere component of the study is also consistent with previous research emphasizing the central role of plant–microbe interactions in ecosystem functioning. [16] highlighted the importance of rhizosphere microbial communities for plant health and nutrient cycling, while [15] emphasized the complexity and context dependence of soil microbiome responses. [12] further demonstrated that particular microbial taxa can influence microbiome structure and functioning. In the present study, the associations among plant biomass, soil properties, microbial activity, and pasture productivity suggest coordinated responses between aboveground vegetation and belowground biological processes. Nevertheless, because the present study did not experimentally manipulate microbial communities or identify causal microbial taxa, the proposed conceptual cascade *Saiga* population → vegetation → soil → rhizosphere microbiome → ecosystem productivity should be regarded as an ecosystem-level framework synthesizing observed associations rather than as a demonstrated mechanistic pathway.

The soil responses observed in the present study are also broadly consistent with previous assessments of Kazakhstan's arid and steppe soils. [11] documented degradation processes in chestnut soils under arid conditions, while [10] characterized the ecological and agrochemical properties of chestnut soils in Northern Kazakhstan. These studies demonstrate the sensitivity of soil properties to environmental and land-use pressures in Kazakhstan. The present study extends this context by linking changes in soil properties with spatial variation in *Saiga* density, vegetation condition, and microbial activity. Such integration is important because soil degradation may not be adequately represented by vegetation indicators alone.

Climatic variability represents another important factor influencing the observed relationships. The dependence of vegetation and pasture condition on climatic variability is particularly relevant for the semi-arid steppe ecosystems of Kazakhstan, where changes in temperature and precipitation can modify forage production and ecosystem resilience. The [4] emphasized that increasing climatic variability and extreme events can alter terrestrial ecosystem productivity and increase environmental stress. In the present study, climatic variability was therefore considered an important contextual factor rather than an independent cause of the observed ecological changes. Longer monitoring periods will be required to separate the effects of *Saiga* grazing pressure from interannual climatic variability.

The spatial analysis further showed that areas of high *Saiga* concentration and major migration corridors overlap with zones of elevated vegetation stress. This finding supports the application of GIS and remote sensing for spatially explicit ecosystem assessment. Principles of geographical information systems provide an appropriate framework for integrating spatial population data, vegetation indicators, migration corridors, and environmental variables [26]. The present results demonstrate the value of combining spatial analysis with field-based vegetation, soil, and microbiological measurements. In contrast to approaches relying on a single vegetation indicator, the integrated framework used here allows areas of elevated ecosystem risk to be interpreted using multiple independent dimensions of ecosystem condition.

Overall, the findings support an ecosystem-resilience interpretation in which moderate grazing pressure may coexist with relatively stable ecosystem functioning, whereas increasing local grazing pressure may be accompanied by progressive

reductions in vegetation biomass, soil biological activity, and pasture productivity. However, the observed relationships should not be interpreted as evidence that Saiga population growth directly causes all measured ecosystem changes. The observational design, spatial heterogeneity, climatic variability, and relatively short monitoring period limit causal inference. The present findings therefore complement rather than replace previous ecological and pasture studies of Saiga in Kazakhstan.

Study Limitations. The present study has several limitations that should be considered when interpreting the results. First, the observational design does not allow direct causal inference regarding the effects of *Saiga* population density on vegetation, soil properties, or rhizosphere microbiome activity. The observed correlations should therefore be interpreted as ecosystem-level associations rather than experimentally demonstrated causal pathways. Second, the three-year monitoring period (2021–2023) may not fully capture long-term climatic variability, extreme drought events, changes in migration routes, or delayed ecosystem responses. Third, satellite-derived NDVI may be affected by spatial resolution, atmospheric conditions, seasonal phenology, and mixed land-cover effects. Fourth, spatial heterogeneity in vegetation and grazing pressure may introduce additional uncertainty into estimates of ecosystem responses. Fifth, the empirical density indicators used for scenario classification were derived from observed ecological responses rather than from formal breakpoint analysis or an independently calibrated mechanistic population model. Finally, the scenario analysis represents evidence-based ecological trajectories rather than deterministic long-term population forecasts.

Practical Implications. The results have practical implications for sustainable pasture management and *Saiga* conservation in Western Kazakhstan. Previous studies have emphasized the importance of forage resources, pasture condition, and the interaction between *Saiga* populations and human land use [6, 7, 23]. Building on these findings, the present study proposes an integrated indicator framework combining *Saiga* density, vegetation cover, aboveground biomass, NDVI, soil properties, and microbial indicators. Such a framework may assist in identifying areas at elevated risk of pasture degradation and in distinguishing regional population recovery from localized grazing pressure. Remote sensing may support regular monitoring of vegetation condition along major migration corridors, while field-based ecological indicators can be used to validate high-risk zones. Management measures may include adaptive regulation of grazing pressure, protection of migration corridors, pasture rotation, and restoration of degraded areas. The proposed indicator framework should be considered a decision-support approach rather than a substitute for field-based ecological assessment.

Future Research. Future research should extend the present observational framework through long-term and spatially explicit monitoring. Multi-year datasets combining satellite observations, vegetation surveys, soil properties, microbiome characteristics, and GPS-based movement data would allow more robust assessment of temporal and spatial interactions between *Saiga* populations and pasture ecosystems. Future studies should incorporate climate projections and extreme-event scenarios to evaluate changes in ecosystem carrying capacity under increasing climatic variability [4]. Structural Equation Modelling (SEM) may be applied in subsequent research to formally test the hypothesized pathways linking *Saiga* density, vegetation condition, soil properties, rhizosphere microbiome activity, and ecosystem productivity. Experimental or quasi-experimental approaches would further strengthen causal inference. SEM was not applied in the present study because the available observational dataset was designed primarily for ecological monitoring and association analysis.

Conclusion

The study demonstrated that increasing *Saiga* population density is associated with measurable changes in the condition and productivity of steppe agroecosystems in Western Kazakhstan. The integrated analysis of field observations, soil properties, microbial activity, vegetation characteristics, and Sentinel-2-derived NDVI revealed a nonlinear pattern of ecosystem response to increasing grazing pressure.

The main quantitative findings were as follows. At *Saiga* densities of 10–20 individuals km⁻², vegetation and soil biological indicators remained comparatively stable, indicating a range of relatively stable ecosystem functioning under the conditions of the study. At higher densities, vegetation degradation became more pronounced. In intensively grazed areas, vegetation cover decreased from 81.3±4.2% in 2021 to 72.6±4.8% in 2022 and 68.9±5.1% in 2023, while aboveground biomass decreased by approximately 24% over the monitoring period. Mean NDVI declined from 0.64 in 2021 to 0.58 in 2022, followed by a partial recovery to 0.60 in 2023, indicating both grazing-related vegetation stress and interannual climatic variability.

The integrated assessment identified an empirical risk-indicator range of approximately 20–25 individuals km⁻². Population densities within and above this range were associated with more pronounced deterioration of vegetation condition and soil biological properties, whereas densities exceeding 30 individuals km⁻² were associated with stronger reductions in biomass,

soil fertility, microbial activity, and pasture productivity. These values represent empirical management indicators derived from the observed ecological responses and should not be interpreted as statistically estimated or universal ecological thresholds.

Correlation analysis confirmed significant associations among *Saiga* density, vegetation condition, soil fertility, microbial activity, and ecosystem productivity. The combined field and remote-sensing assessment further demonstrated that areas with elevated *Saiga* concentrations and major migration routes may coincide with zones of increased vegetation stress. At the same time, the observational design does not permit direct attribution of all observed changes to *Saiga* grazing alone, because climatic variability and other environmental factors may contribute to interannual and spatial differences.

The principal outcome of the study is an integrated ecosystem assessment and decision-support framework linking *Saiga* population density, pasture vegetation, soil condition, rhizosphere microbial activity, and ecosystem productivity. The framework incorporates population-density assessment, GIS-based spatial analysis, NDVI monitoring, empirical risk indicators, migration-corridor mapping, and adaptive pasture-management measures. The 20–25 individuals km⁻² range can therefore be used as an initial empirical risk indicator for monitoring and management, subject to validation through longer-term observations across different climatic and ecological conditions.

Overall, the results provide quantitative evidence for linking *Saiga* population dynamics with changes in pasture condition and provide a practical basis for adaptive management of *Saiga* populations and steppe agroecosystems in Kazakhstan. The final management outcome is a monitoring-oriented approach in which population density, vegetation productivity, soil condition, and microbial indicators are assessed jointly rather than independently, allowing areas of increasing ecological risk to be identified and targeted for adaptive grazing regulation, pasture restoration, and spatial management.

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Author's Contributions

Zhanbolat Ibraibekov: Led the research, conceptualized the study, and contributed to the writing.

Saule Atshabarova: Conducted data analysis, developed the methodology, and contributed to the writing.

Ermeke Gabdullin, Svetlana Derbush: Performed data analysis, created visualizations, and contributed to the writing.

Sayagul Shaikina: Edited the manuscript, created visualizations, and managed the project.

Amanay Myrzabayev: Conducted peer review, edited the manuscript.

Saltanat Kabieva, Elza Geldymamedova: Edited the manuscript, created a visualization.

Tatyana Gavrilova, Natalia Korogod: Edited the manuscript.

Ethics

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