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Transdisciplinary Approaches to Pasture Degradation in Kazakhstan: Herders' Experiences with Dzuds and Droughts

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ABSTRACT

The Anthropocene presents an era of polycrisis, where anthropogenic climate change and socio-political histories intertwine, disproportionately affecting marginalized communities. In Kazakhstan, extreme weather events such as dzud, harsh winter or summer conditions leading to mass livestock mortality, pose existential threats to pastoral livelihoods, yet remain understudied outside Mongolia. Climate change is increasing the frequency and intensity of extreme events, exacerbating the occurrence of both winter and summer dzud. Kazakhstan's expansive grasslands have historically supported pastoral livelihoods, playing a crucial role in the nation's economy and rural development. Livestock herding, deeply rooted in the nomadic traditions of the Kazakh people, continues to play a central role in cultural identity and subsistence. This research explores a transdisciplinary framework integrating indigenous knowledge from herders with remote sensing methodologies. It examines the complex interplay between dzud phenomena, land degradation, and socio-environmental stressors in Kazakhstan. The research begins by contextualising dzud through literature, archival sources, and herder perspectives. It integrates historic research and local narratives with remote sensing to develop a multiscale framework for assessing dzud severity. Particular attention is given to ice-on-snow events and drought-induced forage decline, which are key drivers of summer and winter dzud. Indexes were chosen based on survey data that provided insight into pastoralists' views on climate change, pasture degradation, and adaptation strategies. National livestock statistics are analyzed alongside NDVI trends to evaluate the livestock dynamics and pasture conditions. Findings highlight the vulnerability of Kazakhstan's rangelands, exacerbated by desertification, scarce water resources, an arid climate, and sparse vegetation. Social factors, including insecure land tenure, limited access to winter fodder, and inadequate subsidies, further constrain pastoral resilience. The study underscores the importance of valuing historical knowledge and ancestral adaptation strategies, which offer critical insights for sustainable land management and climate adaptation policies.

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1. Introduction

Forced collectivization, sedentarisation of nomadic populations, and livestock confiscations collided with severe climatic stresses, creating a “perfect storm” of vulnerability. As result, between 1930 and 1933, Kazakhstan experienced one of the most devastating famines of the twentieth century, the Asharshylyk, during which between 1.5 and 2.3 million people perished, amounting to up to 42 percent of the Kazakh population (Cameron, 2016; Cameron, 2019). Unlike the Ukrainian Holodomor or other Soviet famines, the Kazakh famine combined radical political violence with profound ecological disruption. Within Kazakh oral traditions, this catastrophe was also remembered through the concept of dzud (jūt in Kazakh, zud in Mongolian), etreme winter or summer weather events that lead to large-scale livestock mortality. While the dzud has been extensively studied in Mongolia, its impact in Kazakhstan remains under-researched despite its growing severity and frequency (Leary et al., 2013; Middleton et al., 2015a; Robinson & Milner-Gulland, 2003). In Kazakhstan, dzud events, exacerbated by climate change, include harsh winters with deep snow or ice crusts that block forage access, and rapid temperature swings, all of which undermine herders’ capacities to maintain herd health and mobility (Middleton et al., 2015a; Vova et al., 2020).

This dislocation of pastoral systems disrupted traditional patterns of rotational grazing, resulting in concentrated overgrazing near settlements and underutilization of remote pastures, two parallel processes that fuel rangeland degradation in diverging ways (Baytelieva et al., 2023; Kubenkulov et al., 2019; Venkatesh et al., 2022). Ecologically, this has triggered reductions in aboveground biomass, declines in palatable vegetation, and increasing soil erosion and desertification (Alimaev et al., 2008; Chen et al., 2020; Kaliyeva et al., 2025; Kerven et al., 2008; Kubenkulov et al., 2019; Qi et al., 2025; M. Suleimenov et al., 2012; A. Tokbergenova et al., 2025).

Furthermore, in the Soviet Union, the ideology of conquering and subordinating nature was integral to state policy. Nature was framed as disorderly and devoid of meaning unless transformed for human purposes, reinforcing the broader Soviet ambition of total societal reconstruction (Bolotova, 2004). This paradigm was prominently expressed in Virgin Lands Campaign (1954–1963), where extensive grasslands were converted to arable land for grain production., which cast the agricultural transformation of the Kazakh steppe as a civilizing project and a triumph of human will over a supposedly “empty” landscape (Baubekova, et al., 2021; Koza et al., 2024). The Virgin Lands initiative thus exemplified the Soviet effort not only to dominate nature but also to displace alternative ecological knowledge and practices. But moldboard ploughing caused severe wind erosion and soil degradation (Koza et al., 2024). This technocratic approach directly contrasted with the long-established nomadic lifeways of the region, which relied on a flexible, symbiotic engagement with the steppe ecosystem.

For nomadic communities, the landscape held value and coherence independent of intensive exploitation. Traditional nomadic and semi-nomadic communities in Kazakhstan have long demonstrated adaptive resilience to climatic uncertainties (Ferret, 2016). Drawing upon generational ecological knowledge, pastoralists employ strategies such as herd diversification, seasonal migration, and local climate forecasting based on atmospheric and phenological cues (Fernández-Giménez et al., 2015; Okayasu et al., 2010; Reid et al., 2014). These methods, developed over centuries, are foundational to environmental stewardship and risk mitigation in rangeland ecosystems. However, modern constraints, including the expansion of croplands, infrastructure barriers, and restricted access to seasonal grazing lands, have eroded herders' mobility, reducing their capacity to respond effectively to dzud events (Fernández-Giménez et al., 2012; Kappas et al., 2020; Kerven et al., 2016; Robinson & Milner-Gulland, 2003; Vova et al., 2020).

In response to the increasingly complex social-ecological issues facing society, there is a growing trend to conduct transdisciplinary research, although its definition and purpose remain contested (Krueger et al., 2016; Rinaldi, 2023; Roux et al., 2010). Broadly, transdisciplinary research can be understood as an approach that seeks to integrate and, for some authors, even unify knowledge across disciplines, while also extending beyond academia by engaging practitioners, policymakers, and other non-scientific actors in collaborative problem-solving and decision-making (Rinaldi, 2023). Participatory methods, such as oral histories, community climate calendars, and citizen science data collection, offer crucial insights into local understandings of environmental stress, which are indispensable for designing culturally appropriate and ecologically relevant interventions (Becker & Ostrom, 1995; Calheiros et al., 2000; Colding & Folke, 2001; Davis & Wagner, 2003; Huntington, 2000; Mackinson, 2001; Moller et al., 2004). Moreover, integrating citizen science and participatory mapping into environmental monitoring strengthens both data granularity and community engagement (Brown, 2005, 2006; Brown & Fagerholm, 2015; Fagerholm et al., 2013; Käyhkö et al., 2015; Kyttä et al., 2023).

The research team comprised a professor of Kazakh history, a professor specializing in veterinary science and livestock management, a geography professor with expertise in dzud in Mongolia, and an environmental engineer focused on socio-ecological change in Central Asia. Drawing on this diverse expertise, the study proposes a transdisciplinary framework that brings together indigenous pastoral knowledge, oral and archival histories of dzud and pastoral adaptation in Kazakhstan, and research on dzud in Mongolia, alongside remote sensing and GIS-based monitoring tools. While remote sensing methods, including snow and weather factors and vegetation indices, have provided valuable insights into rangeland productivity trends and degradation hotspots, they remain limited without contextual grounding in the lived experiences of pastoralists (Erdenebadrakh et al., 2023; Nandintsetseg et al., 2018; Wang et al., 2013). These approaches support a two-way knowledge exchange: satellite and model-based projections inform local adaptation strategies, while ground-based observations refine the accuracy and usability of scientific models (Conrad & Hilchey, 2011; Theobald et al., 2015). In Kazakhstan, where centralized pasture management institutions remain fragmented and ecological monitoring is under-resourced, such hybrid frameworks are especially vital.

By focusing on dzud as both a climatic hazard and a social vulnerability indicator, this research positions pasture degradation as a site of contestation between climate science, land-use policy, and local agency. The development of a climate-informed dzud risk index, calibrated with both satellite-derived indicators and community input, offers a promising model for adaptive rangeland governance. Ultimately, this study argues that sustaining Kazakhstan's rangelands amid climate change will require co-producing resilience, a process that values herder knowledge, leverages technological innovation, and rebuilds trust in participatory environmental governance systems.

The paper begins by defining dzud based on literature, archival research, and herders' perceptions, followed by a classification of its types and causes. It then presents national statistics on changes in sheep, horse, and large-horn livestock populations, interpreting these alongside NDVI trends derived from remote sensing data. A focused case study examines droughts and frost-on-snow events in selected years and regions. Finally, the study analyzes survey responses to assess pastoralist perspectives on climate change and pasture degradation.

1.1. Background

Dzud: a definition

Dzud (жұт) refers to a catastrophic climatic phenomenon characterised by massive livestock mortality due to snow, ice, or extreme cold preventing access to pasture. Literally translated as "devourer", dzud is deeply embedded in Kazakh oral history and cultural memory, representing periods of great famine of 1932–33, forced sedentarisation, social breakdown, cultural destruction and ecological crisis (S. Cameron, 2018). Kazakh proverb say: "The rich lasts until the first dzud, the brave until the first bullet" furthermore the fact that dzud is not a single disaster, but a season when nature itself turns against the herder can be nicely framed by the next proverb: "Dzud is a devourer with seven brothers: snow, frost, wind, drought, ice, hunger, and negligence" (Kovalskaya, 2018).

Although the term dzud is Mongolian, both Kazakh and Mongolian pastoralists have endured this climatic hazard for centuries. Between 2000 and 2014, dzuds resulted in the loss of around 30 million livestock, significantly affecting the socio-economic landscape of Mongolia, with research indicating that 93.5% of livestock mortality in the country was attributed to a mix of multi-hazards (47.3%) and vulnerability (46.2%), implying that dzuds were influenced by both climatic factors and human activities, and in areas with high mortality rates, the primary causes were linked to multi-hazards, particularly drought-induced pasture shortages and severe snow accumulation (Nandintsetseg et al., 2018). Contemporary scientific literature from Mongolia provides valuable insight into the environmental and anthropogenic drivers of dzud, relevant for understanding its dynamics in Kazakhstan. Dzud is broadly defined as a natural disaster in which abnormal winter conditions prevent livestock from grazing, often following a summer drought that prevents animals from fattening (Reid et al., 2014; Robinson et al., 2017; Robinson & Milner-Gulland, 2003). While often translated as “heavy snow disaster,” dzud encompasses a variety of forms. Mongolian research identifies at least six distinct types (UNDP-NEMA, 2010; Middleton et al., 2015):

- White dzud (tsagaan dzud), caused by thick snow cover
- Black dzud (khar dzud), where pastures are bare but temperatures fall dangerously low
- Iron dzud (tömör dzud), when thaw-freeze cycles create an ice crust over grass
- Cold dzud (khuiten dzud), when extreme cold prevents animals from grazing
- Hoof dzud, where extreme dry weather causes drought
- Combined dzud, where two or more of the above factors occur simultaneously

These types often overlap. For instance, the catastrophic 1999–2000 dzud in Mongolia combined white, black, and iron dzud, affecting 70% of the country’s territory and killing millions of live-stock, resulting in mass movement of herders, who had lost their livestock and were left without viable livelihoods (UNDP, 2000).

Climate and land-use pressures further exacerbate vulnerability. Dzuds often follow spring frosts that destroy seeds, May droughts that stunt pasture growth, and mid-winter thaws that lead to ice formation, all compounding livestock stress (Fernández-Giménez et al., 2012; Morinaga et al., 2003). Traditionally, Kazakh nomads mitigated dzud by moving herds seasonally across diverse pastures. However, Russian imperial policies from the late 19th century onwards, particularly Stolypin’s land reforms and the influx of Russian settlers, severely restricted pastoral mobility (Kovalskaya, 2018). This led to overcrowding on marginal lands, overgrazing, and increased exposure to dzud-related losses.

Thus, dzud in Kazakhstan, like dzud in Mongolia, is not merely a meteorological event but a systemic crisis shaped by ecological, political, and social factors. As Fernández-Giménez et al. (2012) observe, “dzud is a physical hazard, but its severity is a function of vulnerability.” Historical memory, environmental monitoring, and adaptive mobility remain key to understanding and managing its recurrence across Central Asia.

2. Methods and Materials

2.1. Study region

Kazakhstan, the largest landlocked country in the world and the ninth largest overall, spans approximately 2.7 million square kilometers, extending from the Caspian Sea in the west to the Altay Mountains in the east (FAO Regional Office for Europe and Central Asia, 2020; Kabzhanova et al., 2025). Its vast territory lies at the intersection of Europe and Asia, making it one of only two landlocked transcontinental countries. Kazakhstan experiences an extreme continental climate, characterized by hot summers and long, cold winters (Dubovyk et al., 2019). Kazakhstan has a mean annual temperature (Tann) ranging from 0 °C to 10 °C and low and unevenly distributed annual precipitation (Pann) ranging from 100 mm to 400 mm, concentrated mainly in winter and spring (Sun et al., 2025). The country's terrain is diverse, ranging from 100-250 m lowland plains and deserts to mountainous regions (1400 m). A significant feature of Kazakhstan's landscape is the Kazakh Steppe, the world's largest dry steppe region, covering about one-third of the country (~804,500 km^2) (Suleimenov, 2024). This region is dominated by semi-arid grasslands and pastures forming an essential base for extensive grazing and livestock herding (Figure 1).

Kazakhstan ranks fifth globally in pasture area, with over 186 million hectares, which is approximately 84.1% of its agricultural land (Alilmaev et al., 2005; Spaeth et al., 2025). These landscapes form the ecological and economic backbone of the country, sustaining both traditional nomadic and commercial livestock systems, and contributing significantly to rural livelihoods, national food security, and the broader pastoral economy (Kerven et al., 2008; Tokbergenova et al., 2024; Wright et al., 2012). However, Kazakh grassland systems face mounting threats, with nearly 48 million hectares (38%) of pastures having been degraded, of which 27.1 million hectares are at the last stage of degradation (Venkatesh et al., 2022; Kubenkulov et al., 2019). Unsustainable grazing, erosion, subsequent land abandonment, and the loss of seasonal migratory cycles are among the major barriers to rangeland regeneration (Kerven et al., 2016; Kobayashi et al., 2007; Kubenkulov et al., 2019). This degradation is further compounded by climate change, which intensifies aridity, alters precipitation regimes, and increases temperature variability, especially across semi-arid and arid zones in western Kazakhstan (Dubovyk et al., 2019; Gutman et al., 2020; Islyami et al., 2020; Karatayev et al., 2022; Yu et al., 2020).

Figure 1. The Land cover map of Kazakhstan and administrative delineation

2.2. Historical and archival research

This study employed a historical and archival research approach to analyze the phenomenon of dzud (dzhut) in Kazakhstan. Primary focus was placed on collecting and synthesizing historical narratives, ethnographic accounts, and archival documents related to Kazakh pastoral traditions and climatic disasters. The research drew on Kazakh oral histories, proverbs, and early 20th-century writings by Kazakh intellectuals to understand indigenous conceptions of dzud as a multifaceted natural and social disaster.

To enrich the understanding of dzud's causes and types, the study incorporated Mongolian scholarly research and official reports, recognizing the ecological and cultural parallels between Kazakh and Mongolian pastoral systems. Mongolian archival data and studies, such as UNDP-NEMA national reports and climatological analyses (e.g., Fernández-Giménez et al., 2012; UNDP, 2000), provided detailed classifications of dzud types and their climatic drivers, which informed the conceptual framework for Kazakhstan's dzud history.

The archival research involved systematic review and critical analysis of both published academic literature and historical texts, alongside ethnographic collections of proverbs and folklore conducted in Astana, Kazakhstan. This comparative approach allowed for triangulating the climatic, ecological, and sociopolitical dimensions of dzud over time, highlighting shifts in pastoral resilience and vulnerability due to environmental changes and colonial-era land reforms.

By applying this approach, the study constructed a nuanced, historically grounded background of dzud in Kazakhstan, integrating cross-regional insights while respecting local terminologies and experiences.

2.3. Statistical data analysis

Statistical analysis of livestock dynamics in Kazakhstan was conducted using official data from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. Specifically, time series data on the annual number of livestock, including sheep and goats, horses, cattle (large horned), and camels, were obtained from the "Livestock and Poultry Numbers" section of the Bureau's public database (Committee on Statistics, Ministry of National Economy of the Republic of Kazakhstan, 2025). The dataset spans the period from 1990 to 2024, allowing for a long-term assessment of trends and fluctuations in livestock populations.

2.4. Questionnaire

To gain qualitative insights into herders' experiences, a semi-structured questionnaire in Kazakh and Russian was administered to 29 herders across various regions of Kazakhstan, including Akmola, Abai, Karaganda, Aktobe, Kostanai, Almaty, Kyzylorda, North Kazakhstan, and Mangystau. Participants were recruited using a snowball sampling approach via local authorities, national universities, and researchers' personal networks, allowing access to a wide range of pastoralist respondents.

Herders' characteristics are summarized in Table 1, highlighting key variables including region, age, main occupation, herding experience, and herd size by livestock type. Participants ranged from 18 to over 65 years of age, with herding experience varying from 1 to 40 years. Herd sizes and livestock composition differed substantially across individuals and regions, reflecting the diversity of pastoral practices. For example, herders in Akmola and Kostanai primarily managed large horned cattle, whereas Mangystau herders had smaller herds with camels and horses, reflecting ecological and pasture conditions specific to each region.

The aim of this study was not to produce prescriptive solutions or address immediate policy challenges but rather to demonstrate the opportunities offered by a transdisciplinary approach in a region with limited human and research capacity. This explorative study, fully driven by enthusiasm, highlights how integrating different knowledge systems, methods, and disciplinary perspectives can provide novel insights into climate perception and livestock management. As such, the study is fundamental in nature, illustrating methodological innovation and the potential for collaborative, cross-disciplinary research in a region where such approaches are still rare.

The sample included herders from ecologically diverse regions of Kazakhstan: steppe (e.g., Kostanai, North Kazakhstan), semi-desert (Kyzylorda, Mangystau), forest-steppe (Almaty), and mountainous zones (Abai, Almaty). While responses are summarized in the main text to highlight overall trends, we also analyzed regional differences in climate perception and dzud impacts. For example, herders in northern steppe regions reported more severe losses due to winter dzud and spring droughts, whereas semi-desert region herders emphasised water scarcity and pasture degradation as the primary climate hazards affecting livestock.

The online questionnaire consisted of 46 open- and closed-ended questions covering climate hazard perception, livestock dynamics, pasture management, and seasonal weather changes. Respondents provided both quantitative data (e.g., herd sizes, livestock losses) and narrative accounts, enabling a richer understanding of local experiences and adaptive strategies. Responses were recorded, transcribed, and analyzed using thematic analysis to identify and interpret patterns across regions and ecological zones. Inter-coder reliability was assessed through independent coding of a subset of transcripts, ensuring consistent interpretation of qualitative data.

Table I. Key herder's characteristics

#	Region	Status in the household	Age	Main occupation	Herding experience (years)	Large horn cattle (cows, bulls, calves)	Horses	Camels
1	Akmola region	Owner	55-64	Combined herding + other employment	28	850	720	0
2	Akmola region	Owner	45-54	Combined herding + other employment	15	3000	500	
3	Akmola region	Owner	35-44	Combined herding + other employment	19	5	2	0
4	Akmola region	Owner	35-44	Combined herding + other employment	20	2	0	0
5	Akmola region	Owner	55-64	Combined herding + other employment	3	0	50	0
6	Akmola region	Owner	35-44	Combined herding + other employment	3		10	
7	Akmola region	Owner	55-64	Combined herding + other employment	20	2000	1200	0
8	Akmola region	Farm manager	35-44	Herder only	10	5	30	0
9	Akmola region	Owner	55-64	Herder only	27	0	96	0
10	Akmola region	Owner	55-64	Herder only	17	5000	0	0

11	Akmola region	Family member	35-44	Combined herding + other employment	16	85	213	0
12	Akmola region	Owner	45-54	Combined herding + other employment	7	0	10	0
13	Kostanai region	Owner	55-64	Herder only	26	5000	0	0
14	North Kazakhstan region	Owner	55-64	Herder only	22	6	50	0
15	Aktobe region	Owner	45-54	Herder only	12	20	50	0
16	Aktobe region	Owner	65+	Herder only	30	150	20	0
17	Aktobe region	Owner	55-64	Herder only	20	97	0	0
18	Aktobe region	Owner	35-44	Herder only	5	100	20	0
19	Mangystau region	Family member	18-24	Herder only	15	0	30	20
20	Kyzylorda Region	Owner	55-64	Herder only	10	120	10	0
21	Kyzylorda region	Owner	55-64	Herder only	20	0	17	0
22	Almaty region	Owner	45-54	Combined herding + other employment	2	38	0	0
23	Abai region	Owner	45-54	Herder only	30	480	200	0
24	Abai region	Owner	55-64	Combined herding + other employment	40	21	10	0
25	Abai region	Owner	35-44	Combined herding + other employment	10+	20+	30+	0
26	Karaganda region	Owner	55-64	Herder only	15	150	1200	
27		Hired employer	55-64	Combined herding + other employment	20	5	10	0
28		Hired employer	25-34	In education		1	1	1
29		Hired employer	25-34	Combined herding + other employment	7	100	25	10
24	Abai region	Owner	55-64	Combined herding + other employment	40	21	10	0

2.5. MODIS normalized difference vegetation index (NDVI)

Dzud in Kazakhstan is driven by a combination of natural and socio-economic factors that contribute to mass livestock mortality, including summer droughts, severe or prolonged winters, and abrupt temperature fluctuations leading to ice crust formation. However, as noted by herders in the questionnaire survey, adequate preparation and sufficient winter forage reserves can mitigate these losses. Therefore, summer NDVI measurements serve as an important tool for assessing pasture productivity and anticipating potential risks, as poor summer forage may result in weaker animals that are more susceptible to dzud-related mortality during harsh winters. Thus, this study analyzed temporal changes in vegetation health across the grassland regions of Kazakhstan, focusing on the regions of interest, Mangystau, and Kyzylorda, which are most vulnerable to climate risks and were reporting mass losses of livestock in local news and Akmola, which was referred by herders as the region where the livestock was transferred during severe drought. NDVI time series were extracted from the MODIS MOD13Q1 product (MODIS/006/MOD13Q1) for the Julian day 241 (approximately August 28) in the second half of the vegetation season for each year from 2000 to 2022. For each year, the NDVI images within the 16-day period starting on the target date were averaged to reduce noise and cloud contamination. The grassland mask was applied to ensure that only pixels classified as grasslands were included in the analysis. The grassland areas were delineated using the 2019 global land cover dataset from the Copernicus PROBA-V satellite mission (COPERNICUS/Landcover/100m/Proba-V-C3/Global/2019). The dataset's discrete classification band was used to identify grassland land cover (class code 30), which served as a mask to isolate relevant pixels. Spatial averaging of NDVI was conducted separately for the grasslands within each region (Mangystau, Akmola, and Kyzylorda) and for all grasslands across Kazakhstan. Regional boundaries for Kazakhstan were obtained from the FAO GAUL 2015 dataset (FAO/GAUL/2015/level1), which was used to isolate the regions of interest. The mean NDVI values for each year and region were compiled to assess temporal vegetation trends.

2.6. Drought monitoring

To monitor drought conditions in Kazakhstan, we utilized the Standardized Precipitation Evapotranspiration Index (SPEI) from the CSIC SPEI 2.10 ImageCollection, specifically the 6-month timescale (SPEI_06_month) covering the period from 1990 to 2023. The use of a 6-month SPEI was intentional, as this time scale is particularly sensitive to changes in soil moisture and water availability that directly affect agricultural productivity (Sayat et al., 2025). The national boundary for Kazakhstan was extracted from the FAO GAUL 2015 Level 0 dataset to define the study area. Mean SPEI values were computed for each time step using a spatial resolution of 55 km. These values were then classified into seven categories: Severe Drought (≤ -1.5), Moderate Drought (-1.5 to -1), Mild Drought (-1 to -0.5), Normal (-0.5 to 0.5), Mild Wet (0.5 to 1), Moderately Wet (1 to 1.5), and Severely Wet (> 1.5). The classification enabled temporal visualization of drought intensity and frequency using scatter plots, facilitating drought trend analysis over the 33-year period.

2.7. Frost vulnerability analysis

In this study, we proposed a regional vulnerability index to ice crust conditions based on remote sensing data, enabling the spatial assessment of areas at higher risk for dzud-related impacts. We quantified the number of frost days with concurrent snow cover in April across Kazakhstan's provinces from 2018 to 2025 using Google Earth Engine. The selected period (2018–2025) was chosen intentionally to coincide with years most frequently mentioned in herders' interviews and media reports as being associated with severe spring frosts and pasture challenges. These years thus provided a relevant and practical case study to test and illustrate the proposed methodology rather than to quantify long-term climate dynamics. While the developed approach could be extended to include earlier periods, our focus was on demonstrating how such integrative analyses can enhance understanding of climate impacts on pastoral systems rather than on detecting long-term statistical trends. Furthermore, the study by Kauazov et al. (2023) revealed that although snow cover area fluctuates significantly from year to year, the overall trend of change from 2000 to 2022 is weak (about 4% per decade) and statistically insignificant at the 0.05 level. This indicates that modern variations in snow and frost patterns are dominated by short-term climatic and meteorological fluctuations rather than by a clear long-term climatic signal. Given that snow cover duration and melt timing can vary substantially between individual years depending on precipitation and temperature anomalies, extending the analysis period would not necessarily improve statistical robustness or alter the main conclusions.

The focus on April is based on both literature and interview data, where this month was frequently mentioned in the context of the most severe dzud events in Kazakhstan. April marks the beginning of the growing season, and sudden temperature drops or heavy snowstorms during this period can severely affect early forage growth, delaying pasture availability and further compromising livestock already weakened after winter. Daily minimum air temperature data were obtained from the ECMWF ERA5 reanalysis dataset (ECMWF/ERA5/DAILY) and converted from Kelvin to Celsius to identify frost days (minimum temperature < 0°C). Daily snow cover data were sourced from the MODIS NDSI product (MODIS/061/MOD10A1), where pixels with NDSI values above 20 were classified as snow-covered. For each April during the study period, ERA5 and MODIS images were temporally joined, and frost-with-snow pixels were identified through a pixel-wise logical AND operation. The number of such days was summed for each year and averaged over province boundaries.

The Normalized Difference Snow Index (NDSI) uses the green and short-wave infrared (SWIR) spectral bands to effectively separate snow from clouds, soil, and other bright surfaces in optical remote sensing data (Salomonson & Appel, 2004). This index is the most widely applied approach for mapping snow cover because it minimises the influence of atmospheric effects and geometric distortion, while maintaining reliable snow discrimination (Çakir et al., 2025; Stillinger et al., 2023; Tong et al., 2020). The MODIS daily snow cover products (MOD10A1) with its relatively high temporal (1-day) and spatial (500-m) resolution and proven accuracies of 85–99% in various environments have been extensively employed in a great number of studies regarding snow cover variation (Coll & Li, 2018; Gao et al., 2012; Hall & Riggs, 2007; Huang et al., 2011; Liu et al., 2020; Teleubay et al., 2022). While a global NDSI threshold of 0.4 is often recommended, recent research has shown that this value can overestimate snow-free areas in regions with bright soils, sparse vegetation, or thin snow layers (Bousbaa et al., 2024; Riggs et al., 2017; Zhang et al., 2019). For example, in the arid Kashgar Region of northwest China, bordering to Kazakhstan with comparable climatic and surface conditions, the standard 0.4 threshold underestimated snow-covered areas. Testing alternative thresholds of 0.3 and 0.2 demonstrated that NDSI > 0.2 provided the best match with observed snow extent (Maimaitiaili et al., 2018). Similarly, in this study, the lower NDSI threshold of 0.2 was adopted to enhance sensitivity to thin or patchy snow typical of Kazakhstan's dry continental climate. Given that April marks a critical transitional period for vegetation growth and livestock recovery after winter, accurately detecting even minimal snow presence was essential for assessing frost-related risks to pasture and livestock vulnerability.

3. Results

3.1. Herders experience

The survey responses clearly indicate that herders in Kazakhstan perceive significant changes in weather patterns that directly affect their livestock farming activities. Many reported that winters have become warmer overall, but paradoxically, this warming is accompanied by more frequent occurrences of ice crust formation on pastures. This ice crust (dzud) forms when rain or thawing snow freezes, creating a hard barrier that prevents animals from grazing, leading to starvation and increased mortality.

Several herders noted that the timing of seasonal events has shifted. For instance, winter tends to start later but linger longer in some regions, while spring and summer seasons arrive earlier or have become shorter. Some stated that spring now comes later, affecting the growth cycle of forage plants, thereby shortening the grazing season. Others highlighted that summers are warmer and drier, increasing the prevalence of drought conditions, which reduce pasture quality and water availability. These climatic changes, combined with the observed increase in extreme weather events such as floods and heat waves, have made livestock farming riskier and more unpredictable. Respondents expressed concern that these trends (warmer temperatures, more frequent droughts, shifting seasons, and increased ice crusts) are disrupting the ecological balance of the steppe and directly undermining their traditional nomadic pastoralist lifestyle.

Herders also reported changes in precipitation patterns, including an increase in winter rains. Rain falling on snow followed by freezing, results in ice crust formation, worsening pasture accessibility during winter. In some regions, this has led to severe dzud events where animals starve en masse despite snow presence. Snowfall patterns have become more erratic. Some respondents indicated there is less overall snowfall, while others observed more frequent snowstorms but with less stable accumulation. This variability complicates traditional herding practices, as animals depend on predictable snow cover for insulation and foraging conditions. The frequency of droughts and dust storms was also reported to have increased, compounding the challenges for livestock survival. Droughts reduce the growth of key pasture species such as feather grass, ryegrass, and wormwood, forcing herders to purchase expensive feed or face losses. Dust storms not only degrade pasturelands but can also cause changes in how livestock grazing is organised by time of day.

The frequent cause of livestock death identified by herders was starvation due to lack of accessible feed caused by severe drought and snow and ice crusts in 2019 and 2021. Disease outbreaks, theft, and predation by wild animals such as wolves were also commonly mentioned. Additionally, poisoning from plastic waste ingestion and poisonous plants occasionally contributed to losses. When it comes to handling carcasses, most herders reported either burying the dead animals on-site or burning the carcasses to prevent the spread of disease and minimize environmental contamination. In some cases, state or local authorities intervene to manage carcass disposal during large-scale mortality events.

3.2. Drought monitoring

Mirroring the herder's experience, the SPEI analysis over the period 1990-2022, using a 6-month time scale, highlights notable changes in moisture conditions across Kazakhstan (Figure 2). While the early and mid-1990s were characterized predominantly by normal to mildly dry conditions, the latter part of the time series, particularly from the early 2000s onward, shows a clear trend toward more frequent and intense drought events. This is especially evident in the increasing number of months classified under moderate and severe drought categories (SPEI ≤ -1.0), with several occurrences of severe drought (SPEI ≤ -1.5) observed in the 2010s and early

2020s. The findings align with those presented by (Dubovyk et al., 2019), highlighting years 2000, 2008, 2010, 2011, 2012, and 2014, when over 50% of the nation's territory experienced drought conditions of varying intensities, with the most pronounced droughts occurring in 2021. As can be clearly seen in Figure 2 the moderate and severe drought prevailed from 2006 onwards, with the drought pick in 2021.

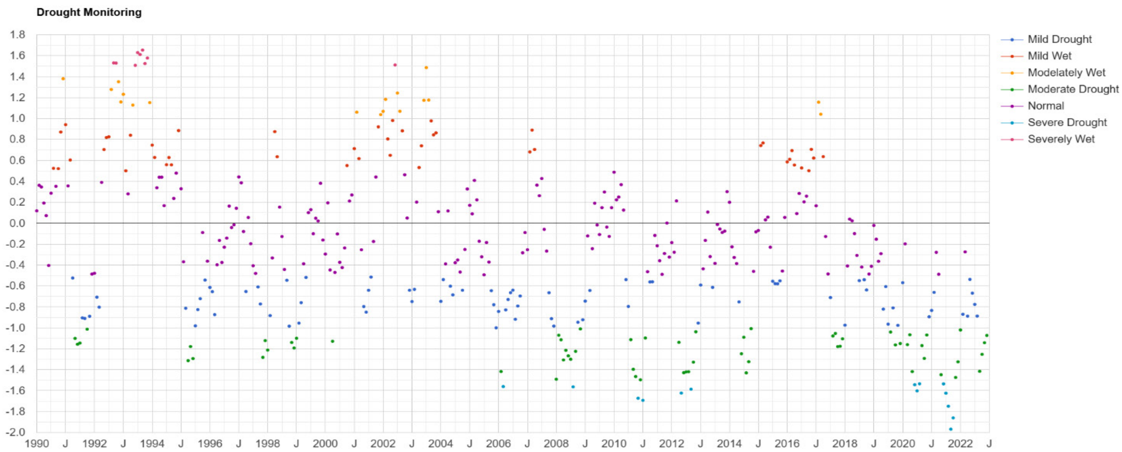

Figure 2. Drought monitoring with SPEI 6-month time scale for the period 1990-2022

At the same time, short periods of wet conditions, including moderately and severely wet months (SPEI > 1.0), were also recorded, but these were generally less frequent and more isolated. The increasing variability and severity of drought conditions toward the end of the study period suggest a growing vulnerability of agricultural systems in Kazakhstan to climate-induced water stress, desertification, and the spread of sandy habitats and saline soils. These findings, accompanied by human overuse of the land, result in nearly 50,000-70,000 km2 of fertile land becoming unusable annually (A. Tokbergenova et al., 2018).

3.3. Frost vulnerability

Based on the historical and literature analysis of dzud events confirmed by the herders' responses and research conducted in Mongolia, the frost vulnerability index has been developed for Kazakhstan, combining the abrupt change from positive to negative temperatures in the presence of snow during April, hypothetically representing the condition of ice crust formation. The results indicate significant spatial variation in the occurrence and intensity of frost days across Kazakhstan's regions from 2018 to 2025 (Table 2). Kazakhstan covers a vast territory with four distinct climatic zones, resulting in substantial differences in weather conditions between its northern and southern regions during the cold season (Karatayev et al., 2022). Regions in the northern and northeastern parts of the country, such as North Kazakhstan (49 days), Akmola (44 days), Pavlodar (43 days), and Kostanay (42 days), experienced the highest total number of frost days, coupled with elevated average frost intensities ranging from 14.4 to 17.9, classifying them as high vulnerability regions. Central provinces like Karaganda and West Kazakhstan displayed moderate frost exposure, both in frequency and intensity. In contrast, southern and southwestern regions, including Zhambyl, Mangystau, and South Kazakhstan, experienced very few frost days (fewer than 6), with low average intensities, placing them in the low vulnerability category. These spatial patterns reflect the country's diverse springtime thermal regime, with prolonged cold and snow cover in the north and relatively early warming in the south (Salnikov et al., 2023). This spatial pattern corresponds with the responses of herders regarding the main causes of livestock mortality and challenges with pasture use. In northern and central provinces, where frost days with snow cover are more frequent and intense, herders often report late spring frosts and lingering snow as major factors contributing to livestock stress, limited forage availability, and delays in pasture access. The southern provinces have fewer frost days and less frost intensity, making it easier for them during that time. However, the hot summers and dry climate, along with sandy and salty soils, make pastures in these regions more at risk from climate change.

Table II. Summary of April frost events across Kazakhstan's regions for the period 2018–2025.

Region	Total Frost Days	Intensity (Avg. Frost Days)	Vulnerability
North Kazakhstan	49	16.43	High
Kostanay	42	14.77	High
Pavlodar	43	14.42	High
Karaganda	31	10.18	Moderate
Akmola	44	17.85	High
West Kazakhstan	28	9.60	Moderate
Aktobe	26	8.82	Moderate
East Kazakhstan	37	12.88	Moderate
Almaty Region	17	5.53	Low
Atyrau	11	3.84	Low
Kyzylorda	6	1.90	Low
Zhambyl	3	1.32	Low
Mangystau	5	1.60	Low

3.4. Vegetation health monitoring

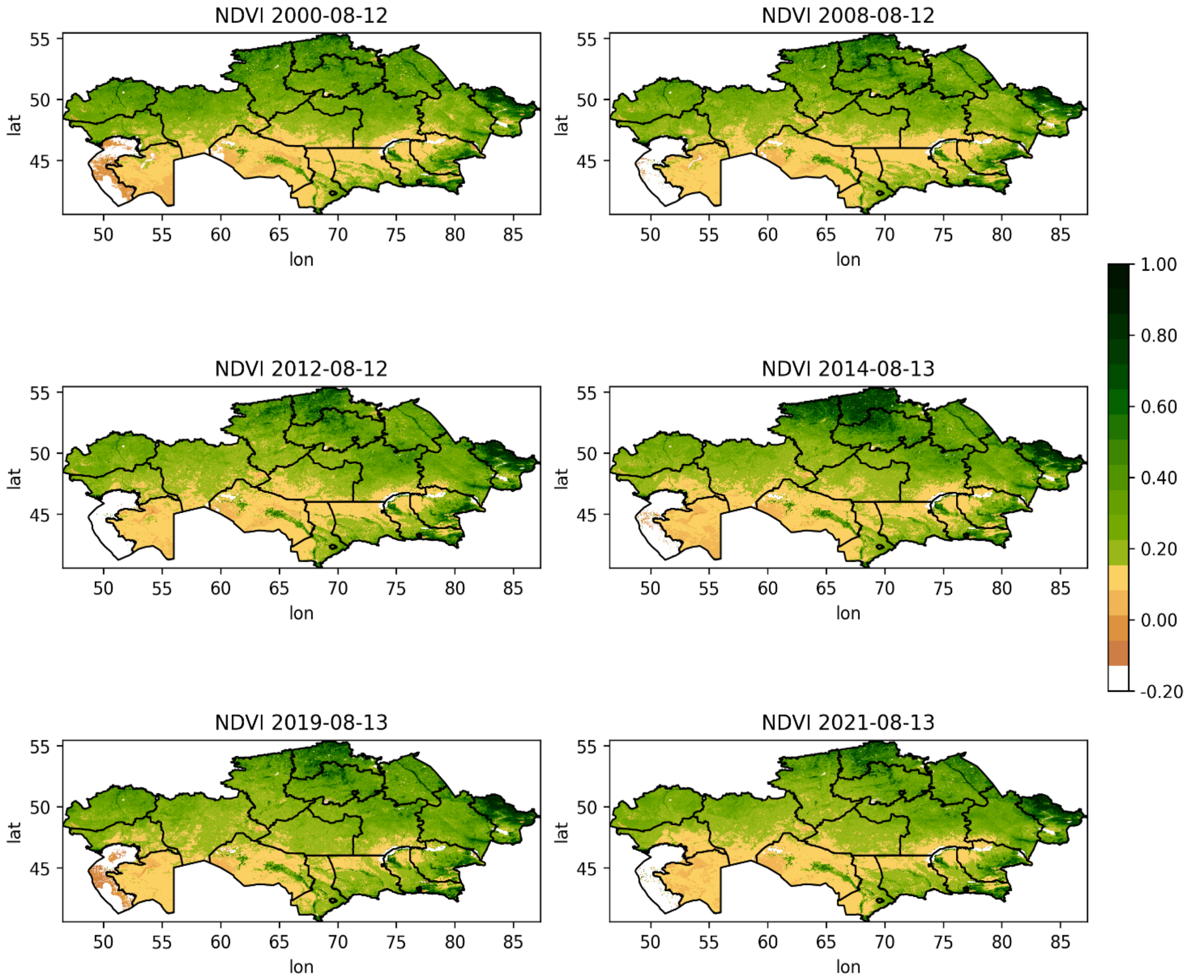

Figure 3. NDVI maps for the critical years: 2000, 2008, 2012, 2014, 2019, 2021

The series of NDVI maps in Figure 3 illustrate spatial and temporal variability in vegetation conditions across Kazakhstan for mid-August snapshots from 2000 to 2021. Across all years, a consistent north-south gradient is evident: northern regions exhibit higher NDVI values (0.6-0.9), reflecting denser and more productive vegetation, while southern and southwestern areas remain persistently lower (0.0-0.3), corresponding to semi-arid and arid landscapes with limited biomass. Interannual variations are also apparent. Years such as 2008 and 2014 show relatively elevated NDVI across central regions, indicating more favorable growing-season moisture conditions. In contrast, 2012 and 2021 display noticeably reduced NDVI in central and southern zones, suggesting vegetation stress likely associated with drought or anomalous heat events. Localized declines in western Kazakhstan in 2000 and 2019 further highlight spatially heterogeneous vegetation sensitivity to climatic fluctuations.

Figure 4 illustrates temporal NDVI variations from 2000 to 2022 for Kazakhstan's rangelands, revealing distinct regional patterns in vegetation productivity. Akmola consistently exhibits higher NDVI values (0.29–0.50), reflecting more favorable climatic conditions and productive steppe vegetation. The national average (0.21–0.28) remains relatively stable, aligning with previous studies describing Kazakhstan's semi-arid grassland ecosystems. In contrast, Kyzylorda (0.13–0.17) and Mangystau (0.10–0.17) display persistently low NDVI values, characteristic of arid and semi-desert environments where limited precipitation and grazing pressure constrain vegetation growth.

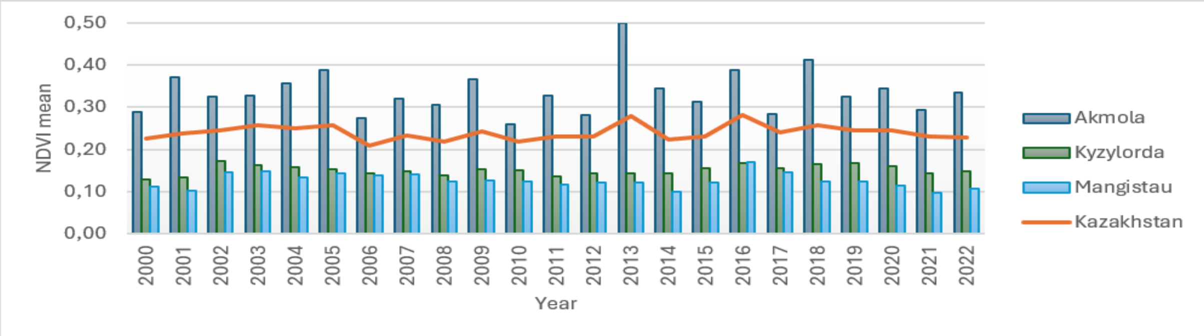

Figure 4. Mean NDVI for 16 days starting from the Julian day 241 in Kazakhstan and selected vulnerable regions (Akmola, Kyzylorda, and Mangystau) from 2000 to 2022.

Normalized Difference Vegetation Index (NDVI) data from Mangystau and Kyzylorda regions for the summer seasons of 2019 and 2021 provide quantitative insight into the severity of pasture degradation associated with mass livestock mortality and the broader agricultural crisis. In Mangystau, NDVI remained critically low in both 2019 (0.12) and declined further in 2021 to 0.10, one of the lowest recorded values since 2000 and below the long-term regional average of approximately 0.13. This stark reduction reflects extreme vegetation stress and minimal biomass availability, corroborating field reports of widespread fodder shortages and animal starvation. Similarly, Kyzylorda experienced a decline in mean NDVI from 0.17 in 2019 to 0.14 in 2021, signaling a deterioration in pasture productivity despite an otherwise stable NDVI trend in preceding years. These values are especially concerning given that 0.14 is typically associated with sparse vegetation, insufficient to sustain grazing herds through the peak summer months (Abisheva et al., 2024). The low NDVI values directly align with reports of emergency conditions in both regions, including the declaration of regional crises and the well-documented death of thousands of livestock, particularly Mangystau province as a whole which reported the death of more than 1,000 horses (Reuters, 2021). The crisis escalated as hay prices surged, reaching up to 42,000 tenge per ton, and the failure of the Ministry of Agriculture to implement effective mitigation or forecasting measures led to the resignation of Minister Saparkhan Omarov in July 2021 (Dusengulova, 2021). These NDVI trends thus serve as crucial empirical evidence validating local narratives of pasture collapse. They also underscore the utility of satellite-based vegetation indices for early warning and response planning in drought-prone pastoral zones. The disconnection between official livestock statistics and on-the-ground realities further emphasizes the need for integrating NDVI and other remote sensing metrics into national livestock monitoring and agricultural risk assessment frameworks.

In contrast to the critically low NDVI values observed in Mangystau and Kyzylorda, Akmola region maintained relatively higher mean NDVI values during the same period, highlighting its more favorable pasture conditions. In 2019, Akmola's NDVI was 0.32, and although it slightly declined in 2021 to 0.29, it remained well above the national average and significantly higher than the severely drought-affected regions in the south and west. These figures indicate moderate to good vegetation cover, sufficient to support grazing, and reflect the region's more temperate climate and higher summer precipitation levels compared to arid Mangystau and Kyzylorda. This ecological disparity is particularly important given that several interviewed herders from Mangystau cited Akmola as a destination for emergency livestock relocation during the 2021 crisis. Facing barren pastures and unaffordable feed prices, some herders undertook long-distance transportation of their animals to more productive areas such as Akmola, in a desperate effort to save their herds. The NDVI data corroborates these decisions, illustrating why Akmola was perceived as a refuge amidst widespread pasture failure elsewhere. This internal mobility underscores the growing spatial inequality in pasture availability and points to the critical role of interregional adaptation strategies in Kazakhstan's rangeland management under climate stress.

3.5. National statistics

After the collapse of the Soviet Union, by the end of the 1990s, livestock numbers in Kazakhstan had dropped dramatically resulting in a 75% decrease in livestock numbers (Robinson et al., 2021). Economic instability, the dissolution of collective farms, and loss of support systems left many rural households unable to sustain their herds (Robinson & Petrick, 2024). Additionally, herder mobility became restricted due to ambiguous land tenure arrangements, market liberalization, and fragmented resource control. (Ellis & Lee, 2003; Kerven et al., 2008; Kobayashi et al., 2007; Robinson & Milner-Gulland, 2003). In Kazakhstan, rural subsistence households, which raise livestock on a significantly smaller scale, have come to represent the majority of the country's livestock holdings. This shift occurred as large-scale agricultural enterprises quickly phased out their livestock operations, while family farms just started to emerge in 2000 (Kobayashi et al., 2007). Since the 2000s, a decolonial revival has taken root, signifying a remarkable resurgence as communities strive to reconnect with their ancestral practices. This is particularly evident in horse herding, with some regions boasting over 300,000 horses, a phenomenon partly fueled by a renewed commitment to traditional tabun horse herding (Bissenova, 2021). In 2022, Kazakhstan ranked 5th in the world in horse population after Mongolia (FAOSTAT, n.d.). By 2024, Kazakhstan's horse population had reached 4.35 million, more than triple the 1990 numbers (1.6 million) and camels almost doubled from 143,000 to 281,000 (Table 3).

Table III. Livestock populations in Kazakhstan, 1990–2024, large-horned livestock (cattle), sheep and goats, camels and horses (in thousands of heads) based on official national statistics (Committee on Statistics, Ministry of National Economy of the Republic of Kazakhstan, 2025).

Year	Large-horned livestock	Sheep and goats	Camels	Horses
1990	9 757.2	35 660.5	143.0	1 626.3
1995	6 859.9	19 583.9	130.5	1 556.9
2000	4 106.6	9 981.1	98.2	976.0
2005	5 457.4	14 334.5	130.5	1 163.5
2010	6 175.3	17 988.1	169.6	1 528.3
2015	6 183.9	18 015.5	170.5	2 070.3
2016	6 413.2	18 184.2	180.1	2 259.2
2017	6 764.2	18 329.0	193.1	2 415.7
2018	7 150.9	18 699.1	207.6	2 646.5
2019	7 436.4	19 155.7	216.4	2 852.3
2020	7 850.0	20 057.6	227.7	3 139.8
2021	8 192.4	20 876.8	243.4	3 489.8
2022*	6 536.3	18 843.0	253.7	3 790.2
2023*	6 616.8	18 667.4	264.9	3 851.2
2024	7 976.7	20 224.4	280.5	4 353.0

*In accordance with paragraph 2 of paragraph 10 of the Rules for the Revision of Published Official Statistical Information for statistical Purposes and on the basis of updated administrative data on household accounting, a special revision of certain indicators of livestock statistics for 2022 and 22023 was carried out in relation to peasant and farm farms and households of the population.

Despite the recent occurrence of dzuds in Kazakhstan during 2019 and 2021, which were widely reported by local authorities and the media, the official end-of-year livestock statistics do not reflect a corresponding decline in livestock numbers. Instead, the statistical data show a steady increase across all key livestock categories, including large horned livestock, sheep and goats, camels, and horses. For example, the number of horses rose from 2.65 million in 2018 to 3.49 million in 2021, while sheep and goats increased from 18.7 million to 20.9 million over the same period. Notably, following administrative data revisions for 2022 and 2023, intended to improve accuracy in household and farm records, the reported figures for some categories, such as large horned livestock and sheep, show slight declines compared to 2021. The revision primarily ad-dressed distortions identified in administrative sources for peasant and household farms. As these revisions were corrections of previously misreported data rather than methodological changes to data collection or estimation procedures, they do not affect the interpretation of trends, year-on-year comparisons, or the overall conclusions of our analysis. However, these adjusted numbers still do not capture the full extent of the losses expected from climate-induced disasters like the 2021 dzud. By 2024, all categories had rebounded and exceeded pre-drought levels, suggesting either a rapid recovery or possible overestimation in reporting. The data need to be treated with caution, however. As this discrepancy raises questions about the reliability of official statistics and underscores the need for improved monitoring and verification mechanisms, particularly during years of extreme climatic stress.

4. Discussion

4.1. Climatic, Ecological, and Economic Pressures on Pastures

Kazakhstan, located in the heart of the Arid Central Asia, which is considered to be one of the driest areas in the world with an annual mean precipitation (Pann) below 200 mm (F. Chen et al., 2008; Narisma et al., 2007; Sun et al., 2025). With climate models projecting a rise in extreme weather variability in Central Asia, including increased drought frequency and more erratic precipitation, the vulnerability of Kazakh herders is likely to intensify (Baytelieva et al., 2023; Chen et al., 2020; Kabzhanova et al., 2025; Leary et al., 2013; Spaeth et al., 2025; Yu et al., 2020). Addressing dzud and broader pasture degradation thus requires a paradigm shift from reactive to anticipatory and adaptive management, grounded in both scientific and local knowledge systems, in line with the Sendai Framework for Disaster Risk Reduction. Rising temperatures and decreasing precipitation are driving more frequent and severe droughts, which significantly threaten agricultural productivity (Salnikov et al., 2017). Research shows that understanding precipitation patterns is essential for effective drought mitigation, a lesson underscored by the severe 2021 drought in Kazakhstan, where timely meteorological data proved critical for government response and preparedness (F. Chen et al., 2008; Middleton et al., 2015b; Narisma et al., 2007; Sadrtdinova et al., 2024; Salnikov et al., 2023; Sun et al., 2025). Effective drought management depends on continuous monitoring of precipitation trends to support early warning systems and guide adaptive strategies such as water conservation, crop diversification, and drought-resistant crops.

Strengthening climate data systems and improving coordination among scientific, governmental, and local stakeholders is therefore vital for reducing vulnerability and ensuring long-term agricultural resilience. (Salnikov et al., 2017) investigated the spatial extent of droughts across regions, concluding that most of the dry months were observed in Northern, Eastern and Southern regions.

The findings from the herders' survey corroborate and deepen our understanding of the profound climatic and ecological transformations affecting Kazakhstan's rangelands. Herders consistently report altered weather patterns, warmer but more variable winters, increased frequency of droughts, and irregular precipitation events, which align closely with broader regional trends identified by climate scientists. These changing weather conditions are reshaping pasture quality, accessibility, and ultimately, livestock survival, underscoring the escalating vulnerability of pastoral livelihoods in Central Asia. Empirical climate data confirm a significant warming trend across Kazakhstan's major ecological zones, with an annual mean surface temperature in Kazakhstan increasing on average 0.31 °C per decade (Karatayev et al., 2022). This warming has intensified evapotranspiration rates and reduced soil moisture, especially in semi-desert and steppe regions, directly impairing pasture vegetation growth. Herders' observations of shorter growing seasons, earlier onset of spring greening followed by premature senescence, and delayed or disrupted grazing windows mirror the phenological shifts documented by (Kariyeva & van Leeuwen, 2011). Moreover, the variability and unpredictability of precipitation patterns reported by herders are consistent with regional findings of increased interannual rainfall variability and reductions in effective precipitation events (Baytelieva et al., 2023; de Beurs et al., 2015). Such changes exacerbate pasture degradation by limiting water availability during critical growth periods, contributing to frequent droughts and reduced forage biomass (A. Tokbergenova et al., 2018, 2025). The herders' accounts of increased ice crust formation following rain-on-snow events, which prevent grazing and cause livestock starvation, align with the emerging recognition of these climatic phenomena as key drivers of the decreased availability of forage leading to massive starvation-induced die-offs of reindeer in Arctic (Serreze et al., 2021; Turunen et al., 2016).

These climatic shifts have cascading effects on pastoral systems beyond vegetation stress. In addition to climatic drivers, social and economic factors critically influence pastoral vulnerability. Traditional seasonal mobility patterns are increasingly disrupted as the predictability of pasture availability declines. Pastoralists face difficulties in planning migrations and rotational grazing, often resulting in overgrazing of accessible pastures and abandonment of others. This undermines centuries-old herding knowledge and adaptive strategies (Davis & Wagner, 2003; Fagerholm et al., 2013; Ferret, 2016; Reid et al., 2014; Theobald et al., 2015; Turunen et al., 2016). Recent dzud events, involving compounded summer droughts along rising prices of winter forage, reduced availability of suitable pastures due to land use changes, and inconsistencies in government subsidies, present further existential threats to livestock survival and pastoral resilience. The cost and accessibility of supplementary feed during harsh winters are major concerns, often forcing herders to sell livestock at low prices or suffer losses. Effective management of winter pastures requires detailed knowledge of topography, weather patterns, vegetation composition, and strategic pasture rotation, supported by a pasture-use map compiled from geobotanical surveys and long-term observations. In winter, deep and compacted snow can make forage inaccessible, so horses must enter the season in good body condition. “Tebenevka”, the practice of pawing through snow to reach forage, is most effective when snow depth does not exceed 40 cm, or up to 50-60 cm if the snow is loose (Naimanov et al., 2018). Early in winter, low-lying areas should be avoided due to rapid snow accumulation following snowstorms; more distant pastures are utilized first, reserving those near shelters for late winter when storms and blizzards are more frequent. The most suitable tebenevka pastures are those with mixed grass and wormwood saltwater vegetation. Among the optimal forage species are various wormwoods (Artemisia spp.), grasses such as fescue (Festuca spp.), feather grass (Stipa spp.), saltworts (Salsola spp.) (Nurushev & Nurusheva, 2005). Many of these plants retain green parts under snow, while saltwort species function as naturally preserved green forage during winter. Importantly, during dzud, when grazing becomes impossible on most pastures, herders move the herds to nearby saltwort-dominated pastures, where the high salt content in the soil and plants prevents the formation of an ice crust, allowing safe grazing even during prolonged icing events. In situations where ice does form but remains thin, herders may drive the herd 500-600 meters as a dense group and then turn them 180 degrees; as the tightly packed horses move together, they break the ice crust with their hooves, allowing access to the forage beneath (Naimanov et al., 2018). However, if the ice becomes too thick for the horses to break, the herd must be provided with continuous supplemental feeding or moved to shelters to avoid serious injuries, abortions, and mass mortalities.

The interplay between climate change and land degradation exacerbates pasture conditions through feedback loops, leading to degraded soils, reduced vegetation cover, and increased local temperature extremes and dust storms, which accelerate desertification (Baytelieva et al., 2023; de Beurs et al., 2015; Gutman et al., 2020; Kaliyeva et al., 2025; Kappas et al., 2020; Kerven et al., 2016; Suleimenov et al., 2012; Tokbergenova et al., 2018, 2025; Vova et al., 2020). These shifts are embedded within what scholars describe as the Polycrisis in the Anthropocene, an era in which ecological degradation is entangled with socio-economic and political stressors, disproportionately affecting marginalized and climate-sensitive communities (Baubekova, Akindykova, et al., 2021; Lawrence, 2024; Søgaard Jørgensen et al., 2024). This cycle threatens the sustainability of Kazakhstan's rangelands and the livelihoods dependent on them. Addressing these challenges necessitates integrated approaches that combine remote sensing, climate modeling, and participatory research to capture spatial heterogeneity and local ecological knowledge. Such strategies are vital for designing adaptive interventions that promote ecological restoration and socio-economic resilience, highlighting the urgent need for policy measures that enhance forage availability, secure pasture access, stabilize subsidy delivery, and incorporate local knowledge into climate adaptation planning to ensure the viability of traditional pastoral systems in a rapidly changing environment.

4.2. Bridging Local Narratives and Historical Evidence in Rangeland Research

This study demonstrates the significant analytical and practical value of a transdisciplinary research approach that combines local knowledge, remote sensing data, and historical as well as media-based documentation to understand socio-ecological dynamics in Kazakhstan's rangelands. In highly variable and climatically stressed environments such as Central Asia's drylands, no single method is sufficient to capture the complexity of pastoral systems and their vulnerabilities. Integrating diverse knowledge sources offers a more robust, situated, and holistic understanding of landscape change and adaptive responses. Local ecological knowledge shared by herders provided critical insights into real-time challenges, such as shifting pasture productivity, increasing unpredictability in seasonal migration, and the economic constraints surrounding winter feed availability. These lived experiences contextualize and ground remote observations, highlighting not only what changed but also how and why those changes affected livelihoods (Fernández-Giménez et al., 2015; Kassam, 2009; Serreze et al., 2021). For instance, herder testimonies on relocating livestock from drought-stricken Mangystau to greener pastures in Akmola aligned with NDVI satellite records, illustrating how remote sensing data can validate and enhance local narratives.

Remote sensing tools, such as time-series NDVI, enabled us to quantitatively track vegetation dynamics across regions and years, revealing the severity and spatial extent of pasture degradation during critical drought periods (e.g., 2019 and 2021). While NDVI alone cannot explain causality or local impact, its integration with herder interviews and media sources helps interpret ecological signals in their social and political context (Eddy et al., 2017; Vrieling et al., 2011). For example, the 2021 decline in NDVI in Mangystau and Kyzylorda coincided with widely reported livestock mortality, hay price surges, and the eventual resignation of the Minister of Agriculture, events not reflected in statistical livestock records alone. Incorporating historical analysis, media coverage, and gray literature filled critical gaps left by official datasets. Despite catastrophic livestock losses during 2019 and 2021, national statistics portrayed steady growth in herd numbers. This discrepancy underscores the limitations of administrative data and points to the importance of triangulating information sources to construct a more accurate picture of rural livelihoods and crisis events (Scoones, 2009). Media narratives, including presidential statements and emergency declarations, provided essential context to interpret policy failures and institutional responses (or lack thereof), highlighting governance dynamics in pastoral risk management.

Moreover, the transdisciplinary method fosters knowledge co-production, an increasingly recognized necessity in climate resilience research. By engaging multiple forms of expertise, from satellite analysts to pastoralists, it helps develop solutions that are not only scientifically sound but also locally relevant and socially legitimate (Lang et al., 2012; Tengö et al., 2014). In Kazakhstan's case, where historical legacies of sedentarization, market liberalization, and state withdrawal continue to shape land use, such approaches are critical to designing adaptive strategies that are responsive to both ecological realities and social constraints. Ultimately, this study underscores that understanding pastoral vulnerability under climate change requires more than data, it requires dialogue across disciplines, scales, and knowledge systems. Transdisciplinary research is not merely additive but synergistic, allowing for deeper insight, stronger validation, and more actionable outcomes in rangeland sustainability and policy design.

4.3. Uncertainty and limitations

Despite the strengths of this transdisciplinary approach, several limitations must be acknowledged. The official livestock statistics do not always reflect on-the-ground realities. For example, mass mortality events during the 2019 and 2021 droughts were not clearly visible in national-level data, likely due to a combination of increased livestock registration following disasters, the low cost of electronic chips, and the availability of compensation for officially registered animals. As a result, post-crisis increases in livestock numbers may represent improved documentation practices rather than genuine herd recovery.

While NDVI is a widely used proxy for vegetation productivity, it does not fully capture pasture quality or ecological suitability for grazing. This is especially evident in Mangystau region, where interviewed herders emphasized that even in years with moderate NDVI values, the dominant vegetation during droughts consists of sparse, unpalatable, and sometimes toxic plants such as adraspan (Peganum harmala). Although this plant may register as "green cover" in remote sensing imagery, it has no forage value and is sometimes even harmful to livestock, while being valued mainly for its spiritual or ritual significance. This mismatch highlights the need for caution in interpreting satellite data without ground verification.

We acknowledge that the limited sample size of the herder survey imposes a constraint on generalizability. While the sample was sufficient for understanding perceptions, awareness, and openness to collaboration, future studies should expand data collection to include a broader and regionally differentiated population. Doing so will allow for the development of more nuanced vulnerability indices and support better-targeted policy interventions.

5. Conclusion

This study demonstrates that a transdisciplinary approach, linking herders' traditional ecological knowledge, remote sensing analyses, and historical and media documentation, provides a more comprehensive understanding of rangeland dynamics and pastoral vulnerability in Kazakhstan, particularly under conditions of increasing climatic stress such as summer droughts and severe winter dzud events. By showing how herder observations of shifting pasture productivity, livestock losses, and adaptive movements align with NDVI trends while simultaneously revealing discrepancies in official livestock statistics, the research highlights the analytical value of integrating diverse knowledge systems and the limitations of relying on any single method. These cross-method linkages substantiate pastoralists' experiential insights, clarify the socio-political context of drought impacts, and expose institutional blind spots that shape risk and response. The findings underscore that effective adaptation and policy design depend on the co-production of knowledge that is scientifically robust, locally grounded, and attentive to governance dynamics. Beyond Kazakhstan and Central Asia, this approach offers a model for farming and pastoral communities globally, emphasizing that resilience in climate-sensitive systems requires synthesizing scientific data with lived experience to inform responsive and inclusive management strategies.

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