

Hankerson, Brett R.

Doctoral Thesis

Pasture, grazing, and meat production in Kazakhstan

Suggested Citation: Hankerson, Brett R. (2025) : Pasture, grazing, and meat production in Kazakhstan, Humboldt-Universität zu Berlin, Berlin, <https://doi.org/10.18452/34649> , <http://edoc.hu-berlin.de/18452/35289>

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Pasture, grazing, and meat production in Kazakhstan – current state and future opportunities

DISSERTATION

zur Erlangung des akademischen Grades
Doctor rerum naturalium (Dr. rer. nat.)

im Fach Geographie

eingrichtet an der
Mathematisch-Naturwissenschaftlichen Fakultät
der Humboldt-Universität zu Berlin

von

Brett Robert Hankerson, M.Sc.

Präsidentin der Humboldt-Universität zu Berlin
Prof. Dr. Julia von Blumenthal

Dekan der Mathematisch-Naturwissenschaftlichen Fakultät
Prof. Dr. Emil List-Kratochvil

Gutachter:

Prof. Dr. Patrick Hostert
Prof. Dr. Dr. h.c. Norbert Hölzel
Prof. Dr. Friedhelm Taube

Eingereicht am: 25. März 2025

Datum der Promotion: 8. September 2025

Acknowledgments

I have had the pleasure and the privilege of working with fantastic people at the Leibniz Institute of Agricultural Development in Transition Economies (IAMO). My supervisor, Daniel Müller, gave me the opportunity to check all the boxes of my graduate research goals: study the geography of agriculture using remote sensing in a former eastern bloc country at a top European university. Daniel provided me with the tools I needed to succeed, and the freedom to develop and adapt my research to the most relevant and interesting topics. I am forever grateful for the many field trips that allowed me to dive deep into Kazakh agriculture and understand on the ground level the questions I was trying to answer with satellites. Thank you, Daniel, for sticking with me through the lean years, when it was not at all clear if I would ever finish.

Alfons Balmann, I thank you for the opportunities I received through my scholarship at IAMO and the freedom you granted me in pursuing my research interests, it was a great pleasure to be a part of the Department of Structural Change. Florian Schierhorn, often my travel companion and co-conspirator in Kazakh agricultural research, thank you for your many contributions and thoughts that helped shape both my research questions and their answers. Similarly, Sasha Prishchepov, thank you for helping me in my early days, honing my scientific focus and enhancing our field trips to Kazakhstan with your local knowledge and contacts. In Kazakhstan, I want to thank Dauren Oshakbaev, often the organizer of our activities, research partner, translator, and tour guide all rolled into one outstanding colleague. Also from Kazakhstan, but who quickly became a fellow student and fast friend, I want to thank Andrey Dara, first for your help and enthusiasm on our field trips, and later for your friendship and collaboration as we developed our dissertations around very similar topics.

Fellow coauthors: I want to thank Changxing Dong, without whose coding expertise I wouldn't have been able to develop the final model for our first paper. Also from that paper, I want to thank Christina Eisfelder for doing all the hard work in determining grassland productivity in Kazakhstan. From my second paper, I would've been lost without the natural processes knowledge of Tobias Kümmerle and the local grassland expertise of Johannes Kamp, thank you.

I also want to thank my first student assistant, Alina Drokina, whose tireless efforts digitizing handwritten statistics and compiling annual bulletins allowed the breadth and depth of Kazakh data utilized in my research. Also instrumental in data collection, I want to thank Max Hofmann for your expertise in R and similar research interests, helping to keep me invested during the lean years. I managed to keep the IT department pretty busy with my numerous and occasionally impudent requests, thank you especially to Tim Illner for always keeping me connected and updated.

My time in Halle was a wonderful period of my life. Besides the incredible travel opportunities that my research afforded me, I was also blessed with the opportunity to travel to my new friends' home countries. I will never forget those trips, and those I took them with. It wasn't all just traveling, either: in Halle lifelong

friends were made during weekend grill-outs, game nights, movie nights, Super Bowl parties, Thanksgiving dinners, and all manner of social get-togethers. If I begin naming everyone now, I won't know where to stop, and so I'm going to do a very annoying thing and say: you know who you are, thank you! I do need to name Lena Kuhn, Vasyl Kvartiuk, and Boris Rajković, exceptional friends who have graciously lent me their couches while I finished this dissertation.

The most recent acknowledgments belong to Patrick Hostert, Norbert Hölzel, and Friedhelm Taube, who have kindly agreed to review this dissertation, thank you.

Abstract

The dramatic increase of demand meat and animal products has placed a strain on land resources and created a livestock sector that is responsible for one fifth of all anthropogenic greenhouse gas emissions and is associated with desertification, deforestation, water contamination, and the loss of wild grazers, biodiversity, and ecosystem services. However, quantifying this strain on land resources remains difficult, as livestock are mobile and grazing is a spectrum. This dissertation focuses on a country with a long history of pastoralism that has undergone dramatic changes in the last century. Kazakhstan has one of the world's largest grassland areas and supports a large livestock population that has fluctuated greatly from early transhumant nomadism, to sedentary pasturing of the Soviet Era, to a partial return of migratory pasturing post-Soviet. Livestock numbers peaked near the end of the Soviet period, plummeted in the 1990s, but have seen steady increase since. Ample evidence of overgrazing during the Soviet Era exists, however with livestock movement severely restricted, many distant pastures fell out of use, and the actual carrying capacity of Kazakh grasslands is poorly understood. With the current expansion of the livestock industry—especially beef—it is crucial that (re)utilization of Kazakhstan's immense grassland reserves is sustainable. A key factor to maintain biodiversity and ecological functions on grasslands is recurrent fire events. Grazing is an important determinant of fire regimes, but the relative magnitude in comparison to climatic factors is poorly understood. The historical context of livestock in Kazakhstan provides an excellent setting to study the effect of grazing on fire occurrence over time.

In the first part of this dissertation, I present a spatial model developed to assess the extent and the intensity of grazing demand by livestock. In Kazakhstan 2015, about half of available pasture was utilized, but most at low intensities. A 31% increase in beef production could be possible without improved infrastructure or intensification practices. In the second part, I correlated the annual change in grazing intensity of the grasslands utilized by livestock with annual burned area over the period 2001-2019, accounting for changes in temperature, precipitation, growing degree days, and relative humidity. There was a clear and negative relationship between grazing demand and burned area. Grazing demand also had more explanatory power in burned area than any of the climate variables tested. In the third part, I explored the potential of horsemeat as an alternative to beef. Nutritionally, horsemeat is the best red meat in almost every way, with a similar taste and texture to beef, and compares favorably to the major white meats (pork and chicken). Additionally, raising horses instead of cattle for meat production would drastically reduce the amount of methane released per kilogram of meat produced. However, horses require more land area, and a full conversion would likely coincide with a reduction in meat consumption. In summation, Kazakhstan has a large potential for pasture-based livestock expansion, a coordinated expansion of grazing livestock could be an excellent strategy for mitigating fire risk, and the most appropriate livestock species to fulfill both roles are horses, due to their mobility, hardiness, meat characteristics, and environmental footprint.

Zusammenfassung

Der dramatische Anstieg der Nachfrage nach Fleisch und tierischen Produkten hat den Druck auf die Landressourcen verstärkt und dazu beigetragen, dass die Tierproduktion für ein Fünftel aller anthropogenen Treibhausgasemissionen verantwortlich ist und zu Wüstenbildung, Abholzung, Wasserverschmutzung, und dem Verlust von Wildweidetieren, Artenvielfalt und Ökosystemdienstleistungen beigetragen hat. Allerdings ist es weiterhin schwierig, den Fußabdruck der Tierproduktion zu quantifizieren, da Weidetiere meist mobil sind und in unterschiedlicher Intensität beweiden. Diese Dissertation konzentriert sich auf Kasachstan, ein Land mit einer langen Geschichte des Pastoralismus, das im letzten Jahrhundert dramatische Veränderungen durchgemacht hat. Kasachstan verfügt über eine der größten Grünlandflächen der Welt und beherbergt einen großen Viehbestand, der sich vom frühen Transhumant-Nomadentum über die sesshafte Weidehaltung in der Sowjetzeit bis hin zu einer teilweisen Rückkehr der wandernden Weidewirtschaft nach der Sowjetzeit wandelte. Der Viehbestand erreichte gegen Ende der Sowjetzeit seinen Höhepunkt, ging in den 1990er Jahre stark zurück und stieg seitdem wieder an. Es gibt zahlreiche Beweise für Überweidung während der Sowjetzeit, aber da die Bewegung des Viehs stark eingeschränkt war, wurden weiter entfernte Weiden nicht genutzt. Außerdem ist die tatsächliche Tragfähigkeit des kasachischen Graslandes kaum bekannt. Angesichts der derzeitigen Expansion der Viehwirtschaft in Kasachstan – insbesondere des Rindfleischsektors – ist eine nachhaltige (Wieder-)Nutzung der immensen Grünlandreserven Kasachstans von entscheidender Bedeutung. Ein Schlüsselfaktor für die Erhaltung der Artenvielfalt und der ökologischen Funktionen von Grünland sind wiederkehrende Brände. Die Beweidung ist eine wichtige Determinante des Brandregimes, aber das relative Ausmaß im Vergleich zu klimatischen Faktoren ist nur unzureichend verstanden. Der historische Kontext der Viehwirtschaft in Kasachstan ermöglichen es die Auswirkungen der Beweidung auf das Auftreten von Bränden im Laufe der Zeit zu untersuchen.

Im ersten Teil dieser Dissertation stelle ich ein räumliches Modell vor, das entwickelt wurde, um das Ausmaß und die Intensität der Weidenachfrage durch das Vieh zu erfassen. In Kasachstan wurde 2015 etwa die Hälfte der verfügbaren Weideflächen genutzt, meist aber mit geringer Intensität. Eine 31% Steigerung der Rindfleischproduktion wäre ohne verbesserte Infrastruktur oder Intensivierungspraktiken möglich. Im zweiten Teil korreliere ich die jährliche Veränderung der Weideintensität der von Tieren genutzten Grünlandflächen im Zeitraum 2001-2019 mit der jährlichen verbrannten Fläche unter Berücksichtigung von Änderungen in Temperatur, Niederschlag, Wachstumsgradtage und relativer Luftfeuchtigkeit. Es bestand ein klarer und negativer Zusammenhang zwischen der Weidenachfrage und der verbrannten Fläche. Ich stellte außerdem fest, dass die Nachfrage nach Weideflächen eine größere Erklärungskraft für das Ausmaß der verbrannten Fläche hat als jede der getesteten Klimavariablen. Im dritten Teil untersuchte ich das Potenzial von Pferdefleisch als Alternative zu Rindfleisch untersucht. Aus ernährungsphysiologischer Sicht ist Pferdefleisch in fast jeder Hinsicht das beste rote Fleisch, es hat einen ähnlichen Geschmack und eine

ähnliche Textur wie Rindfleisch und schneidet im Vergleich zu den gängigen weißen Fleischsorten (Schwein und Huhn) gut ab. Darüber hinaus würde die Haltung von Pferden anstelle von Rindern zur Fleischproduktion die Menge an Methan, die pro Kilogramm produziertem Fleisch freigesetzt wird, drastisch reduzieren. Pferde benötigen jedoch mehr Landfläche, und eine vollständige Umstellung würde wahrscheinlich mit einer Reduzierung des Fleischkonsums einhergehen.

Zusammenfassend lässt sich sagen, dass Kasachstan über ein großes Potenzial für die Ausweitung der Weideviehhaltung verfügt. Eine koordinierte Ausweitung der Weideviehhaltung könnte eine hervorragende Strategie zur Minderung des Brandrisikos sein. Die am besten geeignete Nutztierart zur Erfüllung dieser beiden Aufgaben sind Pferde aufgrund ihrer hohen Mobilität und Widerstandsfähigkeit, der ausgezeichneten Fleischeigenschaften und ihres geringen ökologischen Fußabdrucks.

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Chapter 1: Introduction

1.1 Scientific background

1.1.1 Grasslands and pasture

Grasslands account for more than a quarter of the earth's ice-free land cover, constitute four of the consensus 14 biomes, and are among the most at-risk biomes due to habitat conversion and degradation, which has caused a perilous loss in biodiversity and ecological functioning (Dinerstein et al., 2017; Hoekstra et al., 2005). Agriculture is the dominant, driving force behind much of the conversion of grasslands, as eons of grasses perennially dying and decaying has nurtured fertile soil that is comparatively easy to cultivate (Küster & Keenleyside, 2009). This ease of cultivation, and necessity of agriculture to feed a population that could reach 9 billion by 2050 has allowed a couple of convenient misconceptions to persist and proliferate (Godfray et al., 2010). One, that grasslands are not as biodiverse and do not provide as many ecosystem services—and are therefore not as important—as forested biomes, which receive much more public attention and sustainability policies (Bardgett et al., 2021; Parr et al., 2014). Two, that grasslands are not a “natural state”, as forests can easily grow in the same environment and are often considered (erroneously) the climax of ecological succession, only prevented by man's use of fire. Thus, old-growth grasslands have been targeted for “reforestation” when ample evidence exists that these grasslands have persisted *in situ* and have shaped the evolution of flora and fauna for millions of years (Bond, 2016).

Due to the nature of grasslands—relatively short vegetation, subdued topographical features—many of the iconic fauna of the biome are long-ranging grazers and raptors that require large, intact areas for migration and hunting. Conversion to croplands has fragmented many of the world's grasslands, impairing their ability to be homes to these iconic creatures, a characteristic of the biome that is often overlooked and undervalued in the face of agricultural pressure and lack of awareness (Scholtz & Twidwell, 2022).

Grasslands are also undervalued as carbon sinks. Forests get all of the attention as potential carbon sequesterers despite there being nearly 50% more carbon in the world's grasslands than in forests. Measurement and, equally importantly, visualization of carbon sequestration on grasslands is more difficult, however the potential for degraded grasslands to act as carbon sinks is on the same order as forestry. Improved grasslands have greater biomass productivity, resiliency, and carbon-storing capacity, exemplifying win-win scenarios in low-income regions, where many of the world's grasslands are located and where many of the population rely on livestock for subsistence and livelihood (Conant, 2010).

For as long as there have been grasslands, there have been animals grazing (Taylor, 2024). There are many land cover/land use terms used to describe the spectrum of relationship between grazers and grass. Grassland, pastureland, rangeland, and grazing land are all very similar terms that are often mixed and used interchangeably. This is partly due to the problem of delineating the area utilized by grazers. Determining the definition of “utilized” is difficult: how long, how often, and how intensively land must be grazed to be

considered grazed (Sayre et al., 2017). Grassland is considered a land cover, while pasture- and grazing land are land uses. Rangeland is typically considered a land cover where grazing could occur, but is also used as a term for grazed native grasslands to differentiate from sown pastureland. Unlike grass- and pastureland, range- and grazing land can encompass non-grasslands—shrubland, wetland, woodland, tundra, and semi-desert (Allen et al., 2011). Regardless of the terminology used, determining the extent and intensity of the utilization of land by livestock is difficult (Ramankutty et al., 2008).

1.1.2 Livestock

While defining and delineating pasture is difficult, keeping track of the number of animals utilizing pasture is relatively easier (Figure 1-1). Cattle, goats, and, on smaller scales, buffalo and camels, have all seen steady increases in numbers over the last 60 years. Sheep numbers have fluctuated, but are now higher than ever. Of the grazing livestock included in FAO statistics, only horses and horse crosses (mules and hinnies) have decreased in number since 1961. This can mostly be attributed to the decrease in demand for draft animals (Pearson, 1998).

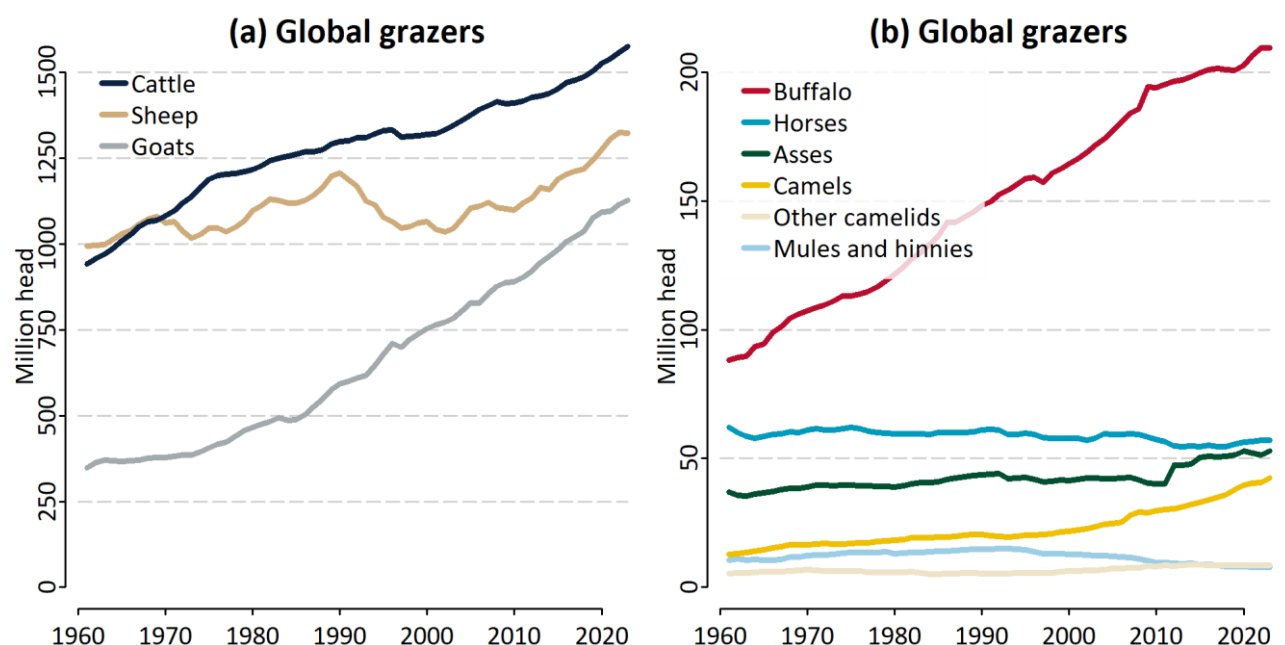


Figure 1-1. Global population of livestock species that obtain energy primarily through forage and fodder, 1961-2023 (FAO, 2025). (a) The three main grazing species. (b) Minor grazing livestock species. Other camelids include llamas and alpacas. Note the scale.

As the global human population has increased, the distribution of wealth has shifted, with some developing countries becoming more affluent and demanding a larger proportion of meat in their diets (FAO, 2023b). This has driven the increase in meat production over the last 60 years (Figure 1-2). In the 1960s and 1970s, beef and pork were produced at nearly equal quantities at the global scale. Beef production increases began to tail off in the 1980s, with pork taking the clear lead in production quantity until the mid-2010s, when African Swine Fever devastated populations in Asia and Europe (Penrith, 2020). Over the last 60 years, chicken has seen the most dramatic upswing in production, and recently overtook pork as the largest meat production sector in the world. Duck, turkey, and goose are often combined with chicken as the

poultry sector. Frequently combined as closely related caprines, sheep and goat often co-occur. Cattle and buffalo are closely related bovines that can also be combined, though they do not often co-occur. Though very important in the few regions where they are raised for meat, equids and camelids (mainly horses and camels, respectively) are not major players at the global scale. Though not expressly defined, game meat likely includes a high proportion of grazing animals, as many deer species are popular hunting targets and are even farmed as a specialty meat in many regions (Serrano et al., 2019).

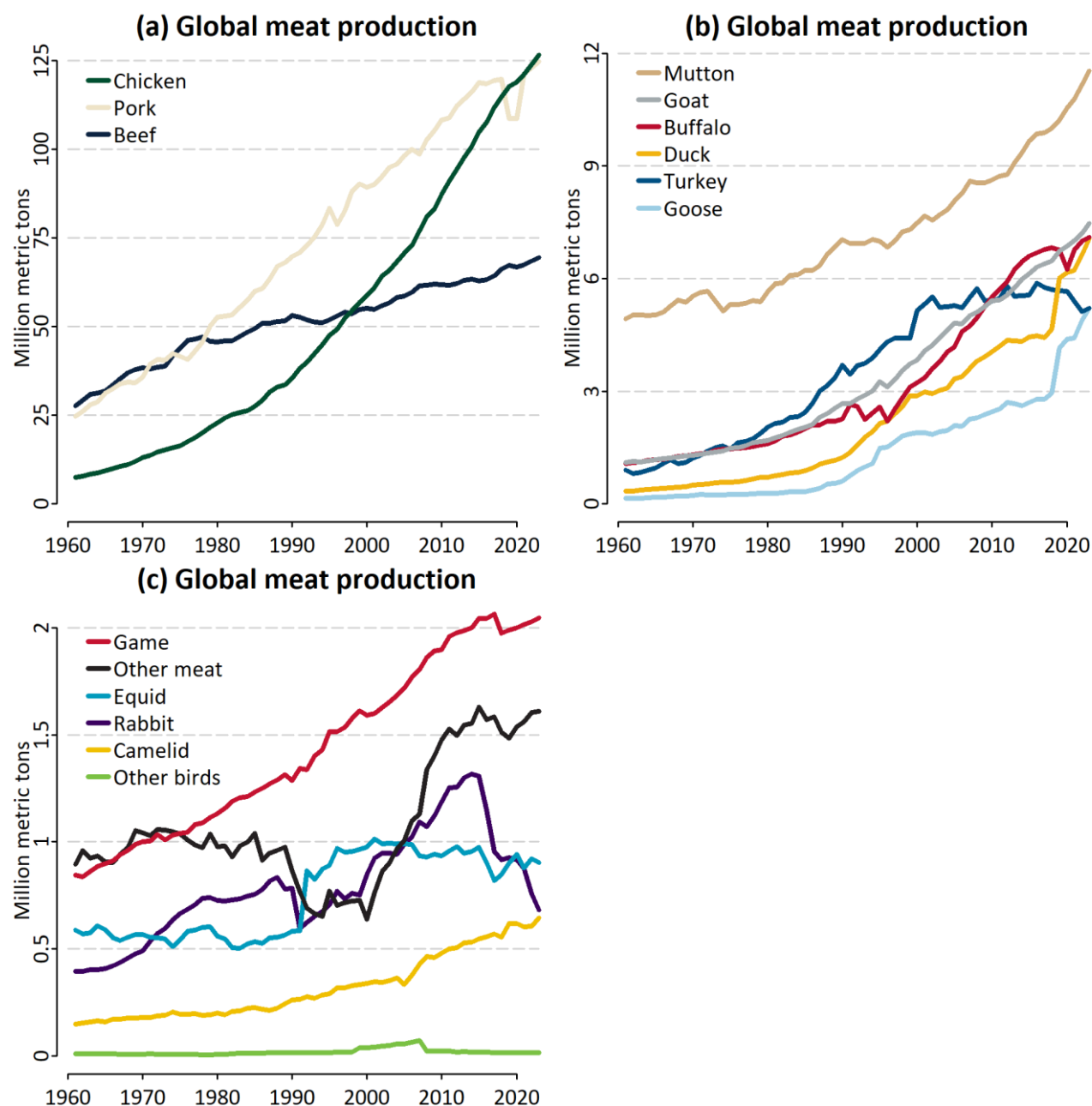


Figure 1-2. Global production of meat, 1961-2023 (FAO, 2025). (a) The three main sources of meat. (b) Secondary sources of meat. (c) Minor sources of meat. Other meat includes rodent and snail. Equid includes horse, ass, and mule. Camelid includes camel, llama, and alpaca. Other birds include but are not limited to parrots, pheasants, and pigeons. Note the scale.

Despite falling to a distant third, steady growth in the beef sector has kept beef production at the forefront of sustainability awareness. In a multitude of metrics, beef is the most inefficient of the major meats: poultry, pork, beef, and mutton/goatmeat. Cattle are much less efficient than poultry or pigs at turning

feed energy into meat (Hou et al., 2016), and account for three fourths of all non-CO₂ greenhouse gas emissions from livestock production, mainly due to methane from their ruminant digestive system (Dunkley & Dunkley, 2013; Herrero, Havlík, et al., 2013). However, cattle and other grazers have one major advantage over poultry and pigs: they obtain the majority of their energy from forage, which can be grown on land that is otherwise unsuitable for agriculture. Thus, grazing livestock provide human-edible food from land otherwise incapable of being a food or energy source (van Zanten et al., 2018).

1.1.3 Study region

Stretching 8000 km from central Europe to northeast China, the Eurasian steppe is a vast grassland biome that is vital to the agricultural economies of the countries it spans. Dryland agriculture supports primarily small grains and grazing livestock. The steppe has been home to transhumant pastoralism for millennia, with significant and established herds of sheep, goats, cattle, horses, camels, and yaks. Wild grazers are also a major feature, with important populations of Przewalski's horse (*Equus ferus przewalskii*), wild ass (*Equus hemionus*), saiga antelope (*Saiga tatarica*), goitered gazelle (*Gazella subgutturosa*), Mongolian gazelle (*Procapra gutturosa*), wild camel (*Camelus bactrianus*), and mouflon (*Ovis orientalis*) (Wesche et al., 2016). Many ecoregions subdivide the Eurasian steppe, with one of the largest falling mostly within the borders of Kazakhstan and, predictably, is called the Kazakh steppe, where several factors make it a very interesting region to study. First, the Kazakh steppe is huge and largely uninterrupted, covering 808,000 km², which places it among three largest temperate grassland ecoregions in the world along with the Mongolian-Manchurian grassland (889,000 km²) and the Pontic steppe (997,000 km²)—both also members of the Eurasian steppe (Dinerstein et al., 2017). Second, in recent history livestock populations within Kazakhstan have fluctuated greatly. While part of the Soviet Union, Kazakhstan underwent substantial land-use conversion to crop cultivation, and livestock production became largely sedentary. During this period livestock numbers skyrocketed, and overgrazing caused degradation and desertification of grasslands (Robinson et al., 2003). The breakup of the Soviet Union in 1991 precipitated a collapse in the Kazakh livestock sector, with livestock numbers decreasing by 70% within a decade (KazStat, 2019). There has been steady growth in livestock numbers since then, providing a natural experiment of huge swings in livestock numbers and dynamic shifts in grazing practices over a relatively short time period. Given the substantial land resources, and the governmental focus on livestock development (The World Bank, 2020), it is an ideal time to identify areas of interest and gaps in the knowledge record.

The eastern and southeastern border of Kazakhstan runs along the edge of the Altai (at the convergence of China, Kazakhstan, Mongolia, and Russia) and Tien Shan (running through Kyrgyzstan and into China) mountain ranges (Figure 1-3). Ecosystems along these borders differ greatly from the majority of Kazakhstan, receiving the highest annual precipitation amounts that support forests and alpine meadows (Figure 1-4). In the south, the climate quickly turns dry traveling west. The Chu, Syr Darya, and Amu Darya rivers support extensive irrigated agriculture producing a variety of fruits, vegetables, and nuts. However,

while Almaty and Shymkent receive upwards of 600 mm/year precipitation, nearby Taraz and Turkistan receive only 350 mm/year and 200 mm/year, respectively, and the montane climate quickly transitions to semi-desert and eventually desert to the west and southwest, with less than 100 mm/year in the Kyzylkum Desert, located between the Amu Darya and Syr Darya. Moving north, precipitation increases gradually across the country (excepting the aforementioned eastern and southeastern border) to over 350 mm/year in Petropavl (Climate Research Unit, 2019). Northcentral Kazakhstan is home to conventional rainfed agriculture, predominately wheat and fodder crops. Livestock are found throughout the country (FAO classifies nearly 70% of the country as “permanent meadows and pastures”) (FAO, 2024), with the highest concentration in the fertile foothills of the Tien Shan. Cattle, sheep, goats, and horses are all ubiquitous and grown for meat, dairy, and other products. Camels are also an important food source in the drier regions of the south and southwest (KazStat, 2019).



Figure 1-3. Topography of Kazakhstan in Central Asia with major water features and cities with over 100,000 residents (European Space Agency & Sinergise, 2021; GADM, 2022; Geofabrik, 2024; KazStat, 2011).

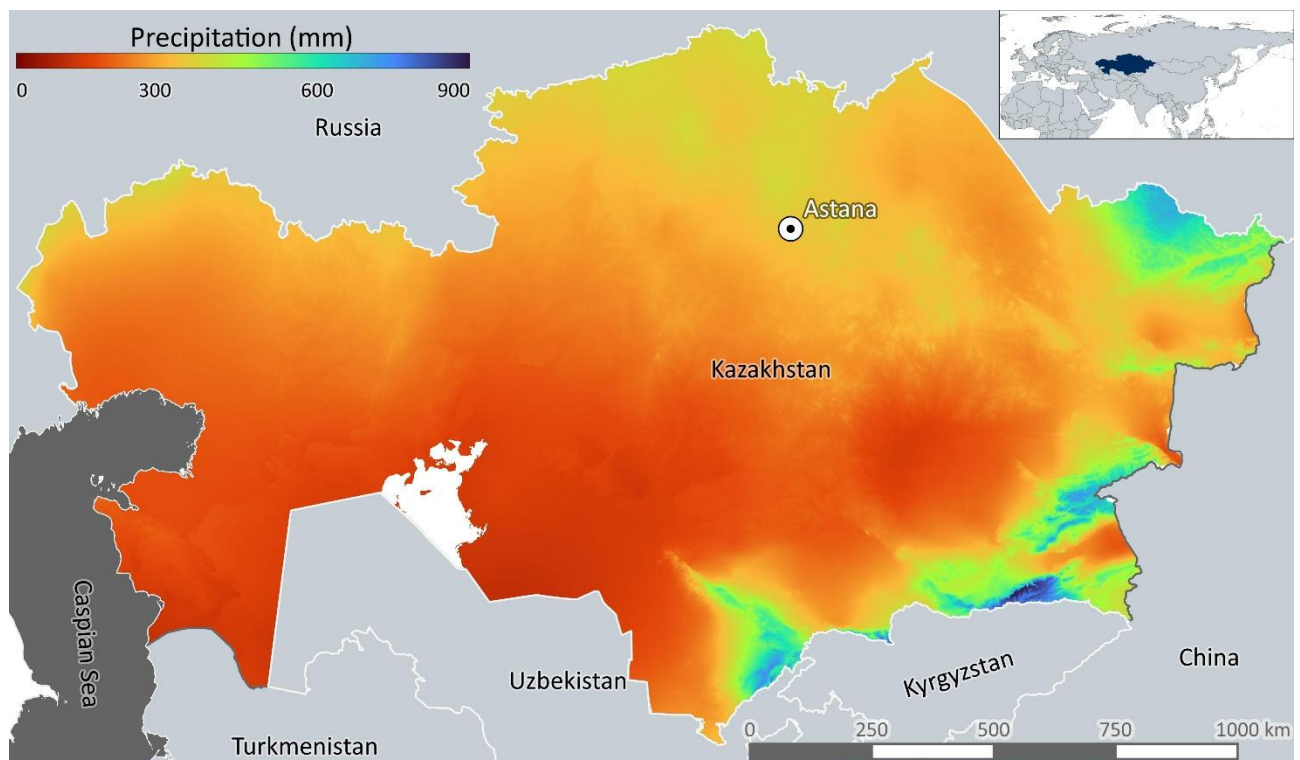


Figure 1-4. Average annual precipitation of Kazakhstan (de Pauw, 2008; GADM, 2022).

1.1.4 Livestock in Kazakhstan

While cattle, sheep, goats, and horses are found in nearly every district of Kazakhstan, and often share pasture, there are distinct niches that the different species occupy at more local scales. Cattle are the breadwinners that receive the choicest grass, either near human settlements or shepherded to seasonal pastures. Cattle almost exclusively graze on grass, but are relatively unconcerned about the quality of grass. They use their tongues to rip easily accessibly grasses, often leaving behind short, young, more nutritious grass. Sheep and goats are not as mobile as cattle, but are sure-footed and occupy more marginal pastures, either degraded lands surrounding settlements or more montane pastures inaccessible to cattle. Sheep are picky grazers in the sense that they seek out highly nutritious grasses and can nibble them to the roots. When an area is overgrazed by sheep this can be devastating, but in a healthy rotation sheep are able to utilize quality grass that cattle leave behind. Goats are the least picky grazers, willing to munch on just about any type of plant. Thus, they can be destructive when left in a private yard or garden, but in a pasture, goats are able to utilize foliage that is snubbed by the other grazers. Horses are the most mobile and often range great distances from their point of origin, accessing a variety of pastures beyond the range of cattle, sheep, and goats. Like sheep, horses are picky grazers that seek high-quality grasses and can chew grasses down to their roots. Unlike sheep, horses are highly mobile, so unless they are confined overgrazing is less of a threat (Goodwin, 2007; Koshkina et al., 2022; Osoro et al., 2015).

The different species also occupy distinct economical niches. Products from cattle are considered the most valuable, both beef and dairy, and receive the majority of governmental stimuli (Robinson et al., 2021). Sheep meanwhile are physically smaller, relatively cheaper, and are the most numerous of Kazakhstan's

livestock. Lamb is a common meat, and mutton is also found from the rural villages to the city supermarkets. Sheep milk is drunk in the countryside and their cheese is popular everywhere. Sheep also have the added value of wool production. The main economic benefit of goats is that they can produce human food out of plants eschewed by other grazers. Goatmeat is not particularly prized, though it can be found in most meat markets. Goat milk and especially goat cheese, however, is quite popular. Horses are treated somewhat like goats in the economic sense, they are able to turn otherwise inaccessible biomass into human food (Taylor et al., 2020). However, horses have the added benefit of being a culturally significant and historically traditional food source (Malacarne et al., 2002). Mare milk is fermented into the traditional drink *kumys*, and horsemeat is found in every butcher shop and in most restaurants.

1.1.5 Grazing and grassland fires

Fire is a natural phenomenon that is integral to the health and functioning of grasslands (Bhagwat et al., 2023). It can also be devastating to livestock, consuming entire herds if there are no means of escape or shelter. Kazakhstan has experienced several periods of unusually high fire occurrence since the breakup of the Soviet Union. Climate variables are always an enabling factor with naturally-occurring fires, and climate change has led to an increase in extreme weather events worldwide (Newman & Noy, 2023), but the sudden and repeated increases in frequency and extent in Kazakhstan warrant investigation.

The biophysical characteristics of grazing—biomass removal, plant damage, soil compaction, riverbank erosion, manure fertilization—change the community structure of a grassland ecosystem (Milchunas et al., 1988). Livestock grazing is generally understood to be a mitigating factor in fire occurrence—their consumption of fuel overshadows any potentially exacerbating feature of animal husbandry. However, the degree to which livestock grazing contributes to fire mitigation has historically been difficult to determine, partially due to the fact that in order to determine the magnitude, a very large, intact grazing area that experiences regular fires would have to be subjected to increases and decreases in livestock numbers that vary over space and time. The large-scale, widespread, and most importantly, well-documented changes in livestock numbers and grazing practices in Kazakhstan over the last several decades—the first at such a scale—provide ample data and opportunity to explore the extent to which livestock grazing can promote or stifle fire occurrence and burned area extent.

1.2 Conceptual framework

The overarching goal of this dissertation is to advance the knowledge and understanding of land use, especially pastureland use, in Kazakhstan. Extent, grazing intensity, productivity, accessibility, and species distribution are all vital aspects of determining the current and future prospects for livestock production and grazing in Kazakhstan. These aspects are explored by 1) developing a fine-scale, spatiotemporal model for livestock distribution and 2) assessing the environmental externalities of livestock production with regard to changes in grazing intensity and species distribution.

1.2.1 Research questions and objectives

1.2.1.1 Question I: Where, and to what extent, could increases in Kazakh livestock production take place?

Determining the land use footprint of livestock is historically difficult. Satellite imagery has been used for decades to accurately map cropland use, however pastures lack the clearly defined boundaries and changes in spectral reflectance that make cropland easy to detect (Shelestov et al., 2017; Yan & Roy, 2014). Additionally, “use” is a matter of degree much more in pastureland than in cropland, as frequency, length, and intensity can all vary greatly on land classified as pasture (Kuemmerle et al., 2013). Moreover, to allocate livestock on pasture provides an additional quandary, as livestock may be housed in feedlots, fenced pastures, or nomadically grazed across hundreds of square kilometers. In Kazakhstan it is typical for all three styles of grazing practices to exist in the same area.

1.2.1.1.1 Objective I: develop a spatial model using fine-scale inputs to allocate livestock in Kazakhstan based on the predominating local grazing practices.

Before the spatial distribution of livestock in Kazakhstan can take place, several inputs are needed. Livestock numbers, herd dynamics, energy requirements, and energy provided by feed and fodder were used to determine grazing demand. Land cover, net primary productivity, and plant species energy content were used to determine grazing supply. Settlement locations were used as a starting point in a search algorithm designed with knowledge of the local grazing practices to estimate the extent and off-take rate of pasture in Kazakhstan.

1.2.1.2 Question II: To what extent are livestock in Kazakhstan actors in fire regimes?

Fire is an integral part of grassland ecosystems, and human activities have altered the natural fire regimes with diverse and diverging effects (Bowman et al., 2011). In Kazakhstan, fire occurrence is widespread, but spatially and temporally varied, and does not appear to be well-explained by climate patterns (Y. Xu et al., 2021). Additionally, livestock numbers have fluctuated greatly over time and space, providing a unique natural experiment to study the links between fire, grazing, and climate variables.

1.2.1.2.1 Objective II: analyze the correlation between livestock grazing demand and burned area extent compared to the traditional climate variables of precipitation, temperature, relative humidity, and growing degree days.

A binomial generalized linear mixed-effects model was used to regress the predictors against the observed values of burned area (Bolker et al., 2009; Warton & Hui, 2011). Akaike Information Criterion was calculated to determine model strength, as well as conditional and marginal R^2 . Since none of the climate or livestock variables occur in a vacuum, interrelations were explored as well, namely with additive, interactive, and quadratic models.

1.2.1.3 Question III: is there a path to sustainable livestock development in Kazakhstan?

In Kazakhstan, like most countries, beef is king. Despite beef currently coming in a distant third in global consumption to chicken and pork, cattle are the standard of wealth for livestock owners in developing countries (Herrero, Grace, et al., 2013). The meat itself is also a driving force behind beef's proliferation, none of the other major meats can easily replace beef's taste and texture. Unlike chicken and pork, beef can be produced on land otherwise unsuitable for human food production, but by many metrics beef is an extraordinarily inefficient source of protein (Hou et al., 2016). What is needed is a more environmentally-friendly source of meat that can still be produced by grazing the earth's vast grassland resources.

1.2.1.3.1 Objective III: explore the potential for the return of a historically popular and gastronomically similar meat in order to at least partially replace beef as the red meat of choice.

Horses were one of mankind's earliest known sources of meat (Taylor, 2024). The current taboo surrounding hippophagy needs to be reevaluated. The environmental externalities of greenhouse gas emissions and land use were evaluated, especially in comparison to beef production. However, all the environmental arguments mean nothing if horsemeat is not desirable as a dish, thus the nutritional characteristics were also evaluated in comparison to beef and other red meats.

1.3 Structure of the thesis

This thesis consists of five chapters. Chapter 1 introduces the core three Chapters 2-4, which address the aforementioned three objectives, and Chapter 5 synthesizes the results and conclusions presented and looks toward the future landscape of livestock, meat production, land use, and grassland ecosystems. Chapters 2-4 were written as independent manuscripts for peer-reviewed journals, and as such have only minor formatting alterations from their published or submitted versions:

- Chapter 2 Hankerson, Brett R., Florian Schierhorn, Alexander V. Prishchepov, Changxing Dong, Christina Eisfelder, Daniel Müller (2019). Modeling the spatial distribution of grazing intensity in Kazakhstan. PLOS ONE, 14 (1), e0210051.
- Chapter 3 Hankerson, Brett R., Florian Schierhorn, Johannes Kamp, Tobias Kuemmerle, Daniel Müller (in review). Changes in livestock systems explain post-Soviet fire trends on the Eurasian steppe better than climate. Regional Environmental Change.
- Chapter 4 Hankerson, Brett R., Daniel Müller (in review). The other red meat: environmental and nutritional advantages of horsemeat over beef and other red meats. Nature Food.

Chapter 2:

Modeling the spatial distribution of grazing intensity in Kazakhstan

PLOS ONE, 2019, Volume 14, Issue 1

Brett R. Hankerson, Florian Schierhorn, Alexander V. Prishchepov, Changxing Dong, Christina Eisfelder,
Daniel Müller

Abstract

With increasing affluence in many developing countries, the demand for livestock products is rising and the increasing feed requirement contributes to pressure on land resources for food and energy production. However, there is currently a knowledge gap in our ability to assess the extent and intensity of the utilization of land by livestock, which is the single largest land use in the world. We developed a spatial model that combines fine-scale livestock numbers with their associated energy requirements to distribute livestock grazing demand onto a map of energy supply, with the aim of estimating where and to what degree pasture is being utilized. We applied our model to Kazakhstan, which contains large grassland areas that historically have been used for extensive livestock production but for which the current extent, and thus the potential for increasing livestock production, is unknown. We measured the grazing demand of Kazakh livestock in 2015 at 286 Petajoules, which was 25% of the estimated maximum sustainable energy supply that is available to livestock for grazing. The model resulted in a grazed area of 1.22 million km², or 48% of the area theoretically available for grazing in Kazakhstan, with most utilized land grazed at low intensities (average off-take rate was 13% of total biomass energy production). Under a conservative scenario, our estimations showed a production potential of 0.13 million tons of beef additional to 2015 production (31% increase), and much more with utilization of distant pastures. This model is an important step forward in evaluating pasture use and available land resources, and can be adapted at any spatial scale for any region in the world.

2.1 Introduction

The global livestock sector has an estimated value of upwards of \$1.4 trillion and employs more than 1.3 billion people (Steinfeld et al., 2006). Animal products make up 40% of the current global food demand (Manceron et al., 2014), which is expected to double by 2050 (from 2005 levels) (Tilman et al., 2011). The largest increases in the demand for livestock products are expected to occur in developing and transitioning countries (Herrero et al., 2009). Livestock production already accounts for around 75% of all agricultural land use, including land that is classified as pasture and cropland that is dedicated to feed production (Foley et al., 2011). The livestock sector is also responsible for up to 18% of all anthropogenic greenhouse gas emissions, due in large part to methane emission during enteric fermentation in ruminants, as well as emissions of nitrous oxide from nitrogen-based fertilizers, methane from manure management, and carbon related to land use change (O'Mara, 2011). Grazing patterns of livestock also play a huge role in native species abundance and distribution (Kamp et al., 2009). Yet, despite the large land requirement and significant environmental footprint of livestock production, knowledge gaps exist when it comes to the area, intensity, and spatial distribution of land that is devoted to livestock production.

Determining the land-use footprint of livestock is difficult. So far, the primary focus has been on land used for crops, due partially to the fact that it is easier to detect accurately with remote sensing: fields have distinguishable spectral characteristics, defined edges, and the location of fields is path dependent (Shelestov et al., 2017; Yan & Roy, 2014). Unlike cropland, pasture often consists of natural grassland, and differentiating grassland and pasture using remote detection is an arduous task that as of yet has no universal solution (Kuemmerle et al., 2013). For this research, we define grassland as a biophysical land cover that includes areas with low-standing vegetation, including shrublands (Klein et al., 2012). Pasture is defined as a land use that includes any area actively utilized by livestock for grazing, which can include grassland as well as other types of land cover, including cropland (Erb et al., 2016). Pasture edges are often undefined, especially in areas with communal grazing, nomadic transhumance, and unclear or unenforced land ownership rights (Behnke et al., 2016). Consequently, little knowledge currently exists on the utilization of grasslands for pasture. Unfortunately, data on pasture extent are scarce, which hinders the accurate estimation of utilized and available land resources.

Several products attempt to map land use on a global scale. Erb et al. (2007) and IIASA and FAO (2012) utilized a subtractive approach (with differing classifications and definitions), while Ramankutty et al. (2008) and Klein Goldewijk et al. (2007) used different allocation rules that combine remote sensing-derived land cover with national statistics. These four global products share a modicum of agreement (17% of the land use classification is in full agreement, with an additional 30% where three maps agree) but marginal pasture areas are particularly discrepant, such as in semi-arid and tundra regions, which are sparsely vegetated and contain transitional classes (Erb et al., 2016). Similarly, global remote sensing products often have lower classification accuracies for grassland ecosystems, particularly in areas where

transition classes and ecotones are common (Giri et al., 2005; Gong et al., 2013; Pflugmacher et al., 2011). Thus, estimating pasture area with global land cover products can only be used as general approximations. As livestock enumeration using remote sensing is currently impractical, it is necessary to develop methods of pasture allocation that combine remote sensing with ground-based data and information on local grazing practices, which is crucial for modeling livestock distribution.

The Gridded Livestock of the World (GLW) was the first global, gridded map of livestock density (Wint & Robinson, 2007). With finer resolution (1 km) and more up-to-date statistics, the GLW was improved in 2014 (Robinson et al., 2014), and again in 2018 with a more advanced spatial weighting model to allocate livestock (Gilbert et al., 2018). The authors used the suitability for pasture as well as socioeconomic factors to predict the density of different livestock species, using national and sub-national livestock statistics. However, the accuracies of the GLW are lowest in semi-arid regions and generally in under-populated areas where livestock numbers are often underrepresented due to seasonal movement of stock in remote and inaccessible areas, and information on specific climate, biophysical and socioeconomic characteristics are not available (Wint & Robinson, 2007). Additionally, despite the high resolution, for many countries livestock statistics were used from first-level administrative divisions. For such countries, including Russia, Kazakhstan, Algeria, Saudi Arabia, Indonesia, and Sudan (all among the world's 15 largest countries), this severely limits the suitability of the GLW for regional and local studies (Robinson et al., 2014). There have also been attempts to assess fine-scale livestock dynamics with spatial extrapolation of local livestock numbers as a proxy for the area used as pasture (Kraemer et al., 2015). However, such approaches fail to account for the productivity of grasslands, the biomass intake by the different types of grazing livestock, or regional grazing practices.

We developed a model to estimate the grazing intensity of livestock (cattle, sheep, goats, and horses) in Kazakhstan. Grazing intensity is the percent utilization of net primary production, and allows for the gridded estimation of grazing pressure based on natural productivity. Kazakhstan is particularly interesting because of its long history of livestock rearing and the vast land resources suitable for grazing. The ninth-largest country in the world, Kazakhstan's permanent pastures and meadows were estimated at 1.87 million km² (69% of total land area) in 2014 by the Food and Agriculture Organization (FAO); by comparison, Russia had 0.93 million km² and the United States 2.51 million km² (FAO, 2017). Historically, large numbers of wild herbivores shared Kazakhstan's grasslands with livestock, the most populous being the saiga antelope (*Saiga tatarica*). However, during the 1990s, populations of saiga plummeted due to the loss of enforcement of hunting quotas and illegal trade in saiga horns (Milner-Gulland et al., 2001; Robinson & Milner-Gulland, 2003). Saiga are also vulnerable to periodic, catastrophic die-offs, one of which occurred in spring 2015 (Kamp et al., 2016; Kock et al., 2018). In summer 2015, saiga in Kazakhstan numbered around 84,000 (Association for the Conservation of Biodiversity of Kazakhstan, 2018). Other wild herbivores of note in Kazakhstan include the kulan (*Equus hemionus*) and the goitered gazelle (*Gazella subgutturosa*),

which in 2015 numbered around 3,500 and 13,000, respectively (Association for the Conservation of Biodiversity of Kazakhstan, 2018). These numbers pale in comparison to grazing livestock numbers (6.2 million cattle, 18 million sheep and goats, and 2.1 million horses in 2015) (KazStat, 2016). Similarly, domestic camels in 2015 numbered 170,000 (KazStat, 2016). While in some districts they represented a noticeable source of grazing demand, camels and wild herbivores contributed very little to total grazing intensity at the national scale and thus were not considered in this research.

The model estimates the distribution of livestock grazing and contributes to closing the knowledge gap regarding the spatial dimension and intensity of pasture use. We used statistical data on livestock numbers and fodder production along with recommended energy intake levels per animal type to estimate the livestock grazing demand (the total energy consumed through grazing) for Kazakhstan in 2015. Based on reported grazing practices, we applied this demand to biomass productivity maps to determine the most likely distribution of utilized pasture. The inverse of the result is the amount of energy that is available for grazing, but not currently utilized. Specifically, we were interested in whether the differences in grazing practices among the predominant farm structures and climatic zones would be captured in the output. We aimed to answer the following research questions:

- (1) What was the energy demand and associated pasture requirement for Kazakh grazing livestock in 2015?
- (2) What was the spatial distribution of this pasture?
- (3) Where was the pasture being underutilized, and what is the potential for increasing the herd size and the production of meat and milk?

2.2 Materials and methods

2.2.1 Study area

Situated in the middle of the Eurasian Steppe, Kazakhstan has a northeast-southwest precipitation gradient that allows rain-fed grain production in the north (upwards of 350 mm/year), but transitions quickly to dry steppe and further to desert climate in the southwest (less than 100 mm/year). Precipitation does not suffice for cropland agriculture in many parts of the country where grazing is the only agriculturally significant activity possible (Klein et al., 2012).

Unlike many other grassland regions of the world, Kazakhstan once supported a much larger livestock population than it has at present, particularly while a part of the Soviet Union, when livestock production was viewed as a pillar of centrally planned economies (Petrick et al., 2013). After the Soviet Union dissolved, livestock numbers in Kazakhstan plummeted and widespread abandonment of pastures and croplands occurred (Kraemer et al., 2015; Löw et al., 2015; Meyfroidt et al., 2016). While livestock numbers have been steadily recovering since 2000, as of 2015 they are still only two-thirds of 1990 levels (KazStat, 2016).

However, Soviet levels of production cannot be assumed the desirable goal, as it is generally accepted (though poorly documented) that soil degradation was widespread, with overgrazing a major contributor (Hölzel et al., 2002). Furthermore, degradation of grazing lands has continued up to the present, despite the drastic reduction in grazing livestock numbers (Brinkert et al., 2016). Under the Soviet system, the human population was settled in permanent villages. Livestock migration continued, but was structured and strictly regulated. To supplement grazing (especially during winter), there was a large, subsidized network of fodder supply. When the Soviet Union dissolved, so too did the fodder supply network. Yet the human population remained sedentary, with livestock held almost exclusively in small, household farms. This led to localized overgrazing around settlements, as distant outposts fell into disrepair, and long-distance migration all but stopped (Robinson et al., 2003).

2.2.2 Kazakh farm structure

The type of farm that livestock are raised on in Kazakhstan determines to a great degree how the livestock are grazed (Petrick et al., 2013). There are three distinct farm types in Kazakhstan: the largest farms are called agricultural enterprises (AE), ranging from a few thousand to tens of thousands of animals. These farms are the spiritual (and often actual) descendants of Soviet farms and usually have the resources to provide high-quality fodder and support longer-distance grazing migrations. The second group are the private farms (PF). Since 2000, this is the fastest-growing farm type, and the most diverse in terms of size and grazing practices, ranging from tens to thousands of animals. The third and smallest farm type, households (HH), typically have only a few animals per unit, but overall in Kazakhstan, 60% of grazing livestock are kept in this farm type. Livestock are usually housed overnight in the owner's backyard, meaning that their grazing area is limited to the distance they can walk in one half-day. This immobility results from the sedentarization of farms under the Soviet regime, and the path dependency following its dissolution (Alimaev & Behnke, 2008; Ellis & Lee, 2003; Robinson, 2000). Prior to the Soviet era, livestock generally grazed in large, transhumant, communal herds (Olcott, 1995).

2.2.3 Model development

Three main components are used as inputs to our livestock distribution model (Figure 2-1). Grazing supply (1) is the base map, which consists of energy stored in all the biomass that could be used for grazing. Grazing demand (2) is the sum of all energy required by livestock for growth, maintenance, and lactation, less the amount of energy that they receive through supplied fodder. Energy supplied through fodder is calculated based on statistics (KazStat, 2016) and energy conversion ratios used in Kazakhstan (Forage On-Line, 2009). To spatially distribute the grazing demand, grazing characteristics (3), including home base location, daily grazing range, seasonal migration, and off-take rate (percentage of produced biomass that is consumed) need to be defined.

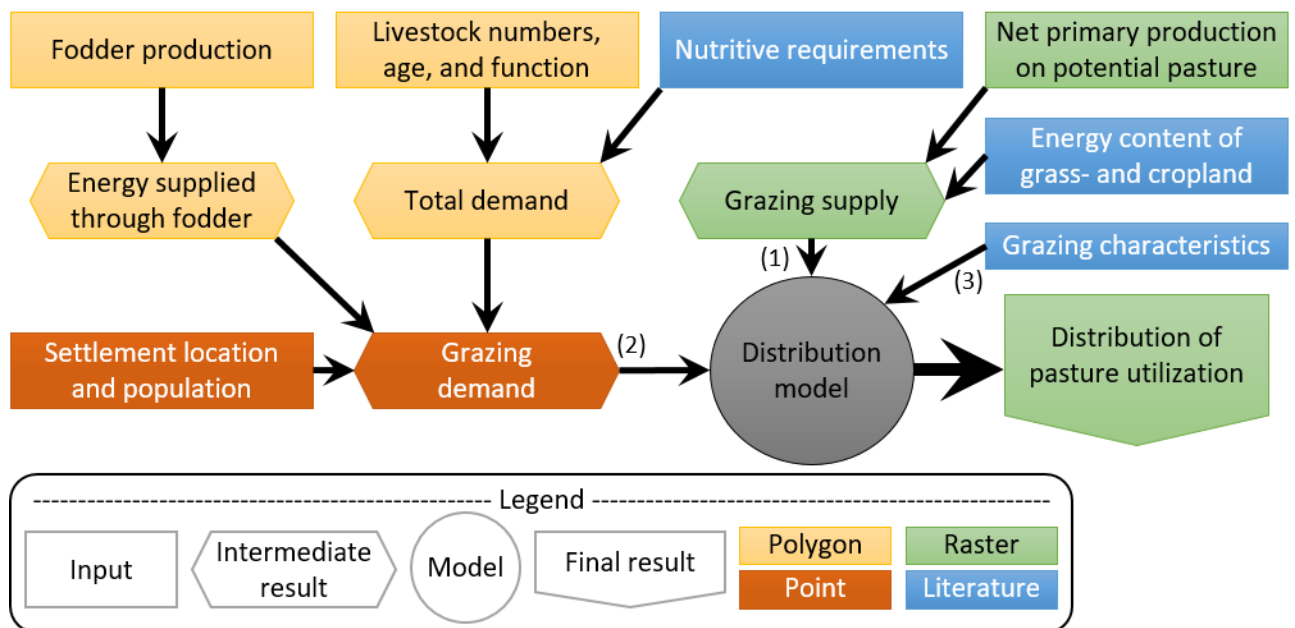


Figure 2-1: Flow chart for the distribution of utilized pasture. (1), (2), and (3) are the inputs to the distribution model. Polygon data is at the district level, point data is at the settlement level (there are 7,234 settlements in Kazakhstan), and raster data is resolved to 500 meters. Nutritive requirements and grazing characteristics are derived from literature and defined differently for the three farm types.

Knowing that the livestock are clustered around settlements (Coughenour et al., 2008), and assuming that they, to some extent, behave as optimal foragers (Deli et al., 2005; Robinson et al., 2016b), we defined a search algorithm to seek out the most productive grassland for grazing surrounding the geographic coordinates of the settlements (Geofabrik, 2016). Grassland productivity was captured using net primary productivity (NPP) (Eisfelder et al., 2017; Eisfelder et al., 2014). As a way to disaggregate livestock numbers from district-level statistics to the settlement level, the human population of each settlement was used (KazStat, 2011), along with a piecewise linear function (Equation 2-S1) describing the relationship between settlement size and number of livestock owners, determined from expert opinion and personal observation (Figure 2-S1).

The search radius defines the area around the settlement within which pixels are selected. Our model allows the search radii to be defined independently for each livestock/farm type combination. The search radii used in this research were developed based on farmer interviews and the findings of Kamp et al. (2012) and Coughenour et al. (2008). Three different radii were used to simulate three different grazing practices found in Kazakhstan. For cattle, sheep, and goats on households and private farms, the search radius was set to 2 km to represent the relative immobility of these livestock. For cattle, sheep, and goats on agricultural enterprises, the search radius was set to 5 km, to represent the increased resources of the enterprises to seek better pastures farther from the settlement (displaying slightly more “optimal forager” activity) (Robinson et al., 2016b). For horses on all farm types, the search radius was set to 10 km, because horses are more mobile and rarely return to the settlement overnight, and thus have the greatest ability to approach optimal foraging. For a summary of the assumptions made in the distribution model, and their implications, see Table 2-S1. To distribute the demand spatially and realistically, we use an iterative

approach. For each combination of livestock type and farm type, a radius r is defined (2, 5, or 10 km, as defined above). For every settlement, the pixels within r are sorted according to their NPP value, and the settlement's demand is distributed to the pixels, choosing higher values first, and precluding chosen pixels from possible duplicate distribution. If the demand is not met within the initial search radius, the search radius is increased to $2r$. The distribution process repeats with increasing search radii ($3r$, $4r$, etc.) until the demand is satisfied. Moreover, the distribution for all settlements is performed simultaneously to allow fair competition, reflecting the reality. This results in the distribution of all available land in $(n-1)$ radii around a settlement, with the final radius containing the last pixels distributed to meet the demand. A magnification of the results, showing the settlement-level pixel distribution, is shown in Figure 2-S2. We chose to distribute the demand of sheep and goats before cattle, though their grazing areas for the most part overlap (literature indicates cattle will travel slightly further during a day) (Walker et al., 1985; Webber et al., 2015). Thus, for sheep, goats, and cattle, farm type is more important than animal type, and the algorithm distributed all sheep, goats, and cattle in households first, then private farms, and finally agricultural enterprises. Horses, on the other hand, typically graze separate from the other livestock, and occupy areas distant from settlements, because they are more mobile and remain on the pasture overnight. To account for this, horses of all farm types were distributed last, thus receiving the pasture furthest from the settlements. Based on the characteristics of the different farm types, and the mobility of the different animal types, the livestock were distributed in this order: 1. sheep and goats in households, 2. cattle in households, 3. sheep and goats in private farms, 4. cattle in private farms, 5. sheep and goats in agricultural enterprises, 6. cattle in agricultural enterprises, 7. horses in households, 8. horses in private farms, and 9. horses in agricultural enterprises. The model is run within the R environment, with image processing carried out in R and in QGIS (QGIS Development Team, 2017; R Core Team, 2017).

2.2.4 Grazing supply

For grazing supply, we used net primary productivity (NPP) produced by Eisfelder et al. (2014) who used the Biosphere Energy Transfer Hydrology Model (BETHY/DLR) (Wißkirchen et al., 2013). NPP is dry matter production per unit area per unit time. We used the best available land-cover map for the region (Klein et al., 2012) to mask out areas that are unavailable for grazing, namely forest, water, ice, and artificial surfaces. Grazing is known to occur in all types of protected areas except nature preserves (*zapovedniki*), which cover 1370 km² and have the highest level of protection (Kamp et al., 2015). Thus, nature preserves were also excluded.

Areas defined as “bare soils” were included as grassland because they, though low in NPP, contain areas where grazing is known to occur (Coughenour et al., 2008). A common practice in Kazakhstan is the foraging of crop residues after harvest, especially on wheat fields. To account for this, we split the map into a grassland and a cropland map. For both maps, we created a composite with the mean of the nine-year NPP data (compiled into annual totals) and converted NPP (grams carbon/square meter) to biomass

production (grams dry matter/square meter) using the conversion coefficient of 0.47 grams carbon/grams dry matter (IPCC, 2006). On the grassland map, we converted biomass to available energy using a value of 8.6 Megajoules (MJ) per kilogram dry matter (kgDM), based on literature from similar regions and climates (Figure 2-) (Grebennikov & Shipilov, 2012; Nasiev et al., 2014; Safin et al., 2011). The total energy available from grasslands was calculated to be 3537 PJ. To estimate the biomass available from the foraging of crop residues, we applied a harvest index of 0.48 (using wheat as the base reference) to the annual NPP (Chen et al., 2014; Sommer et al., 2013). The harvest index is the mass ratio of crop yield (grain) to the crop's total aboveground biomass (Smil, 1999). Wheat is the dominant crop grown in Kazakhstan and thus was used for the calculation of crop residues (KazStat, 2016). At harvest, around 90% of wheat biomass is aboveground (Baret et al., 1992). The energy contained in crop residues is generally less than that of pasture, and a value of 6 MJ/kgDM (using wheat as the base reference) was used for croplands (Ørskov et al., 1988; Smil, 1999). The total energy available for grazing from croplands was calculated to be 293 PJ. The grassland map and cropland map were then merged to produce a map of grazing supply (Figure 2-2).

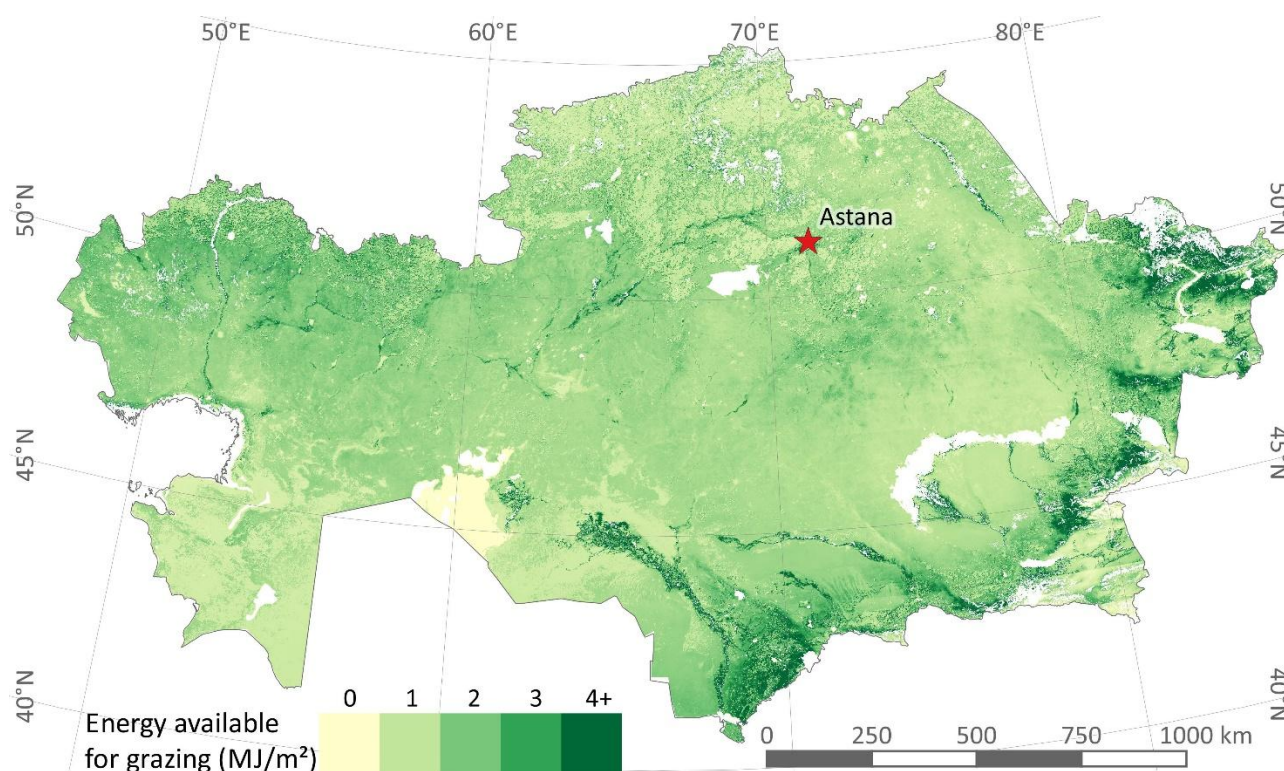


Figure 2-2: Map of annual available grazing supply (MJ/m²) derived in this study. Based on total NPP measured by Eisfelder et al. (2014). The land-cover classification used for masking is from Klein et al. (2012), and the protected area mask is from Kamp et al. (2015). Low available NPP for foraging on croplands can easily be seen in the northcentral. White areas are unavailable for grazing.

2.2.5 Grazing demand

To calculate grazing demand, we gathered data on livestock numbers, fodder yield and fodder consumption at the district level (2nd level administrative division) for 2015 from the Kazakh National Statistics Agency (Figure 2-3) (KazStat, 2016). In Kazakhstan, there are 200 district-level units, consisting of districts (*rayons*) and city administrative units (*gorodskie administratsii*). Livestock nutritive requirements were taken from recommended values published in a livestock nutrition handbook by KazAgroInnovation (2008), a

subordinate of the Kazakh Ministry of Agriculture. These values are specific to Kazakh livestock at different stages of growth and for different animal functions (e.g., beef heifers for breeding vs. beef heifers for finishing), as well as for different desired growth rates. Because sheep far outnumber goats in Kazakhstan, and because of their similar grazing characteristics and energy requirements, all goats were treated as sheep.

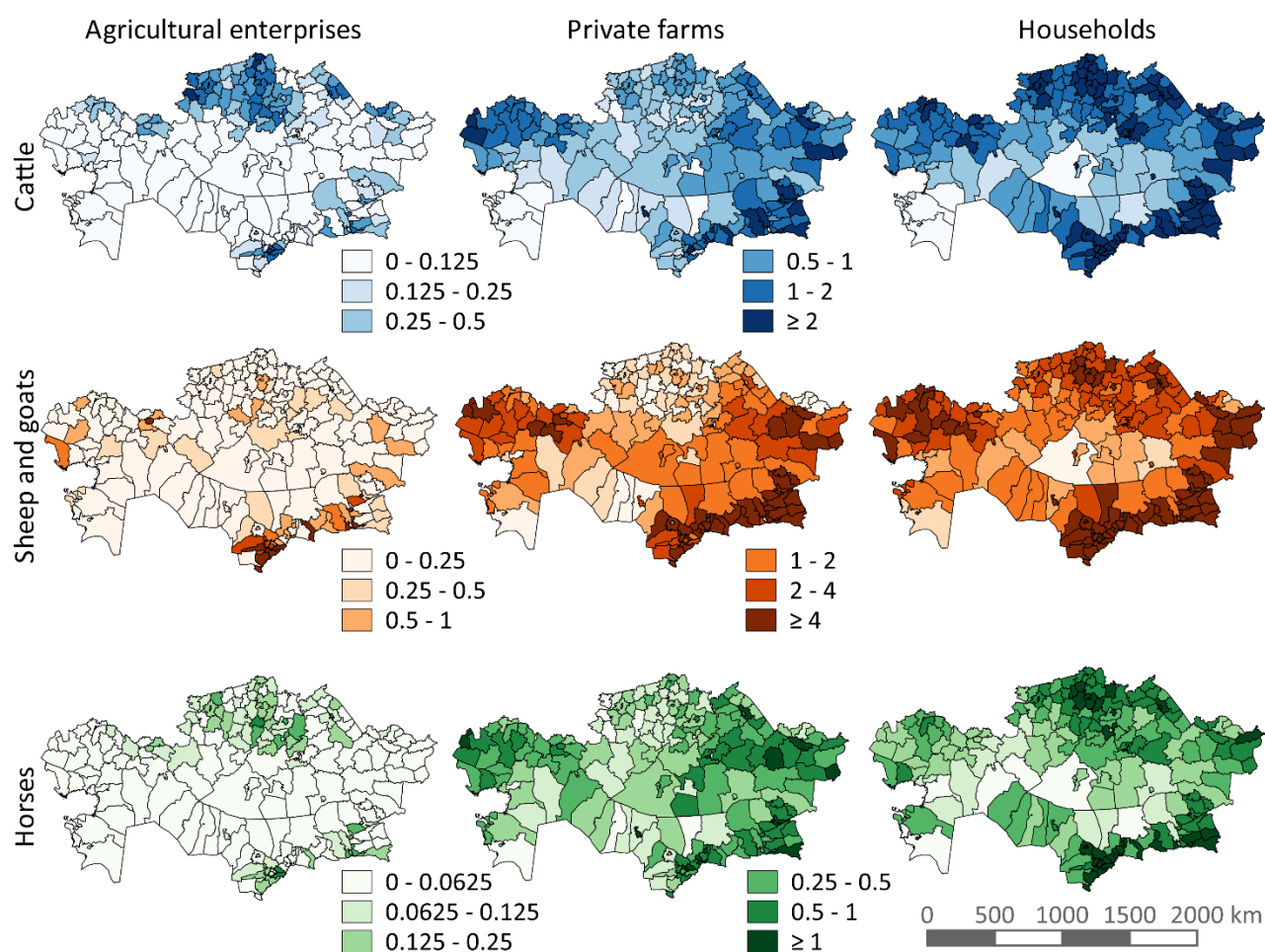


Figure 2-3: Livestock density (head/km²) at the district level for the three farm types in Kazakhstan for the year 2015 (KazStat, 2016). Livestock in Kazakhstan are not distributed evenly across space, nor across the three farm types.

To calculate the total nutritive demand (Figure 2-), we used information on the age group and animal function of the Kazakh livestock herds. The proportions of the different age groups and animal functions were available at the province (oblast) level for the different livestock types from the 2006 agricultural census (KazStat, 2008). As no newer or more detailed data exist, these proportions were applied to the 2015 numbers in our disaggregation equation (Equation 2-S2). Animal productivity differs depending on living conditions, and living conditions in Kazakhstan can broadly be defined based on the farm type. The differences in animal productivity, and thus energy demand, on the different farm types was estimated using different animal growth rates (g/day) as indicated in the handbook (Table 2-S2) (Zhazylbekov et al., 2008). A description of how the handbook values were used to calculate the different animal age and function groups can be found in Table 2-S3.

The fraction of total energy demand that is not met by fodder and therefore must be met by grazing (i.e., grazing demand divided by total demand) is called the grazing gap, and was obtained by subtracting the amount of energy that is consumed as fodder from the total demand (Fetzel, Havlík, Herrero, Kaplan, et al., 2017). The estimation of fodder consumption was not straightforward, as such statistics are reported consistently only for agricultural enterprises. Instead, gross yield of harvested fodder crops at the district level was used (KazStat, 2016), and fodder consumption statistics were used in an equation (Equation 2-S3) to allocate fodder to the different livestock types using their relative proportions (i.e., proportion of total fodder consumption allocated to cattle, sheep, goats, pigs, poultry, horses, and camels). This was the only possible way to estimate the total amount of fodder consumed by grazing livestock in Kazakhstan. Fodder crop yields were converted to energy values using the Soviet system of “fodder units” (Forage On-Line, 2009), due to its easy conversion to MJ and its widespread use in Kazakh agricultural literature and statistical reporting (Table 2-S4 shows the conversion rates used).

Table 2-1 details the inputs used to distribute the demand onto the supply as shown in Figure 2-. When distributing the supply, it is important to acknowledge that only a fraction of the total NPP can be consumed by livestock. The Eisfelder et al. (2014) map is a measurement of total NPP, which includes the portion that is belowground and unavailable to the livestock. We used the work of Propastin et al. (2011), who found aboveground NPP in central Kazakhstan to be on average 77% of total NPP. In addition, a considerable portion of the aboveground NPP must be left to allow regrowth. Published values of recommended stocking rates and pasture utilization in similar climatic conditions suggest a maximum off-take rate of 40% of aboveground NPP (Hall et al., 1998; Holechek, 1988; Wirsenius, 2000), and thus the maximum sustainable off-take rate was estimated at 40% of 77%, or 30% of total NPP.

Table 2-1: Summary of parameters used. Net primary production was taken as an average of the annual products from 2003 to 2011.

Input parameter (units in parentheses)	Spatial resolution	Reference period	Source
Livestock numbers	District	2015	KazStat (2016)
Fodder production (Joules)	District	2015	KazStat (2016)
Fodder consumption (Joules)	District/Province	2015	KazStat (2016)
Nutritive requirements (Joules)		2008	KazAgroInnovation (2008)
Herd age structure	Province	2006	KazStat (2008)
Human population	Settlement	2009	KazStat (2011)
Settlement location	Settlement	2016	Geofabrik (2016)
District and municipal areas	District	2015	GADM (2015), GIS-Lab (2013)
Net primary production (gC/m ²)	1 km	2003-2011	Eisfelder et al. (2014)
Land cover	250 m	2009	Klein et al. (2012)

Obviously, not all pasture is grazed at the maximum sustainable off-take rate. Mapping actual grazing intensity requires estimating the variation in off-take rate on a spatial scale. To map variation in off-take rate using our model, we first ran the model under a range of eleven different off-take rate assumptions (5% increments from 10%-60%). We then calculated the maximum distance from each settlement that each

livestock type needed to fulfill their grazing demand under each off-take rate. To determine an accurate off-take rate for each settlement, we used the maximum grazing distances for cattle in households as the defining variable, as they, along with sheep and goats (which are distributed before cattle), are the most restricted by distance from settlement. We chose 10 km as the maximum distance for cattle in households based on the findings of Kamp et al. (2012). We grouped settlements into their districts, and for each district, we selected the lowest off-take rate that corresponded to the median of maximum grazing distances for cattle in households being less than 10 km. In cases where districts had no reported cattle in households, sheep and goats in households instead were used (districts without either of these had no grazing livestock of any kind). The model was then run again, with settlements maintaining their determined off-take rate.

2.2.6 Production potentials of meat and milk

We estimated the potential to increase production of meat and milk in Kazakhstan based on the efficiency with which pasture is being used. To estimate pasture use efficiency, we took meat and milk production in 2015 from the national statistics (KazStat, 2016). We calculated pasture requirement from the model results and estimated the yield of meat and milk (tons per km² utilized) for the different livestock types. Our model results do not differentiate between beef and dairy cattle, so we made an adjustment based on the relative proportions of beef and dairy cattle. The fraction of cattle classified as dairy in 2015 for agricultural enterprises, private farms, and households was 0.40, 0.50, and 0.85, respectively (KazStat, 2016). We multiplied the land requirement by this fraction as a rough estimate for the area used by dairy cattle. We then divided milk production by the adjusted land requirement to estimate milk productivity.

We used the calculated land use efficiencies to estimate production potential. First, we made a conservative assumption that all land within 10 km of a settlement could currently be utilized. Therefore, unutilized land within 10 km of a settlement was considered for potential expansion. The modeled off-take rates were used to calculate the number of additional livestock that could be supported. Second, we proposed a scenario where pasture was grazed at its maximum sustainable intensity (30% off-take rate), and calculated the resulting unutilized area within 10 km of a settlement. Using a less conservative assumption that all land within 20 km of a settlement could be utilized, we repeated the previous two calculations. Potential increase in beef production was calculated with the assumption that all additional livestock were beef cattle. Similarly, for potential increase in milk production, we assumed that all additional livestock were dairy cattle. Therefore, the results presented are “either-or”, and the reality likely falls somewhere in between.

2.3 Results

2.3.1 Grazing gap and demand distribution

The grazing demand was calculated for each animal and farm type combination (Figure 2-4). The total energy demand by all livestock types in 2015 (the sum of all bars in Figure 2-4) was 368 Petajoules (PJ). The grazing gap is displayed above each bar as the fraction of total energy demand obtained through grazing. Of the three livestock types, the grazing gap is lowest for cattle, and of the three farm types, the grazing gap is lowest for agricultural enterprises, with the lowest being cattle on agricultural enterprises. This is due to cattle on agricultural enterprises receiving more and higher-quality fodder than other livestock and on other farm types. The total amount of energy supplied by fodder was 82 PJ (sum of all darker portions of the bars), leaving 286 PJ to be obtained through grazing.

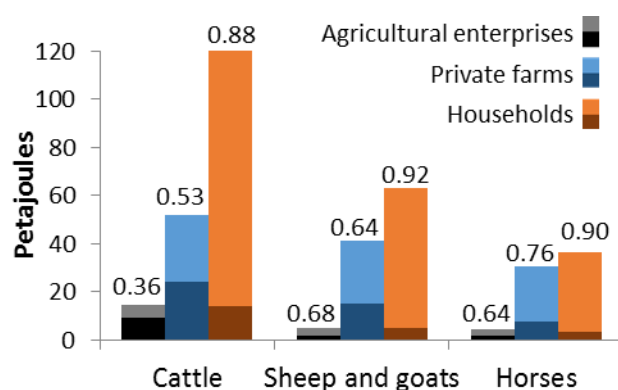


Figure 2-4: Energy balance for Kazakh grazing livestock in 2015. The darker bottom portion of each bar is the fodder supply, and the lighter top portion is the remaining demand that must be acquired from grazing. The total demand is represented by the full bar height. Fractions above each bar show the grazing gap (grazing demand divided by total demand). Nutritive demand information is from KazAgroInnovation (2008) and supply statistics from KazStat (2016).

Figure 2-5 shows the total grazing demand of all livestock types for each settlement in Kazakhstan. Grazing demand is not distributed evenly across the country. In the north, the demand is large, but dispersed across many settlements, whereas in the south it is also large, but concentrated in relatively fewer settlements. The center and southwest have both few settlements and little grazing demand.

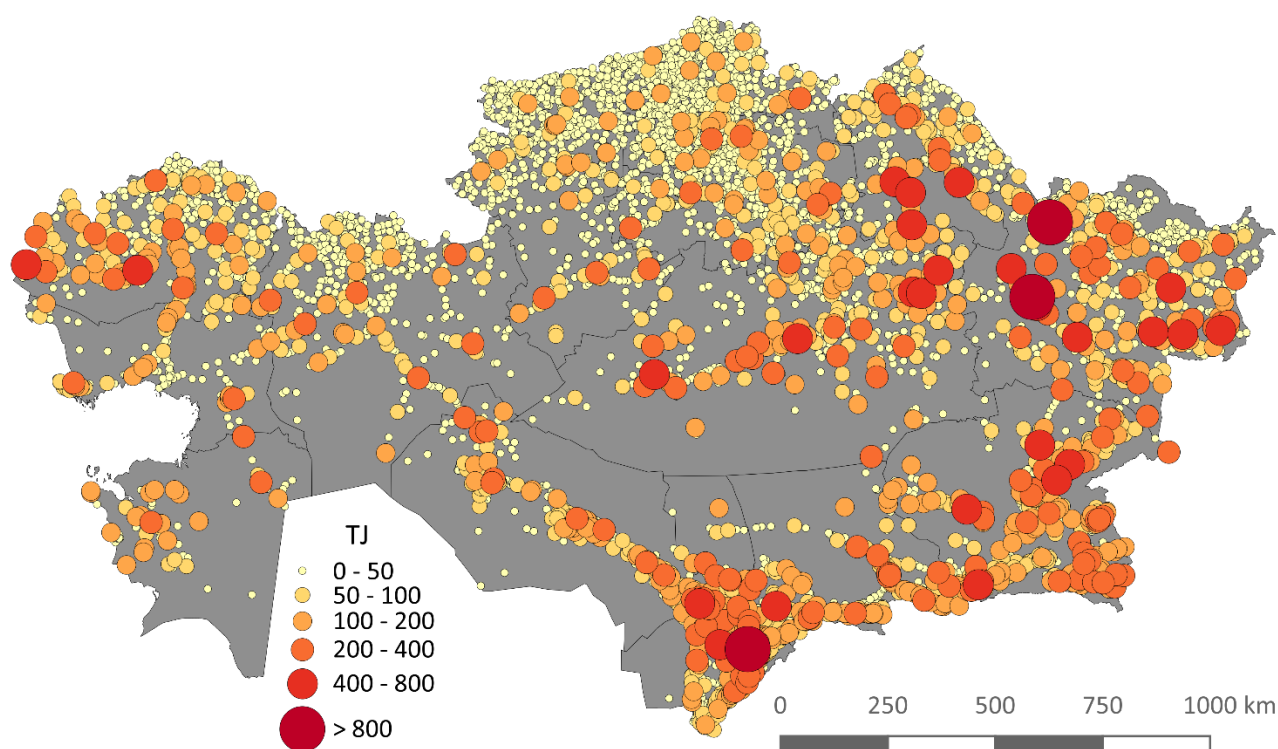


Figure 2-5: Grazing demand (in Terajoules, TJ) in 2015 disaggregated to settlements (all farm types combined).

2.3.2 Off-take rate

Off-take rate is not uniform across Kazakhstan. The grazing demand for 2015 was 7.5% of the total biomass supply (when converted to energy)—i.e., if the off-take rate were 7.5%, all available land would be utilized. We tested the sensitivity to off-take rate by running the model with eleven different off-take rates, from 10% to 60% (5% increments) (Figure 2-6). As the off-take rate decreases, the area required for grazing increases exponentially (Figure 2-7). In our results, all off-take values used are as a percent of total available NPP.

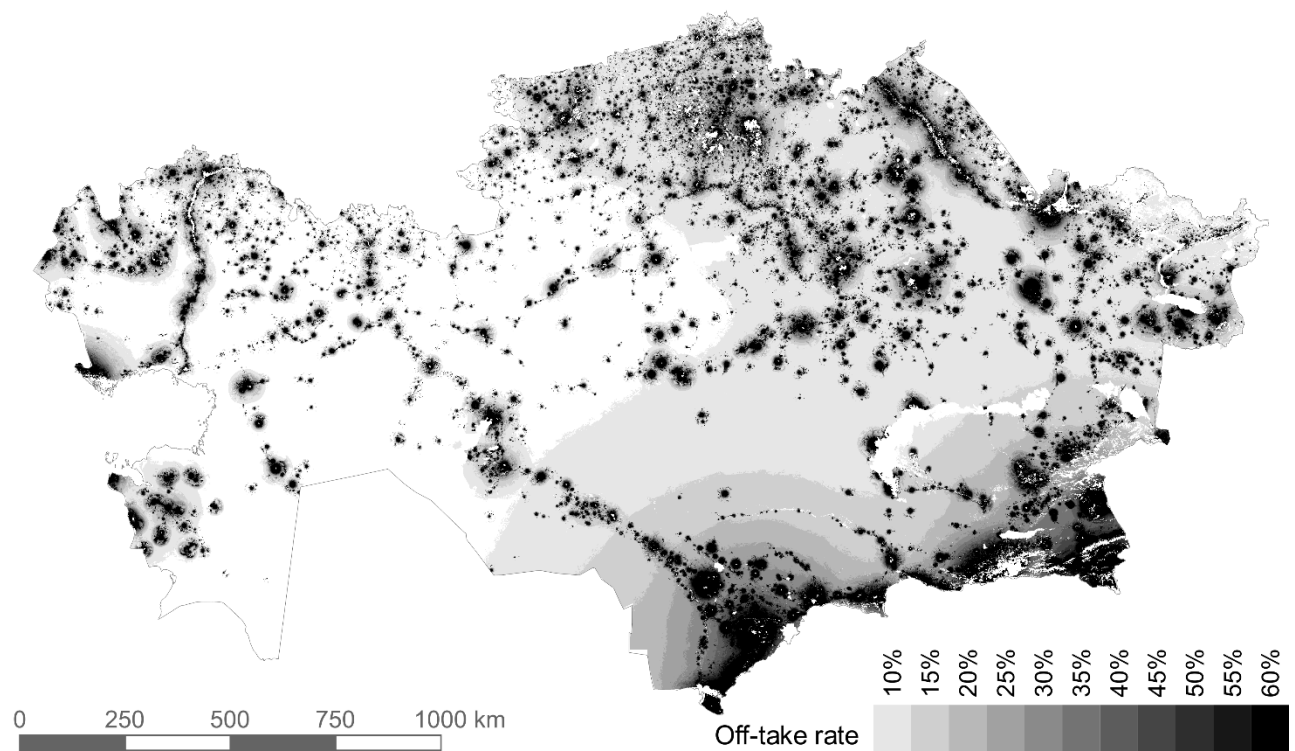


Figure 2-6: Grazing extent by all livestock under varying off-take rates. The image is a superimposition of the eleven model runs. The map of each individual off-take rate includes the area of all higher off-take rates.

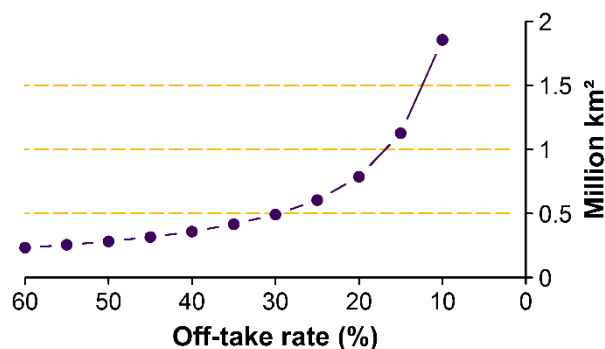


Figure 2-7: Area required by grazing livestock depending on the percent of biomass off-take.

2.3.3 Grazing distances and pasture extent

The maximum distances traveled by household cattle under each off-take rate assumption were analyzed at the district level to determine the average off-take rate in each district. The model was re-run with variable off-take rates to derive the maximum grazing distances. Figure 2-8 shows the median and quartiles of these distances by animal and farm type. A smaller quartile range on the left-hand side of the median for every livestock type is a result of the distances being skewed by relatively few settlements with a large livestock population located close to one another, most notably in southcentral Kazakhstan (Figure 2-5). Most settlements had much shorter maximum grazing distances, within 6 km for cattle, sheep, and goats in households, and within 15 km for cattle, sheep, and goats on private farms. Despite being distributed later, cattle on agricultural enterprises were found to have lower maximum grazing distances than sheep and goats on agricultural enterprises. This was due to agricultural enterprises specializing in cattle production

being located mainly in the north in small settlements, whereas agricultural enterprises with sheep and goats were located mainly in the south and southeast in or near large settlements.

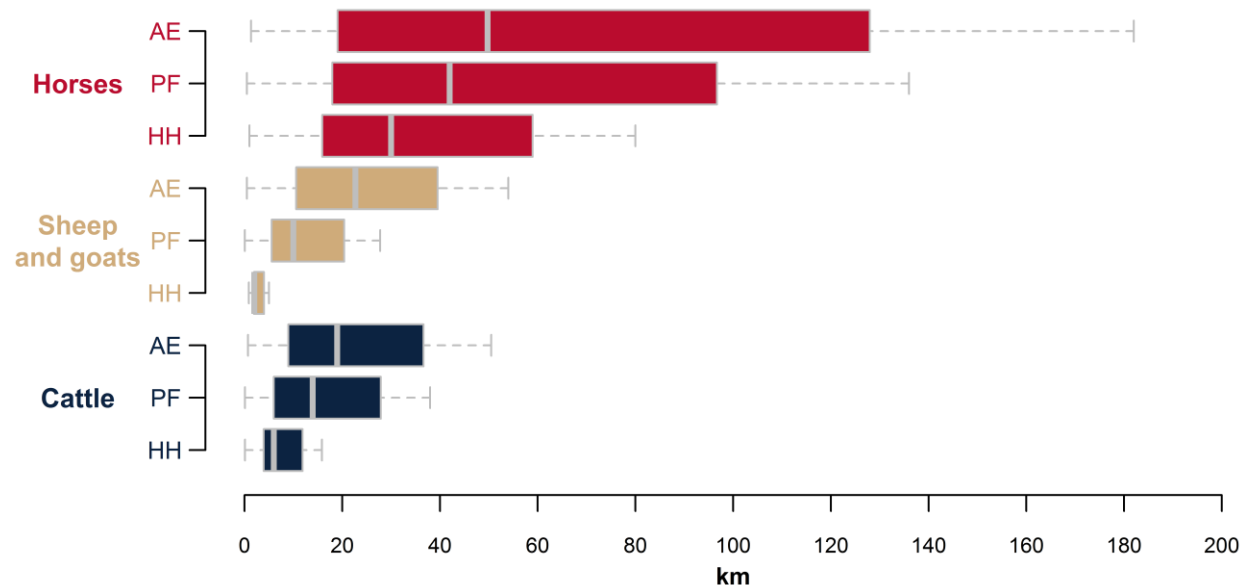


Figure 2-8: Maximum grazing distances of the variable off-take rate map. Box shows 50% of settlements (with median), whiskers are 1/2 inter-quartile range. AE: agricultural enterprises, PF: private farms, HH: households.

Figure 2-9 shows the land-use footprint of grazing livestock in 2015, using variable off-take rates at the district level. The area required was 1.22 million km², 48% of the area theoretically available for grazing. While the off-take rate was determined at the district level, the result shows that off-take rates did not strictly adhere to district boundaries, as individual settlements are not obliged to graze within district boundaries. In the north, a relatively higher number of livestock are kept in private farms and agricultural enterprises, which are not as restricted as household livestock to the immediate vicinity of settlements. Thus, they can utilize distant pastures at lower off-take rates, and almost all of the north and northeast was utilized to some extent. The south and southeast showed less land being utilized, however at a much higher off-take rate. In the east, high NPP allows for lower off-take rates, and high numbers of private farm livestock can search out distant pastures. Two riparian pasture regions are clearly visible due to their course running through otherwise arid and semi-arid regions: the Ural in the far west and the Syr Darya flowing northwest out of the southern tip. The Chu River (to the east of the Syr Darya) is a historically important river that used to flow into the Syr Darya, but for many years has been diverted for irrigation and now disappears before reaching the Syr Darya. The Ili River in the southeast flows from the mountains of Tian Shan into Lake Balkhash, where it forms a large delta, providing grazing opportunities in an otherwise arid landscape.

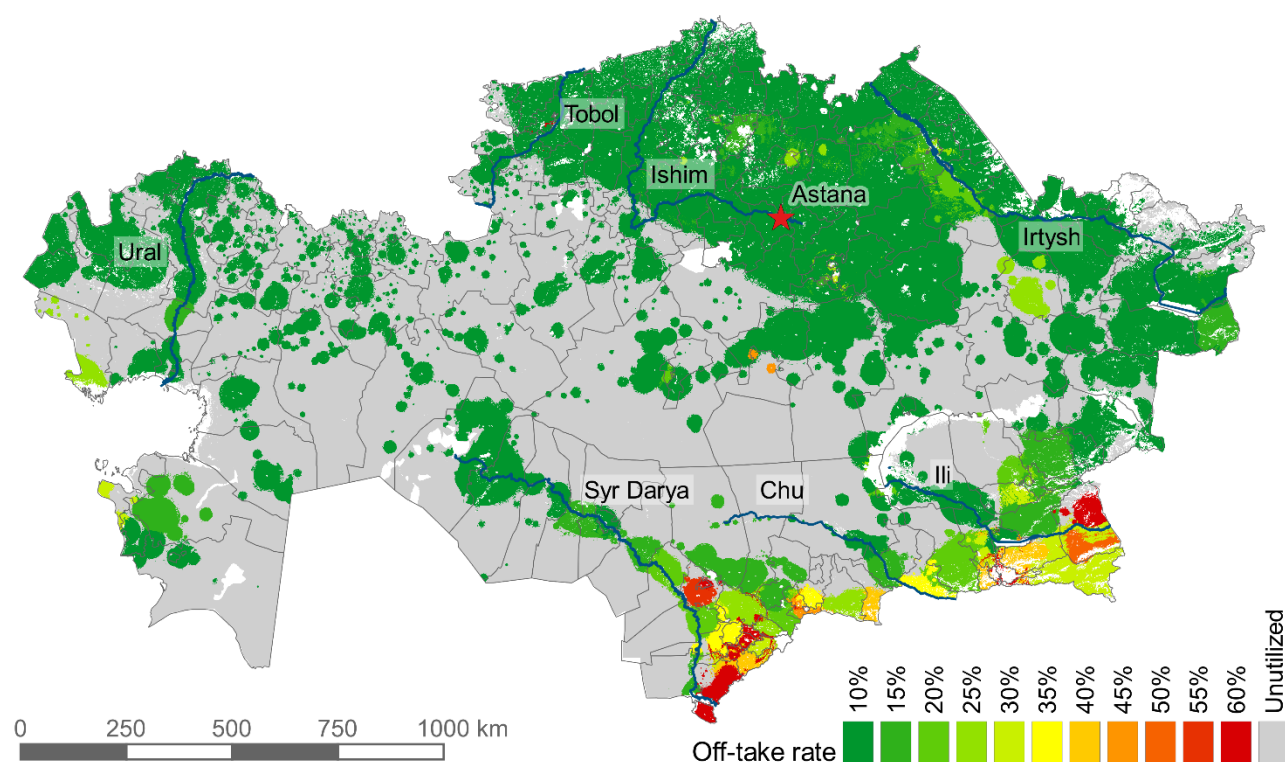


Figure 2-9: Distribution of grazing intensity in Kazakhstan for the year 2015. Off-take rate is the percent of total available biomass that is consumed. I.e. on croplands, it is the percentage consumed of the biomass that remained after harvest. Major rivers are shown in blue with names.

2.3.4 Production potentials of meat and milk

The summarization of utilized pasture made it possible to estimate the associated productivity of livestock production with regard to pasture use. Table 2-2 shows the area of pasture utilized and the respective productivity of meat and milk (production per km² utilized). Meat productivity is highest for cattle on agricultural enterprises, but not by a lot. With the much smaller grazing gap for cattle on agricultural enterprises (Figure 2-4), one would expect the meat productivity (which doesn't account for fodder) to be much higher. This is not the case because most cattle on agricultural enterprises are in northcentral Kazakhstan (Figure 2-3), where the off-take is low (Figure 2-9) and a lot of grazing on cropland (Figure 2-2) occurs. Both factors increase the land utilized by cattle on agricultural enterprises compared to other livestock and on other farm types, and thus decrease the relative meat productivity. Total beef production in 2015 was 417 thousand tons (kt), and total dairy milk production was 5.1 million tons (Mt).

Table 2-2: Pasture use, production, and productivity of meat and milk in 2015. Meat and milk production statistics from KazStat (2016). These numbers do not account for land used for fodder production. *Adjusted for relative proportion of cattle in dairy production. AE: agricultural enterprises, PF: private farms, HH: households.

Livestock type	Farm type	Pasture utilized (mil. km ²)	Meat production (kt)	Meat productivity (t/km ²)	Milk production (kt)	Milk productivity (t/km ²)
Cattle	AE	0.30	28.44	96.09	263.01	2213.05*
	PF	1.47	77.80	52.90	777.55	1048.46*
	HH	4.44	310.57	69.98	4101.06	1091.96*
Sheep and goats	AE	0.10	3.16	32.52	0.04	0.38
	PF	1.14	38.74	34.11	0.33	0.29
	HH	1.82	123.19	67.60	1.25	0.68

<i>Horses</i>	AE	0.17	2.17	12.94	0.69	4.14
	PF	1.35	25.01	18.47	9.76	7.21
	HH	1.44	74.26	51.44	15.42	10.68

For sheep, goats, and horses, meat productivity is highest in households. For sheep and goats, this is due to sheep on agricultural enterprises and private farms primarily being raised for wool, with meat only a byproduct. Similarly, for horses, most meat production is done at the household level. Regarding milk production, cattle on agricultural enterprises are clearly the most land productive (when adjusted for the proportion of dairy production). Milk productivity is very low for sheep and goats, with almost all production coming from the very few goats in the country. Horse milk productivity is somewhat higher, because of the demand for the traditional horse-milk drink *kumys*, which is produced mainly at the household level.

We produced a conservative estimate for increased production potential by implementing the scenario where all land within 10 km of a settlement is utilized. Assuming the estimated off-take rates shown in Figure 2-9 as business-as-usual (BAU), the additional pasture utilized was 0.14 million km², with an associated energy of 29.9 PJ. Assuming a proportional increase in fodder production (i.e., that the grazing gap remains the same), if the additional 0.14 million km² of pasture was used entirely for cattle on agricultural enterprises, beef production could be increased by 0.13 Mt, an increase of 31% (Figure 2-10). Conversely, if all expansion was used for dairy on agricultural enterprises, dairy milk production could be increased by 3.11 Mt (above 2015 level) under the business-as-usual scenario, an increase of 60%. These are conservative estimates, as off-take rates were very low for most settlements (Figure 2-9). If all land within 10 km was used at its maximum sustainable off-take rate (30%), and if all additional livestock on pasture within 10 km were cattle on agricultural enterprises, beef production could be increased 1.91 Mt (above 2015 level), an increase of 457%. By comparison, Brazilian beef exports in 2013 totaled 1.25 Mt (Schierhorn et al., 2016). Hence, Kazakhstan has the potential to become one of the leading beef exporters in the world. If the radius of land around a settlement that can be utilized was increased to 20 km, with business-as-usual off-take rates, and if all additional pasture was utilized by cattle on agricultural enterprises, beef production could be increased by 0.41 Mt (98%). Assuming maximum sustainable off-take rates within 20 km, this estimate increases to 3.96 Mt.

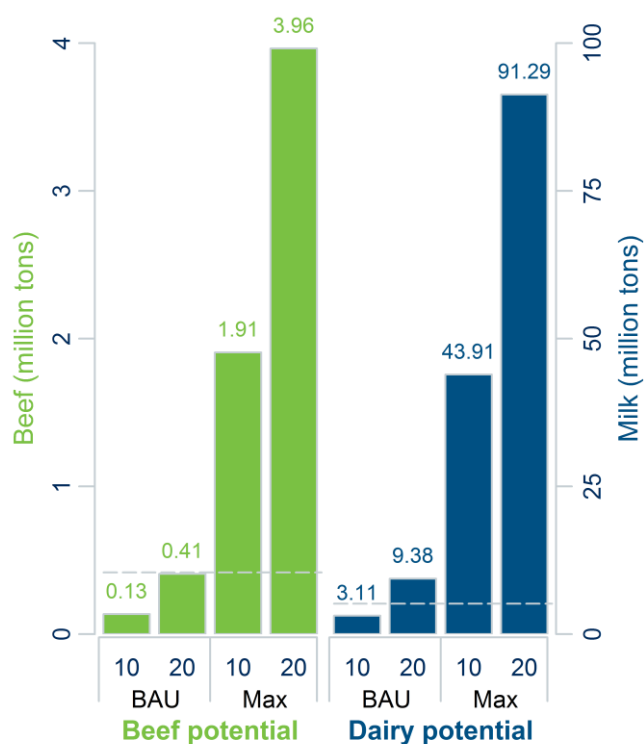


Figure 2-10: Production expansion scenarios. Additional beef and milk production under scenarios of business-as-usual (BAU, based on 2015 levels) and the maximum sustainable (30%) off-take rate, considering unutilized lands within 10 km of a settlement as well as within 20 km of a settlement. Based on 2015 productivity levels of agricultural enterprises (Table 2-2). The dotted line shows beef and dairy production in 2015.

2.4 Discussion

This model is a new and unique way to analyze pasture use. As such, it cannot be compared directly to existing products. Most maps of livestock distribution or pasture extent are at the global scale, and we endeavored to create a more accurate map by focusing on the regional scale. We used detailed information on livestock nutritive requirements to calculate the total energy demand and we used district-level data on fodder supply to determine the grazing gap and grazing demand. To measure the energy available for grazing, we obtained NPP estimates as opposed to using suitability indices, which allowed us to estimate grazing intensity instead of probability of pasture occurrence or stocking density. Based on extensive literature review and field experience, we defined regional grazing practices specific to different farm and animal types to better distribute grazing demand. The result is a model that can distribute pasture utilization at fine spatial scales.

2.4.1 Comparison to global products

We compared our results visually to global products. The Gridded Livestock of the World (GLW) (Robinson et al., 2014) shows very dense populations of cattle, sheep, and goats in southcentral and southeastern Kazakhstan, whereas the north and northeast is less dense, but fairly uniform across a larger area. This agrees with the high off-take rates calculated in the south and the low off-take rates in the north, which results in very large continuous pasture in the north (Figure 2-9). More recently, Nicolas et al. (2016) improved on the GLW by, among other things, preventing the GLW from placing livestock where humans

are absent, which was also the aim of our model. However, they found no systematic improvements, likely due in part to their coarse distinction between urban and rural areas. The definition of urban and rural areas (and the presence of livestock in each) varies greatly between countries, and using one gradient for the entire world is unlikely to produce accurate results.

Compared visually to Erb et al. (2007), our model found less utilized pasture. This was due to the subtractive method used by Erb et al. (2007)—if land was not used for crops or anything else and as long as it was above the precipitation threshold, then it was considered grazing land. That qualifies almost all land in Kazakhstan as grazing land, including lands—such as in central Kazakhstan—where few, if any, livestock exist. However, Erb et al. (2007) also published a grazing suitability map, which shows most of Kazakhstan, save for the far south and southeast, to be in the lowest suitability class. Though suitability is not necessarily related to utilization, the areas of high suitability (the south and southeast) match our areas of high off-take rates. Overall, the four global grazing land-use maps reviewed in Erb et al. (2016) have low agreement in Kazakhstan, and especially in the drier central and southwest part of the country, where the difference in estimates of grazing area range by up to 100%. In another study based on Haberl et al.'s (2007) estimation of Human Appropriation of NPP, Erb et al. (2016) estimated the grazing intensity as a percent of actual NPP, and almost all of Kazakhstan is in the 0-10% range. Only in the southeast and especially in the southcentral does grazing intensity increase, up to about 50%, which is in line with Figure 2-9.

Fetzel et al. (2017) combined the efforts of the previously described global pasture extents (Erb et al., 2007; IIASA & FAO, 2012; Klein Goldewijk et al., 2007; Ramankutty et al., 2008) with the GLW (Robinson et al., 2014), grazing suitability (Erb et al., 2007), Human Appropriation of NPP (Haberl et al., 2007), Moderate-resolution imaging spectroradiometer net primary productivity (Zhao et al., 2005), and feed intake estimates (Bouwman et al., 2005; Herrero, Havlík, et al., 2013; Krausmann et al., 2008) to create a global, gridded map of grazing intensity. Shortcomings in the grazing intensity distribution include the use of FAO statistics for livestock numbers, the resolution of the 2007 GLW (5 km), as well as the spatial scale of feed intake estimates (usually national level) (Fetzel, Havlík, Herrero, Kaplan, et al., 2017). These are general issues with global-scale models, which underline the usefulness of regional-scale approaches, as long as these can make use of data with higher spatial and temporal resolution. Further comparison to our results can be found in Figure 2-S3. As regional studies of the spatial distribution of grazing intensity do not exist, we compared our results to the global product by Fetzel et al. (2017), cut to the area of Kazakhstan (Figure 2-S3a). While the resolution of the maps is not comparable, the suitability algorithm employed by Fetzel et al. (2017) resulted in a similar relative distribution of grazing intensity. The takeaway from this comparison is that our maps agree in the areas of high, and low, grazing intensity. There are a number of reasons why the results are not directly comparable, not the least of which being that Fetzel et al. measured grazing intensity in 2000, when grazing livestock numbers were 57% of their 2015 levels (KazStat, 2016). Also, the

assumptions and inputs used in our model were specific to Kazakhstan. Our calculation of grazing gap (Figure 2-4) produced a much higher grazing demand in Kazakhstan than the average grazing demand calculated in Herrero et al. (2013) for the region defined as the Commonwealth of Independent States. Additionally, our search parameters—using settlements as “home bases”—resulted in a smaller, more intensely grazed area. One noticeable inconsistency between the two maps is in the east. This is likely due to the very high NPP in the region, which would make it seemingly ideal for intense grazing. However, there are relatively few livestock in the region (which is only seen in district-level statistics), and much of the far eastern parts are covered in forest, which were not available for grazing in our model.

2.4.2 Validation

For this research, we combined remotely sensed NPP, livestock statistics, feed recommendations, and allocation rules. Each of these components may contribute a degree of uncertainty. For instance, official statistics can be subject to manipulation and inconsistent measurements, particularly during the transition period. We utilized 2015 livestock numbers, after the reformation of reporting livestock statistics that occurred in 2010-11, which included livestock tagging. Similarly, actual feed consumption may vary according to individual production costs, output, and available fodder resources or other endogenous factors, such as experience and background of the farmer. Yet, agricultural producers tend to follow the recommendations of the extension services and the Ministry of Agriculture.

McNaughton et al. (1996) summarize the pitfalls associated with ground-based measurements of grazing intensity, mainly—but not limited to—the difficulty in measuring plant growth, removal, and re-growth over a season. More recently, remote sensing-based global pasture products acknowledge the inherent difficulty in detecting pasture existence, much less determining grazing intensity (Garnett et al., 2017; Phelps & Kaplan, 2017). Grazing, especially low-intensity grazing, can leave almost no detectable signature. Adding the mobility of livestock and differing land covers, detection and measurement of grazing intensity is extremely difficult. As elaborated by Verburg et al. (2011), improving or re-thinking the current methods of ground-truthing is a very immediate need in land use and land cover products and a cause for future research. Our research combined satellite-derived data (NPP) with sub-national livestock statistics. This makes our approach a member of the group of methods described by Kuemmerle et al. (2013) that, while not ground-truthed themselves, use ground-truthed products to disaggregate spatially-aggregated data, a group that also includes the work by Neumann et al. (2009) and the GLW (Gilbert et al., 2018; Robinson et al., 2014; Wint & Robinson, 2007).

2.4.3 Targeting areas for livestock expansion

Expanding on the GLW, Chang et al. (2015) estimated the potential livestock density for Europe and found that virtually everywhere there is large room for expansion. However, competition for land use in Europe is very high, and expansion is unlikely to occur at a large scale. This is not the case in Kazakhstan, where land

is abundant and much of it is not utilized or utilized at low intensity levels. Increases in livestock mobility through improved infrastructure can reduce localized overgrazing and allow pastoralists to regain access to the vast steppe that is currently out of reach. Areas high in NPP, but with low off-take rates and relatively low livestock numbers, can be found in the east and in the northwest of Kazakhstan. These regions could be the easiest targets for increases in livestock production. In the south, there appears to be less pasture utilization in terms of area, but that belies the much higher off-take rates. It is possible that a 10 km threshold for household livestock is too restrictive in the south, where a much higher proportion of livestock are kept on household farms, and some medium-range seasonal migration is known to still occur (Robinson et al., 2016a). This would result in more utilized pasture, with lower off-takes rates. In the north, a much higher proportion of livestock are held on agricultural enterprises, and the relatively low numbers of household livestock contribute to the low calculated off-take rate, usually 10%. This forces the agricultural enterprise cattle to range at large distances, further than 100 km for several settlements in Akmola Province. While this is certainly possible for agricultural enterprises with labor and capital resources, it is more likely that they graze closer to the farm at higher off-take rates. It is well-documented that overgrazing of pasture is still a feature of Kazakh livestock production, especially around settlements (Mirzabaev et al., 2016). This would result in an overall smaller utilized pasture in the north, with higher off-take rates.

2.4.4 Notes on model inputs and assumptions

In the estimation of maximum sustainable off-take rate, we used the findings of Propastin et al. (Propastin et al., 2011), based on 14 test sites in Karaganda Oblast. While they have corroborated their results with other similar studies, in fact the proportion of above- to belowground NPP varies depending on the plant species, soil type, soil texture, and climate (Wesche & Treiber, 2012). To date, robust datasets that map the spatial distribution of above- and belowground NPP in Kazakhstan are lacking. In similar fashion, no countrywide spatial datasets exist on the energy content of predominant species. In our model, a distinction was made only between cropland and grassland, and another improvement on the energy supply side would be to distribute spatially energy content based on predominant plant species. Including the spatial heterogeneity of the above- and belowground NPP and the plant energy content would improve the accuracy of our model's estimation of grazing supply.

Our study found an overall grazing gap of 78%. Erb et al. (2016) report the overall grazing gap for 11 world regions, with Central Asia and the Russian Federation having an aggregated grazing gap of around 40%. However, Russia has a large amount of production on primarily mixed feedlot systems and thus a low grazing gap, and similar climatic regions to Kazakhstan, such as Australia and Sub-Saharan Africa, have grazing gaps between 70 and 80% (Erb et al., 2016). We should note, in Kazakhstan, it is likely that there is substantial fodder production that is not being reported and is therefore unaccounted for in our model. Hay cutting by households and private farms on grassland is a common practice and usually goes

unreported. At the same time, communication with local experts and farmers suggested that it is unlikely that fodder imports from other countries occur in significant quantities, which is supported in official statistics (FAO, 2017). However, some limited amounts of high-energy fodder may be traded from districts with large cropland areas to districts with large grassland areas (and vice versa with hay moving from grassland-dominant districts to cropland-dominant districts), which has not been accounted for in our model. However, the degree of fodder transport between districts is unknown.

Also unknown is the extent to which livestock utilize crop residues. As residues may or may not be left in the field, there are no statistics on the yield of residues available for livestock. However, expert opinion and field experience suggested that there is wide-scale grazing of harvested lands, and a lack of physical boundaries (such as fences) led us to assume in our model that all crop residues were available to livestock. NPP from crop residues available to livestock was calculated to be 293 PJ. This is small in comparison with the grassland supply of 3537 PJ (less than 7% of the total energy supply, yet occupying 14% of the total area), but is a significant source of energy for livestock, particularly in northcentral Kazakhstan. Notably, the time of year that livestock forage on croplands changes from year to year. The wheat harvest can sometimes last into winter when weather conditions prevent earlier harvest. In our model, we do not account for this, making the implicit assumption that most residues from these late harvests will still be available for foraging the following spring, or for horses that graze year-round. Indeed, for an average annual grazing supply map such as we used, whether the residues are consumed in spring or in fall is moot.

The area utilized in 2015 covers much of the highest-productivity areas shown in Figure 2-2, and there are clear trends of pasturing near rivers and in other areas of high NPP (Figure 2-9). As the restriction to settlement location is much more important than the productivity of the pasture, this is a result of the location of the settlements and not the model search algorithm. Most settlements were founded because of their proximity to water or other biophysical characteristics that favor higher biomass productivity. Indeed, the average energy production on land within 10 km of a settlement in Kazakhstan is 1.75 MJ/m², whereas land further than 10 km from a settlement averages 1.37 MJ/m². This also supports the hypothesis of abandonment of pastures occurring mainly on marginal lands (Kraemer et al., 2015). Additionally, analysis of Figure 2-7 shows that the off-take rate increases more than the expected function 1/x as off-take rate decreases, indicating lower productivity as the distance from settlement increases.

The model assumes that livestock are only located where people are located, similar to assumptions made by others (Nicolas et al., 2016). While this is generally the case, livestock are not distributed evenly among the settlements, especially on agricultural enterprises. For example, agricultural enterprises hold a large number of animals and are commonly located in medium and small settlements, where they are the main source of jobs for the residents. Since some (but not all) small settlements have an agricultural enterprise, there is no way to place agricultural enterprises accurately within a district without preexistent knowledge of their location. This means that, in reality, herd sizes in small settlements are very unbalanced, whereas in

the model, similarly sized settlements within a district receive equal numbers of livestock. Additionally, settlements that exist for a specific industrial purpose may have pasture distributed in the model where in fact no livestock are kept.

Briefly mentioned but unelaborated on is the role that access to water plays in livestock distribution. Wells have been an integral part of grazing migrations in Kazakhstan for centuries, and during Soviet times, thousands of new pump wells were installed to accommodate the regulated migrations of much larger herds (Kerven et al., 2016). Around these wells, outposts were erected and served as seasonal base camps for livestock herders. However, many of these outposts were abandoned after the collapse of the Soviet Union and the wells fell into disrepair (Behnke, 2008). There is currently no accessible countrywide data on the prevalence or location of working wells or occupied outposts. For this reason, wells and outposts were not considered in the distribution of livestock. Inclusion of these water sources as potential home bases for livestock would give the search algorithm access to grazing supply that was previously far from settlements, and thus it is possible that there is pasture utilized in remote areas not captured in the model.

2.4.5 Livestock productivity on private farms

The low meat and milk productivity of cattle on private farms is surprising (Table 2-2), especially given that private farms have much lower grazing gaps than households (Figure 2-4). In the scenarios explored for Figure 2-10, a similar expansion on only private farms would result in an increase of 67 kt (16%), compared to 113 kt for agricultural enterprises. Through personal observation and anecdotal evidence, this lower productivity could be because private farmers do not have the resources necessary to provide proper nutrition to their livestock, resulting in suboptimal meat and milk production. Indeed, outside of agricultural enterprises, almost all fodder produced is hay, which is one of the least energy-rich fodder types. On agricultural enterprises, hay comprises 57% of fodder by mass, whereas on private farms hay comprises 95% of fodder by mass (KazStat, 2016). Additionally, in many regions private farms are essentially large households, and have similar grazing practices. In those situations, private farms at best share pasture with household livestock and at worst are pushed to the less productive lands far from the settlement. In the model, private farm livestock are always distributed after the same type of livestock in households, which biases private farm livestock to pastures with lower NPP, though across the country the effect should be rather small. Private farms are currently the most dynamic and fastest growing sector in livestock farming, but so far, their efficiency has not surpassed that of household farms.

2.5 Conclusion

Here we have presented a new model to allocate livestock and pasture spatially, using a map of biomass production and information on animal types, farm types, and fodder intake. Our methods of delineating land used by livestock and estimating the intensity with which the livestock are using the land allow pinpointing the extent and location of underutilized grazing resources.

The model enabled a gridded estimate of the utilized pasture in Kazakhstan, which is a prime example of a country well suited to grazing livestock production. Kazakhstan's dry continental climate also reduces the suitability of livestock production's main competitor for land, crop production, making it a suitable target area for development of range-based livestock production. Our results show that despite relatively low natural productivity, ample capacity exists to increase livestock production in Kazakhstan because large areas are characterized by low pasture utilization and off-take rate, and available biomass resources could support many more grazing animals, especially in the east and the northwest (Figure 2-9). Under conservative estimates of grazing range constraints and with 2015 productivity levels, beef production could be increased by 0.13 Mt (31%) or milk production by 3.11 Mt (60%), or some combination. However, harnessing even a fraction of these potentials would necessitate infrastructure development measures, such as more, improved processing facilities and improved road networks and market access. Repaired wells and outposts would allow the rejuvenation of old migration patterns and would open up distant pastures for even more potential production increases.

This research is an important step forward in the field of livestock mapping. Our model uses much finer-scale inputs than other global-scale products, and a direct measurement of biomass production, enabling us to make a gridded estimate of pasture distribution based on the energy demand of the livestock. The search algorithm we created is easily transferable to other regions where livestock are restricted to a central point, but can be adapted to any region where grazing patterns can be defined. The result of our research can be used to find patterns in livestock distribution, and to target areas where the supply is underutilized. Moreover, our results help the spatial targeting of possible investments for expanding the production of grazing livestock, including assessing the tradeoffs of production expansion with greenhouse gas emissions and biodiversity conservation.

2.6 Acknowledgments

We want to thank several colleagues who provided invaluable assistance and advice. We thank Anne Jungandreas for help with coding the early versions of the search algorithm, Alina Drokina for compiling the agricultural statistics from KazStat, Johannes Kamp for his expertise in grazing patterns, Norbert Hölzel for his expertise in plant species distribution, Matthias Baumann for his insights into land cover dynamics, Martin Petrick for his insights into household socioeconomics, Andrey Dara, Natalya Tsyhuyeva, and Alyona Chukhatina for their guidance and expertise during field trips, and Yerlan Syzdykov for his efforts in data procurement and his insights on large farm management in Kazakhstan. We are particularly grateful to Dauren Oshakbaev for his assistance, expertise, and coordinative efforts, and without whom this research could not have been completed.

Additionally, we are thankful to Ruslan Urazaliyev, Albert Salemgareyev, and the colleagues working for the Altyn Dala Conservation Initiative for their knowledge and information on wild grazers in Kazakhstan. We

are also grateful to Tamara Fetzl for sharing her map of global grazing intensity, allowing us to perform a qualitative comparison of similar research.

2.7 Supplementary material

Equation 2-S1: The piecewise linear function used to estimate the number of livestock owners in a settlement based on the total settlement population.

$$f(P) = \begin{cases} 0.95 * P, & P \leq 1000 \\ (0.95 - \frac{0.15}{5000 - 1000} * (P - 1000)) * P, & 1000 < P \leq 5000 \\ (0.8 - \frac{0.5}{10000 - 5000} * (P - 5000)) * P, & 5000 < P \leq 10000 \\ (0.3 - \frac{0.2}{50000 - 10000} * (P - 10000)) * P, & 10000 < P \leq 50000 \\ (0.1 - \frac{0.095}{1000000 - 50000} * (P - 50000)) * P, & 50000 < P \leq 1000000 \\ 0.005 * P, & P > 1000000 \end{cases}$$

where:

P = settlement population (2009 census)

$f(P)$ = settlement livestock owners

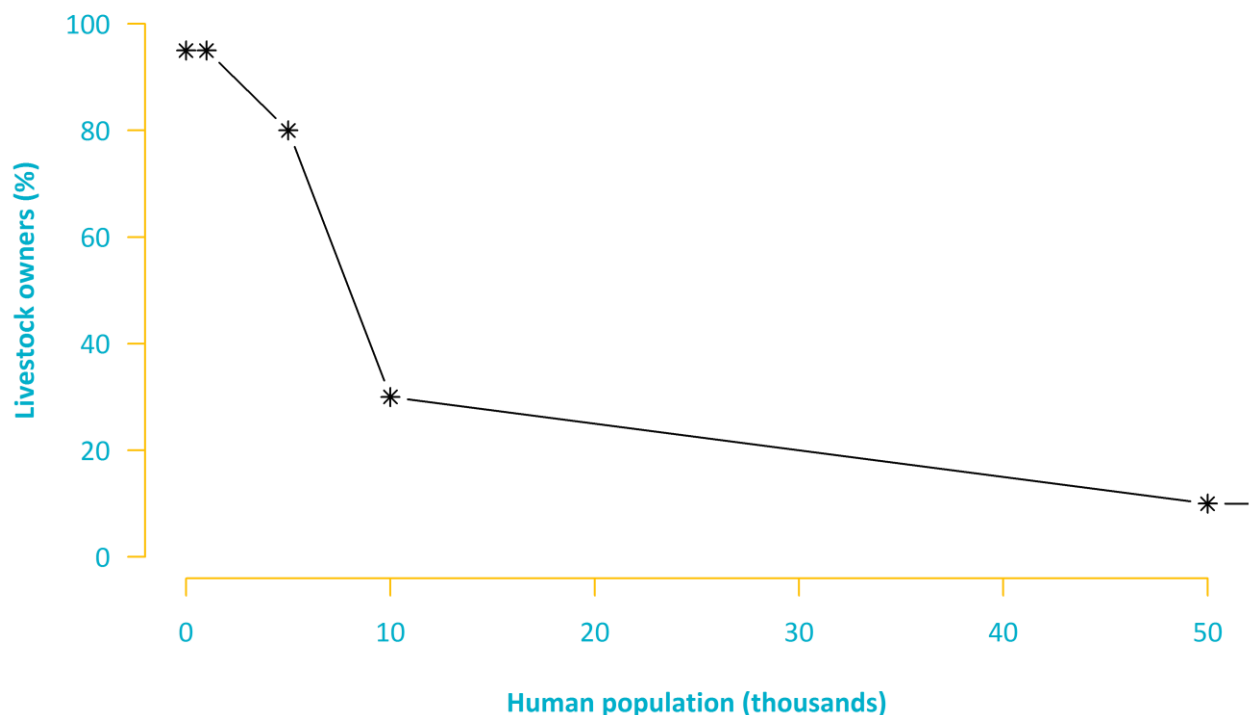


Figure 2-S1: Piecewise function for the distribution of livestock to settlements based on human population. The steps are 95% from 0-1,000, 80% at 5,000, 30% at 10,000, 10% at 50,000, and 0.5% at 1 million residents (not shown), with linear interpolation. Values were determined from expert opinion and personal observation. Note that this does not affect the total number of livestock, only their distribution within a district.

Table 2-S1: Assumptions made in the distribution model.

Assumption	Source	Impact
Livestock are located in settlements	(Alimaev & Behnke, 2008; Coughenour et al., 2008; Ellis & Lee, 2003; Kamp et al., 2012;	Nomadism is precluded, as are potential outposts and wells that are located far away from any settlement. Thus the areas furthest from settlements are the least likely to be distributed in this model

	Robinson, 2000)	
Livestock seek pastures with the highest productivity	(Deli et al., 2005; Kerven et al., 2016)	“Optimal forager” activity is severely truncated due to the introduction of search radii. Affects the distribution of individual livestock/farm types. The overall distribution is affected only at the edge of each settlement’s grazing area, where distributed area is clustered due to the priority of high-NPP values
Livestock graze on croplands	(Coughenour et al., 2008)	The total energy available for grazing increased by 293 PJ, or 8.3%. Most of this energy was located in the northcentral, where cropland dominates.

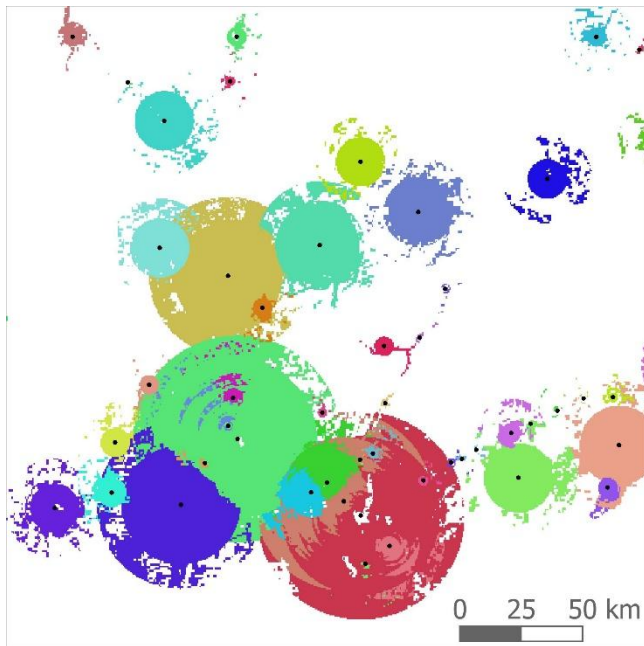


Figure 2-S2: A magnified view showing the result of the distribution model at the settlement level. Each unique color represents the land distributed to a unique settlement (black dots). This illustrates the operation of the search algorithm when settlements are in close proximity and their pasture requirements conflict.

Equation 2-S2: The equation used to estimate the number of livestock in each age group in each district in 2015 using the more detailed 2006 agricultural census.

$$L_{mr1a} = L_{mrl} * \frac{L_{oa}^C}{L_o^C}$$

where:

L = number of livestock

m = farm type

r = district

l = livestock type

a = age group

o = region where $o \ni r$

L^C = number of livestock in 2006 census

Table 2-S2: Values used in the calculation of total energy demand (Zhazyzbekov et al., 2008). The number of each livestock species are recorded at the district level for each farm type. Livestock numbers for each age group were recorded in the 2006 agricultural

census at the regional level (in which cattle were further divided into beef and dairy) (KazStat, 2008). The number of livestock in each age group of each livestock species in each district was estimated by multiplying the number of each livestock species by the number in each species' age group (in 2006) and dividing by the number of each livestock species (in 2006). Sheep and goat numbers were combined and sheep nutritive requirements were used, due to the low number of goats and their similar nutritive requirements.

Type	Breed	Age/Sex	Period	Mass (kg)	Gain (g/d)	Milk (kg/d)	ME (MJ/d)
Cattle	Beef	Cows	2 mos pre calving	400			91
Cattle	Beef	Cows	2 mos pre calving	450			98
Cattle	Beef	Cows	2 mos pre calving	500			105
Cattle	Beef	Cows	2 mos pre calving	550			112
Cattle	Beef	Cows	3-4 mos post calving	400			113
Cattle	Beef	Cows	3-4 mos post calving	450			117
Cattle	Beef	Cows	3-4 mos post calving	500			122
Cattle	Beef	Cows	3-4 mos post calving	550			127
Cattle	Beef	Cows	2nd half lactation	400			92
Cattle	Beef	Cows	2nd half lactation	450			101
Cattle	Beef	Cows	2nd half lactation	500			109
Cattle	Beef	Cows	2nd half lactation	550			117
Cattle	Beef	Bulls	Not coupling	800			83.2
Cattle	Beef	Bulls	Avg load	800			90
Cattle	Beef	Bulls	Inc load	800			110
Cattle	Beef	Heifers	9-10 mos	244	575		69
Cattle	Beef	Heifers	9-10 mos	260	675		78
Cattle	Beef	Heifers	11-12 mos	277	575		76
Cattle	Beef	Heifers	11-12 mos	300	675		85
Cattle	Beef	Heifers	13-14 mos	311	575		83
Cattle	Beef	Heifers	13-14 mos	340	675		94
Cattle	Beef	Heifers	15-16 mos	345	575		90
Cattle	Beef	Heifers	15-16 mos	380	675		104
Cattle	Beef	Heifers	17-20 mos	413	575		105
Cattle	Beef	Heifers	17-20 mos	420	675		112
Cattle	Beef	Bull calves	9-10 mos	279	825		72
Cattle	Beef	Bull calves	9-10 mos	285	925		79
Cattle	Beef	Bull calves	11-12 mos	330	825		80
Cattle	Beef	Bull calves	11-12 mos	340	925		88
Cattle	Beef	Bull calves	13-14 mos	379	825		86
Cattle	Beef	Bull calves	13-14 mos	396	925		94
Cattle	Beef	Bull calves	15-16 mos	428	825		92
Cattle	Beef	Bull calves	15-16 mos	451	925		102
Cattle	Beef	Calves	0-6 mos				32
Cattle	Beef	Calves	6-9 mos				54.6
Cattle	Beef	Calves	10-12 mos				78.5
Cattle	Beef	Calves	13-15 mos				93.5
Cattle	Dairy	Cows	Milking 1st half	400		6	72.5
Cattle	Dairy	Cows	Milking 1st half	400		10	106
Cattle	Dairy	Cows	Milking 1st half	400		14	127.5
Cattle	Dairy	Cows	Milking 1st half	400		18	149
Cattle	Dairy	Cows	Milking 1st half	400		22	172.5
Cattle	Dairy	Cows	Milking 1st half	400		26	197.5
Cattle	Dairy	Cows	Milking 1st half	400		30	227.5
Cattle	Dairy	Cows	Milking 2nd half	400		5	61
Cattle	Dairy	Cows	Milking 2nd half	400		7	83.5

Cattle	Dairy	Cows	Milking 2nd half	400	9	100.5
Cattle	Dairy	Cows	Milking 1st half	500	6	79.5
Cattle	Dairy	Cows	Milking 1st half	500	10	115
Cattle	Dairy	Cows	Milking 1st half	500	14	137
Cattle	Dairy	Cows	Milking 1st half	500	18	158
Cattle	Dairy	Cows	Milking 1st half	500	22	180.5
Cattle	Dairy	Cows	Milking 1st half	500	26	205.5
Cattle	Dairy	Cows	Milking 1st half	500	30	230.5
Cattle	Dairy	Cows	Milking 2nd half	500	5	65
Cattle	Dairy	Cows	Milking 2nd half	500	7	94.5
Cattle	Dairy	Cows	Milking 2nd half	500	9	109.5
Cattle	Dairy	Cows	Dry or sterile	400	0	66
Cattle	Dairy	Cows	Dry or sterile	500	0	78
Cattle	Dairy	Cows	Dry or sterile	400	0	78
Cattle	Dairy	Cows	Dry or sterile	500	0	86
Cattle	Dairy	Bulls	Not coupling	600		70
Cattle	Dairy	Bulls	Not coupling	700		78
Cattle	Dairy	Bulls	Not coupling	800		84
Cattle	Dairy	Bulls	Not coupling	900		91
Cattle	Dairy	Bulls	Not coupling	1000		97
Cattle	Dairy	Bulls	Not coupling	1100		102
Cattle	Dairy	Bulls	Not coupling	1200		108
Cattle	Dairy	Bulls	Avg load	600		76
Cattle	Dairy	Bulls	Avg load	700		83
Cattle	Dairy	Bulls	Avg load	800		90
Cattle	Dairy	Bulls	Avg load	900		97
Cattle	Dairy	Bulls	Avg load	1000		104
Cattle	Dairy	Bulls	Avg load	1100		110
Cattle	Dairy	Bulls	Avg load	1200		117
Cattle	Dairy	Bulls	Inc load	600		92
Cattle	Dairy	Bulls	Inc load	700		102
Cattle	Dairy	Bulls	Inc load	800		110
Cattle	Dairy	Bulls	Inc load	900		119
Cattle	Dairy	Bulls	Inc load	1000		127
Cattle	Dairy	Bulls	Inc load	1100		134
Cattle	Dairy	Bulls	Inc load	1200		141
Sheep	Wool	Ewes	Preg 1st half	50		12.5
Sheep	Wool	Ewes	Preg 1st half	60		13.5
Sheep	Wool	Ewes	Preg 2nd half	50		14.5
Sheep	Wool	Ewes	Preg 2nd half	60		16.5
Sheep	Meat/wool	Ewes	Preg 1st half	60		12.1
Sheep	Meat/wool	Ewes	Preg 1st half	70		13
Sheep	Meat/wool	Ewes	Preg 2nd half	60		16
Sheep	Meat/wool	Ewes	Preg 2nd half	70		17.2
Sheep	Meat/tallow	Ewes	Preg 1st half	60		13.5
Sheep	Meat/tallow	Ewes	Preg 1st half	70		14.5
Sheep	Meat/tallow	Ewes	Preg 2nd half	60		17.5
Sheep	Meat/tallow	Ewes	Preg 2nd half	70		18.5
Sheep	Wool	Ewes	Suckling 1st half	50		20
Sheep	Wool	Ewes	Suckling 1st half	60		23
Sheep	Wool	Ewes	Suckling 2nd half	50		15.5
Sheep	Wool	Ewes	Suckling 2nd half	60		17

Sheep	Meat/wool	Ewes	Suckling 1st half	60		22
Sheep	Meat/wool	Ewes	Suckling 1st half	70		23
Sheep	Meat/wool	Ewes	Suckling 2nd half	60		18.4
Sheep	Meat/wool	Ewes	Suckling 2nd half	70		19.2
Sheep	Meat/tallow	Ewes	Suckling 1st half	60		21
Sheep	Meat/tallow	Ewes	Suckling 1st half	70		22
Sheep	Meat/tallow	Ewes	Suckling 2nd half	60		18.5
Sheep	Meat/tallow	Ewes	Suckling 2nd half	70		19.5
Sheep	Wool & meat/wool	Rams	Not coupling	90		19
Sheep	Wool & meat/wool	Rams	Not coupling	100		20
Sheep	Wool & meat/wool	Rams	Not coupling	110		21
Sheep	Meat/tallow	Rams	Not coupling	80		19
Sheep	Meat/tallow	Rams	Not coupling	90		20
Sheep	Meat/tallow	Rams	Not coupling	100		21
Sheep	Wool & meat/wool	Rams	Coupling	90		24
Sheep	Wool & meat/wool	Rams	Coupling	100		25
Sheep	Wool & meat/wool	Rams	Coupling	110		26
Sheep	Meat/tallow	Rams	Coupling	80		24
Sheep	Meat/tallow	Rams	Coupling	90		25
Sheep	Meat/tallow	Rams	Coupling	100		26
Sheep	Wool	Ewe lambs	4-6 mos	27.5		8.525
Sheep	Wool	Ewe lambs	6-8 mos	33		9.625
Sheep	Wool	Ewe lambs	8-10 mos	38		10.725
Sheep	Wool	Ewe lambs	10-12 mos	41		11
Sheep	Wool	Ewe lambs	12-18 mos	46		11.275
Sheep	Meat/wool	Ewe lambs	4-6 mos	38.5		11
Sheep	Meat/wool	Ewe lambs	6-8 mos	38.5		12.1
Sheep	Meat/wool	Ewe lambs	8-10 mos	43		13.2
Sheep	Meat/wool	Ewe lambs	10-12 mos	47.5		14.025
Sheep	Meat/wool	Ewe lambs	12-18 mos	51.5		14.025
Sheep	Wool	Ram lambs	4-6 mos	32		11.275
Sheep	Wool	Ram lambs	6-8 mos	39.5		12.43
Sheep	Wool	Ram lambs	8-10 mos	45		13.75
Sheep	Wool	Ram lambs	10-12 mos	49.5		15.18
Sheep	Wool	Ram lambs	12-18 mos	61.5		15.4
Sheep	Meat/wool	Ram lambs	4-6 mos	36.5		13.2
Sheep	Meat/wool	Ram lambs	6-8 mos	44.5		14.3
Sheep	Meat/wool	Ram lambs	8-10 mos	52.5		15.4
Sheep	Meat/wool	Ram lambs	10-12 mos	60		16.775
Sheep	Meat/wool	Ram lambs	12-18 mos	70		17.325
Horses	Meat	Stallions		350	1000	93.2
Horses	Meat	Stallions		400	1000	97.4
Horses	Meat	Stallions		450	1000	101
Horses	Meat	Stallions		500	1000	108.8
Horses	Meat	Stallions		550	1000	112
Horses	Meat	Stallions		600	1000	122.4
Horses	Meat	Foals	0-1 mos	70	1300	42
Horses	Meat	Foals	1-2 mos	105	1000	45
Horses	Meat	Foals	2-3 mos	133.5	900	47
Horses	Meat	Foals	3-4 mos	160.5	900	52
Horses	Meat	Foals	4-5 mos	187.5	900	56
Horses	Meat	Foals	5-6 mos	214.5	900	60

Horses	Meat	Foals	6-7 mos	235.5	900		60
Horses	Meat	Foals	7-8 mos	258	1000		71
Horses	Meat	Foals	8-9 mos	291	1300		88
Horses	Milk	Mares			400	10	84.8
Horses	Milk	Mares			400	12	92.1
Horses	Milk	Mares			400	14	98.4
Horses	Milk	Mares			500	14	105.7
Horses	Milk	Mares			500	16	113.1
Horses	Milk	Mares			500	18	120.4
Horses	Milk	Mares			500	20	126.5

Table 2-S3: Age groups used in the estimation of livestock energy demand. Restrictions are noted when the age group is a subset of the Age/Sex in Table 2-S2. Nomenclature of the age group is as follows (square brackets enclose string variables): [*Beef/Dairy*][Function]_*age*_*reproduction stage*]. * – if applicable. Function – common name considering age, sex, and castration.

Age group	Age/Sex in Table 2-S2	Period/weight restriction
BeefCows	Beef Cows	
BeefBulls_breeding	Beef Bulls	
BeefHeifers	Beef Heifers	
BeefHeifers_1to2yrs	Beef Heifers	13-16 mos.
BeefHeifers_1to2yrs_inseminated	Beef Heifers	17-20 mos.
BeefHeifers_2yrs	Beef Heifers	17-20 mos.
BeefCalves_heifers_0to1yr	Beef Calves	0-12 mos.
BeefCalves_bulls_0to1yr	Beef Calves	0-12 mos.
BeefCalves_bulls_1yr	Beef Bull calves	13-16 mos.
BeefSteers	Beef Bull calves	
BeefOxen	Beef Bulls	Not coupling
BeefCattle_finishing	Beef Bull calves	15-16 mos.
BeefBuffaloes	Beef Bulls	Not coupling
DairyCows	Dairy Cows	
DairyBulls_breeding	Dairy Bulls	
DairyHeifers	Beef Heifers	
DairyHeifers_1to2yrs	Beef Heifers	13-16 mos.
DairyHeifers_1to2yrs_inseminated	Beef Heifers	17-20 mos.
DairyHeifers_2yrs	Beef Heifers	17-20 mos.
DairyCalves_heifers_0to1yr	Beef Calves	0-12 mos.
DairyCalves_bulls_0to1yr	Beef Calves	0-12 mos.
DairyCalves_bulls_1yr	Beef Bull calves	13-16 mos.
DairySteers	Beef Bull calves	
DairyOxen	Beef Bulls	Not coupling
DairyCattle_finishing	Beef Bull calves	15-16 mos.
DairyBuffaloes	Beef Bulls	Not coupling
EweDoe_1yr	Ewes	
RamBuck_breeding	Rams	
LambKid_0to1yr	Lambs	
Wethers_1yr	Rams	Not coupling
Mares_3yrs	Mares	
Stallions_breeding	Stallions	
Foals_0to1yr	Foals	
Fillies_1to3yrs	Stallions	350 kg, 400 kg, 450 kg
Colts_1to3yrs	Stallions	350 kg, 400 kg, 450 kg
Colts_3yrs	Stallions	500 kg, 550 kg, 600 kg
Geldings	Stallions	

Equation 2-S3: The equation used to estimate the amount of energy supplied by fodder to each livestock species in each district in 2015.

$$C_{mrfl} = P_{mrf} * \frac{C_{ofl}}{C_{of}}$$

where:

C = consumption (MJ)

P = production (MJ)

m = farm type

r = district

f = fodder type

l = livestock type

o = region where $o \ni r$

Table 2-S4: Conversion ratios used to convert kg to MJ (Forage On-Line, 2009). Production of each fodder type is recorded at the district level for each farm type. Consumption of each fodder type by each livestock species is recorded at the regional level (all farm types combined). The consumption of each fodder type by each livestock species at the district level for each farm type was estimated by multiplying the production of each fodder type by the consumption of each fodder type by each livestock species and dividing by the total consumption of each fodder type by each livestock species.

Feed class	ME (MJ/kg)
FeedGrain	12.98
FeedLegume	13.2
SilageNonCorn	1.98
FeedRoot	1.65
FeedMelon	0.88
FeedCorn	2.2
CornGreenFodder	2.2
CornSilage	2.2
Hay	5.72
HayPasture	5.72
HayPastureCultivated	5.72
HayPastureSeeded	5.72
HayPastureNatural	5.72
HayAnnualGrass	5.61
HayPerennialGrass	5.61
GrassFodder	2.75
GrassFodderSeeded	2.53
GrassFodderNatural	2.86
GrassFodderAnnual	1.87
GrassFodderPerennial	2.75
SeedGrassAnnual	3.41
SeedGrassPerennial	3.41
GrazingGrassAnnual	2.53
GrazingGrassPerennial	2.75

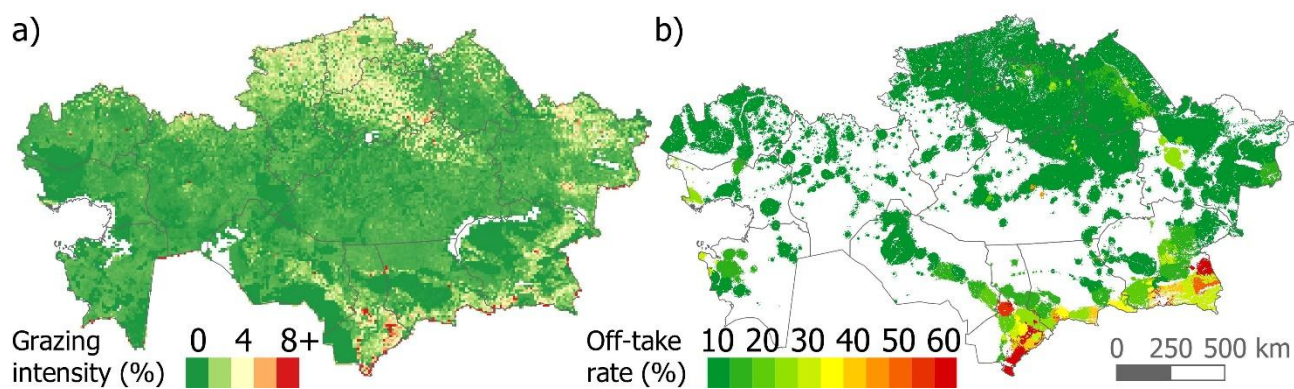


Figure 2-S3: Side-by-side comparison with the results of a) Fetzel et al. (2017) and b) our model. Note that the units are not directly convertible. However, using very different methods and inputs, both maps show similar distributions of relative grazing activity. White areas in both maps represent unutilized area. a) Reproduced with permission of the authors.

Chapter 3:

Changes in livestock systems explain post-Soviet fire trends on the Eurasian steppe better than climate

Regional Environmental Change, 2025, submitted

Brett R. Hankerson, Florian Schierhorn, Johannes Kamp, Tobias Kuemmerle, Daniel Müller

Abstract

In grassland ecosystems, fire plays an important role in maintaining biodiversity and ecological functioning but also causes substantial greenhouse gas emissions. Both climate and herbivory are key determinants of fire regimes, yet the relative importance of these factors remains debated. We focused on the steppes of Kazakhstan—one of the world’s largest grasslands and a global fire hotspot—to assess the relative importance of climate and grazing patterns on fire regimes. Specifically, we made use of the natural experiment that the post-Soviet collapse of the Kazakh livestock sector provided. We used the MODIS Burned Area Product and calculated annual livestock grazing demand (required forage intake) from 2001 to 2019. We estimated a binomial mixed-effects model to extricate the impact of grazing demand and climate factors on fire occurrence. Our results show that fire regimes changed markedly on the Kazakh steppes, with exceptionally high frequencies and extent of fires in the 2000s. We found a clearly negative association between grazing demand and burned area; in other words, more heavily grazed areas burned less frequently. Moreover, annual grazing demand added more explanatory power to trends in fire occurrence than precipitation, temperature, relative humidity, or growing degree days. Given that livestock herding is declining in many grassland regions, and native grazers have been lost or greatly reduced in the past, our study highlights the increasing risk of fire with less grazing, but also the potential for grazing restoration to mitigate such risks in the world’s grassland regions.

3.1 Introduction

Grasslands cover more than a quarter of Earth's ice-free land surface (Dinerstein et al., 2017), harbor unique biodiversity, and are an integral part of the global carbon cycle (Bai & Cotrufo, 2022). However, large areas of former grasslands have been converted for human uses, such as cropland, cities, and infrastructure (IPBES, 2019; Ramankutty & Foley, 1999; Stevens et al., 2022; White et al., 2000). Moreover, even where grasslands were not converted, they are often used for livestock husbandry, either as pastures or for growing fodder and forage (Herrero, Havlík, et al., 2013). As a result, few natural, undisturbed grasslands remain (IPBES, 2019; Scholtz & Twidwell, 2022). Grasslands are among the most at-risk ecosystems in the world, imperiled by conversion due to expanding agriculture (Hoekstra et al., 2005; Lambin & Meyfroidt, 2011), fragmentation (Haddad et al., 2015; Hobbs et al., 2008), degradation (Bardgett et al., 2021; Prishchepov et al., 2021), and climate change (Godde et al., 2020). Additionally, grassland conservation receives less attention than other habitats, such as forests (Andrade et al., 2019; Grau et al., 2015; Pärtel et al., 2005; Scholtz & Twidwell, 2022). Much remains unknown or hotly debated about grasslands, from the seemingly simple estimation of their global extent to their capacity to store carbon, their resilience in the face of climate change, and what sustainable livestock production on these grasslands entails (Arneth et al., 2019; Carbutt et al., 2017; Godde et al., 2018; Piipponen et al., 2022).

Fire is an integral feature of grassland ecosystems, with widespread effects on their functioning (Bond et al., 2005). For example, fires determine plant community composition and plant diversity in grasslands (Fuhlendorf & Engle, 2004), and recurring fires can suppress the growth of woody plants and herbs while favoring fire-adapted grasses (Freitag et al., 2021). Fires release nutrients stored in plants and can promote post-fire vegetation productivity increases. Many charismatic animals, such as large, mobile grazers, apex predators, and birds of prey benefit from the conditions fires create in grassland ecosystems (Smelansky et al., 2015). Likewise, restoring natural fire regimes, and thus the links between fire and grazing, can lead to healthier, more sustainable grasslands, regardless of whether the grazing is done by wild animals or livestock (Fuhlendorf et al., 2009). However, fires can also promote the spread of invasive species and cause considerable air pollution (Dubinin et al., 2010; Scholes & Archer, 1997). The carbon cycle on grasslands is greatly influenced by the predominate fire regime, with fires leading to considerable greenhouse gas (GHG) emissions (van der Werf et al., 2010). Many land-use practices, including livestock husbandry, have been linked to increases in fire occurrence and thus higher pollution and emissions (Moreno et al., 2014). Altering natural fire regimes can also have detrimental effects on biodiversity, with savannas and grasslands at the highest risk of species extinction from changes in fire activity (Kelly et al., 2020). Many smaller grassland animals, such as rodents and ground-nesting birds, have a precarious relationship with fire, a balance that, when upset, can be disastrous for species populations (Koshkina et al., 2022; Smelansky et al., 2015). Given that globally up to 40% of total burned area occurs on grasslands

(Rabin et al., 2015), it is important to understand the trends in grassland fires and which factors determine these trends.

Three factors contribute to fire occurrence in grasslands: ignition sources, fuel moisture, and fuel load (Bowman et al., 2011; Dubinin et al., 2011). Ignition sources may be natural—predominantly through lightning—or anthropogenic, either inadvertent (e.g., sparks from agricultural machinery, cigarettes) or intentional (e.g., to remove senescent vegetation from pastures) (Bradstock, 2010). Fuel moisture is driven by temperature, precipitation, wind, and humidity (Bradstock, 2010). These variables can be measured over short time periods (i.e., weather) or longer periods (i.e., climate), with fire occurrence being strongly linked to both weather and climate (Flannigan & Wotton, 2001). Finally, fuel load is determined by two opposing factors. On one hand, fuel load is driven by net primary productivity (NPP), which in turn is driven by climate, soils, and anthropogenic factors such as land use (Marlon et al., 2008). On the other hand, fuel load is also determined by the amount of biomass that is removed, which happens predominantly through herbivory (i.e., natural herbivores or domestic livestock). Where herbivory is suppressed or absent, fuel loads increase and fire becomes the main force through which biomass is consumed (Fuhlendorf et al., 2009). There are also important interactions and feedbacks between fire and grazing. For example, recently burned areas produce higher quality forage, which can attract grazers, increasing herbivory and promoting vegetative growth (Allred et al., 2011; Díaz et al., 2007). Conversely, heavy grazing suppresses fires through a reduction of fuel loads. Given these complex interactions between climate, fire, and herbivory, it is perhaps unsurprising that the relative importance of these factors continues to be understudied and weakly understood, particularly for temperate grasslands (Smelansky et al., 2015).

Two additional factors contribute to fire size (burned area), and thus complete the picture of regional fire regimes: wind speed and fuel continuity, both driven by topography and land cover (Bowman et al., 2011). Globally, burned area has decreased considerably, by approximately 30% from 2000 to 2019 (Zheng et al., 2021). Precipitation patterns explain much of the inter-annual variability in burned area, but changes in climate parameters do not explain well the long-term decline in burned area, which appears to correlate more strongly with land use, including livestock grazing (Rouet-Leduc et al., 2021). Importantly, burned area has not declined universally, with some areas seeing an increase in fire activity. Areas that deviate from the global trend are particularly interesting and can help to unravel the relative importance of climate vs. land-use factors in determining burning. One such region are the Eurasian steppes, an arid grassland region where fires are frequent, intense and large (Archibald et al., 2013), rendering the region a global fire hotspot (Cao et al., 2015; Hantson et al., 2013). Understanding what drives fire patterns and trends in these steppes is therefore valuable.

Fire occurrence in the Kazakh steppe is widespread, but spatially and temporally diverse. There is a strong north-south precipitation gradient, from 350 mm per year on the northern edge down to 150 mm per year on the southern edge of the steppes (Afonin et al., 2008). However, this precipitation gradient does not

appear to be well-reflected in spatial patterns of burning (Y. Xu et al., 2021). At the same time, Kazakhstan has seen drastic fluctuations in livestock populations over the last decades, resulting in spatial and temporal variations in grazing pressure. Specifically, with the collapse of the Soviet Union, grazing livestock numbers in Kazakhstan plummeted to 30% of 1990 numbers in less than 10 years (KazStat, 2019), with an 80% decline in sheep numbers and a more than 50% decline in cattle numbers after 1991, and there was widespread cropland abandonment (Kraemer et al., 2015). Since the 2000s, grazing livestock numbers have recovered to over 60% of 1990 numbers (KazStat, 2019), however, these increases were neither uniform in space nor among farm types (which have varying degrees of access to advanced technology and infrastructure). As a result, there is large heterogeneity in grazing pressure on Kazakh steppes (Kerven et al., 2021). This provides a unique “natural experiment” to study the links between fire, grazing and climate variables.

Steppe fires have been identified as both a threat to biodiversity and a major research need in Kazakhstan (Kamp et al., 2016). Prior work has attempted to assess aspects of fire regimes and the factors that determine them but have often focused on limited time periods or study regions. Recently, burned area in northcentral Kazakhstan was mapped across three time periods (Dara, Baumann, Hölzel, et al., 2020): the peak of agricultural production in the late Soviet period (1989-1991), the low point of agricultural production (1999-2001), and after a major recovery of cropping and livestock sectors (2014-2016). Fires increased in size and number on croplands and pastures between 1990 and 2000, especially on abandoned former cropland. Between 2000 and 2015, total burned area decreased slightly, and burning shifted from croplands to grasslands (Dara, Baumann, Hölzel, et al., 2020). While this revealed important insights, the work is limited by the snapshot-like analysis, failing to capture the temporal variability, and not exploring the relevance of climate variables. The latter is particularly noteworthy, as in nearby Kalmykia, southern Russia, climate became strongly correlated with burned grassland area after livestock numbers had plummeted (Dubinin et al., 2011). In a nation-wide study for Kazakhstan, wetter climate conditions and increased grazing pressure were the principal drivers of the decline in burned area between 2002 and 2016 (Hao et al., 2021). However, Hao and others (2021) utilized coarse, global climate and vegetation products, and province-level livestock numbers, which is a major limitation given that there are distinct and spatially heterogeneous patterns of grazing pressure as shown by Dara and others (2020). In addition, no conversion to livestock units was made (i.e., a sheep was treated as equal to a cow), and horses, which are a major grazer in Kazakhstan, were ignored altogether (Hao et al., 2021). In sum, although prior work has highlighted the potential roles of both livestock grazing and climate variables in driving the strong changes in fire regimes in Kazakhstan’s steppes, an assessment at the spatial and temporal resolutions necessary to unravel the relative importance of these factors is missing.

Against this background, we aimed to answer two overarching research questions: 1) How has the burned area extent evolved across the Kazakh steppe from 2001 to 2019, and 2) what were the important factors

determining observed changes in burned area? We hypothesized that grazing demand is an important predictor of burned area when compared to climate predictors, namely precipitation, temperature, relative humidity, and growing degree days. We further hypothesized that grazing demand in one year will have a larger impact on the subsequent year's burned area, and that this impact will be negative.

3.2 Materials and methods

3.2.1 Study area

Northern Kazakhstan contains a massive tract of the Eurasian steppe, including large, intact areas (Scholtz & Twidwell, 2022). Much of the far northern part of this region is used for rainfed agriculture. Aridity increases toward the south and southwest, where the landscape transitions to semi-desert and eventually desert around the Aral Sea and along the border with Uzbekistan. To the east and southeast, foothills and eventually the western edge of the Altai Mountains and the northern edge of the Tien Shan Mountains rise up, supporting alpine ecosystems. We limited our research area to the region that has the highest co-occurrence of grazing and fire (1.83 million km² across northern Kazakhstan, encompassing 124 districts (*rayon*); Figure 3-1). We chose to use the land-cover map of Klein and others (2012) for its representation of the midpoint of the study period and its creation specifically for Central Asia with local expertise and ground-truthing. We further masked areas where livestock grazing is unlikely to occur: urban areas, forests, and croplands. Of the 1.83 million km² total, we considered 1.48 million km² available for grazing.

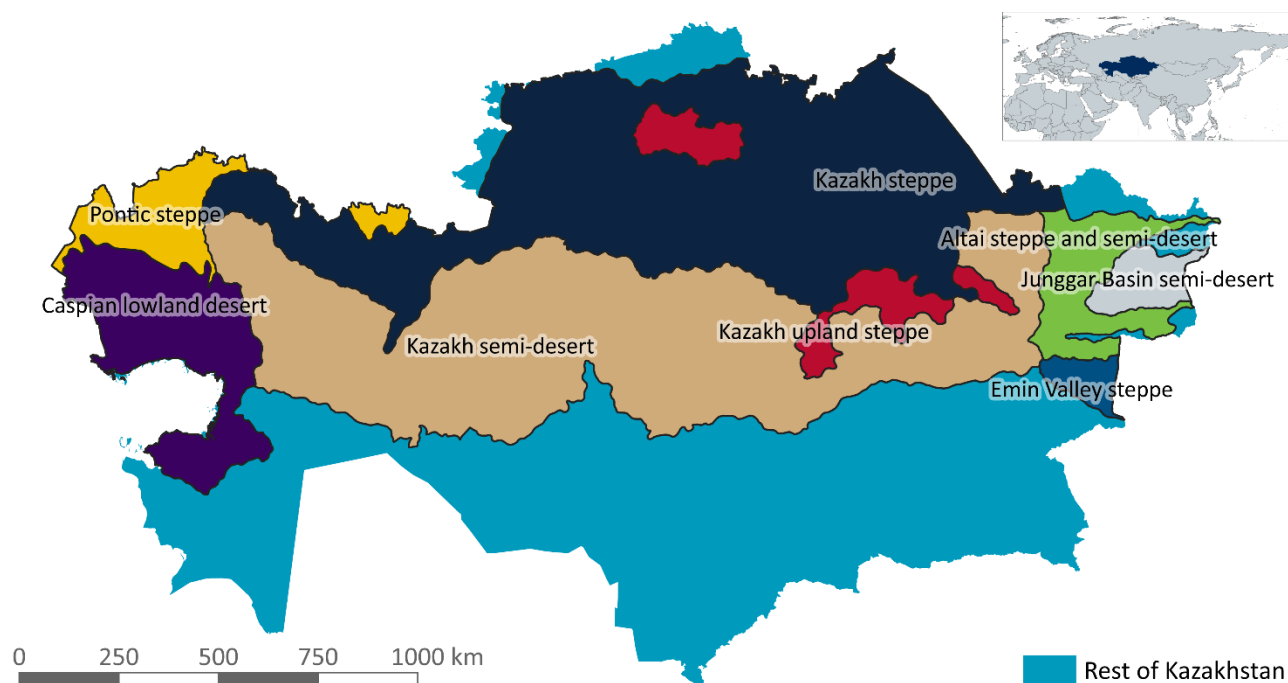


Figure 3-1. Ecoregions used in this research (Dinerstein et al., 2017). The Kazakh steppe and its ecologically similar neighboring regions (colored polygons) encompass 124 of Kazakhstan's 200 administrative districts.

3.2.2 Livestock grazing demand

Grazing demand is the required intake of forage by livestock. We expanded the calculations of Hankerson and others (2019) (originally calculated for 2015) to determine the annual livestock grazing demand across

the study region. We obtained annual livestock numbers at the district level from the Kazakh National Statistics Agency (KazStat, 2019). To determine the energy demand of the livestock, we used the 2006 agricultural census to divide the herds into age and function groups (e.g. beef heifers) (KazStat, 2008). We then applied recommended energy intake values from the Ministry of Agriculture (Zhazylybekov et al., 2008). We summed these values to create a total livestock energy requirement for each district. We used district-level gross yields (KazStat, 2019) to determine annual fodder production, which we converted to energy and then subtracted from total livestock energy demand, resulting in the total energy demand of livestock from grazing. We then converted the annual grazing demand to units of energy per area grassland for each district. We introduced a lag of one year to account for the “end of year” value of grazing demand (Table 3-).

3.2.3 Climate indicators

Monthly precipitation and average temperature values were obtained from the Climate Research Unit (CRU) (Harris et al., 2014). Annual growing degree days (base 5°C) (Wouters, 2021) and monthly relative humidity (Hersbach et al., 2018) were taken from ERA5 reanalyses. The gridded data were averaged to produce a single value for each district. Here we were interested in annual and seasonal values—spring (March-May), summer (June-August), fall (September-November), and winter (December-February), as well as fire season (May-October), and fire off-season (November-April). For simplicity we refer to these variables as climate, for both annual and long-term analyses. For precipitation, the sum of the given period was calculated. For temperature and relative humidity, the mean of the given period was calculated. There were 124 districts and 19 years, of which we used 18 after excluding the lag year, hence 2,232 observations of each variable. Lagging the climatic variables by one year did not improve the model, therefore the current-year climatic variables were combined with the previous year’s grazing demand.

3.2.4 Fire indicators

We used the Terra and Aqua combined MCD64A1 v6 Burned Area product to estimate the annual area burnt in the study area (Giglio et al., 2015). We stacked the monthly MODIS 500m resolution images to create an annual binary time series of burned or unburned areas. We used the land-cover map of Klein and others (2012) to mask cultivated areas, artificial surfaces, forests, bare areas, ice and snow, and waterbodies. The resultant grassland map, along with an administrative district map (GADM, 2018), allowed us to calculate the proportion of grassland burnt in each district for each year.

3.2.5 Statistical analysis

We used a binomial generalized linear mixed-effects model (GLMM) to regress the predictors against the observed values of burned area (Bolker et al., 2009; Warton & Hui, 2011). Fixed-effects variables in our models were annual grazing demand (MJ/km²), annual cumulative growing degree days, and seven aggregations of total precipitation (mm), average temperature (°C), and relative humidity (%): annual, fire

season, off-season, spring, summer, fall, and winter. We included administrative district identifiers as random effects to account for the non-independence of repeated sampling of burnt areas within the same district in different years. We assume topography doesn't change over the study period, and thus slope—an important driver of fire—is accounted for at the district level as a random effect. All variables were normalized to compare different units and different scales of magnitude. The binomial regression followed the form $p = \frac{e^{\beta_0 + \beta_1 x + \beta_2 x^2}}{1 + e^{\beta_0 + \beta_1 x + \beta_2 x^2}}$ where $p = \text{proportion burnt}$ and $\beta_0 + \beta_1 x + \beta_2 x^2$ is the quadratic (or linear if reduced to $\beta_0 + \beta_1 x$) regression expression (Crawley, 2013). We determined the goodness-of-fit for the aforementioned combinations of variables using conditional and marginal R^2 . Marginal R^2 measures variance explained by fixed factors, while conditional R^2 measures variance explained by both fixed and random factors (Nakagawa & Schielzeth, 2013). Akaike Information Criterion (AIC) was calculated to determine model strength (Mazerolle, 2006). The calculations were performed using the “arm” and “lme4” packages within R (Gelman et al., 2022). In addition to single-variable models, we explored multi-variable models to determine if combining variables produced better models.

3.3 Results

3.3.1 Temporal trends in burned area

Between 2001 and 2019, the annual burned area exceeded 5% (about 74,000 km²) of the total grassland area in seven years (Figure 3-2a), of which six years occurred between 2001 and 2010. The Kazakh steppe has experienced a general downward trend in burned area of 3,670 km² per year over these 19 years, though with high variation between years. Precipitation experienced a general decrease during the 2000s, followed by large inter-annual variation throughout the 2010s (Figure 3-2b). Temperature was relatively stable and relatively high during the 2000s, before also entering a period of larger inter-annual variability in the 2010s. Grazing demand has risen steadily (mirroring the rebounding livestock numbers since circa 2000) (Figure 3-2c). The observable break in 2011 is an artifact of a referendum in statistical counting (Nazarbayev, 2010), and is accounted for by the GLMM.

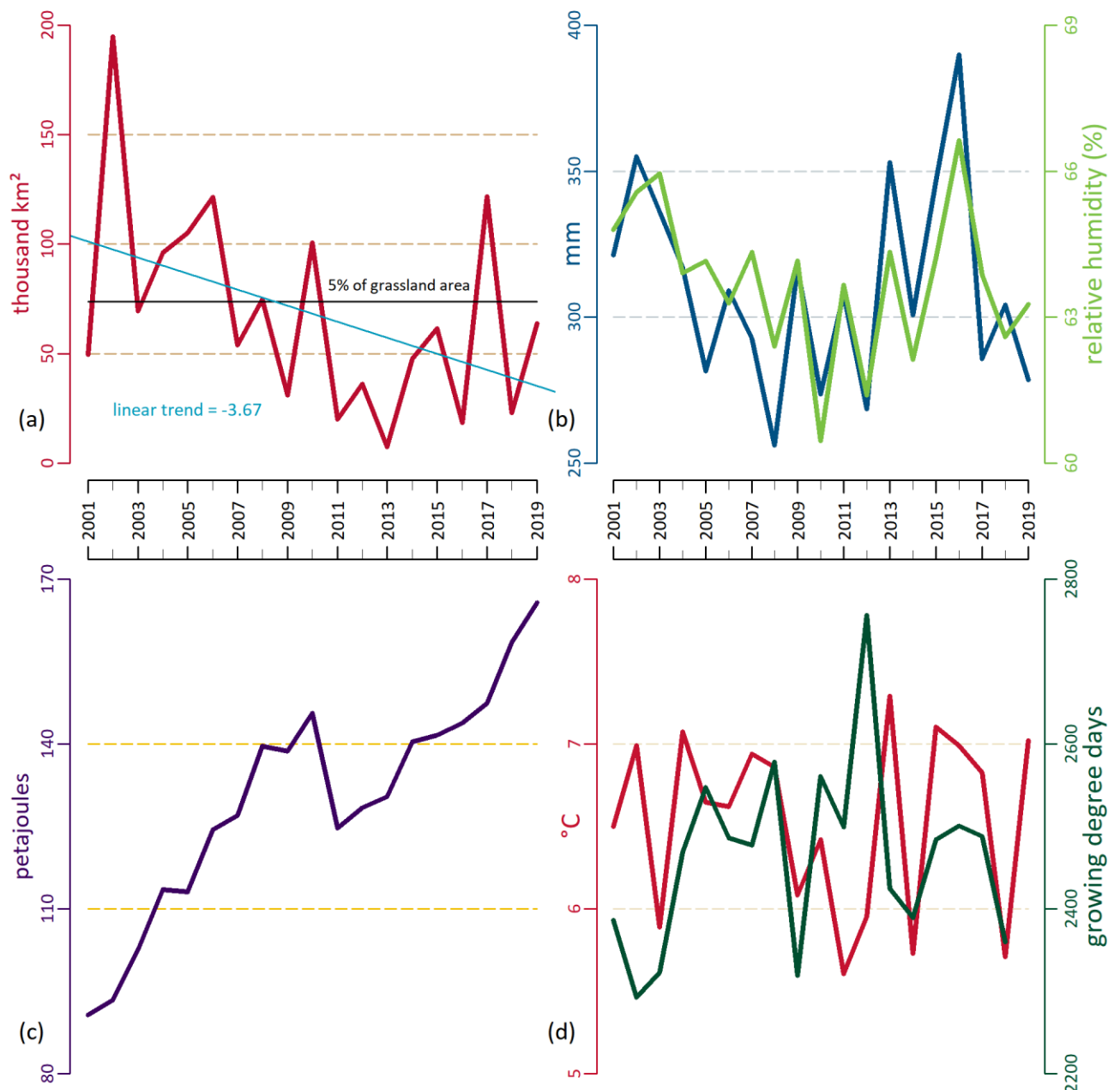


Figure 3-2. (a) Annual burned area extent on grassland in our study region (Giglio et al., 2015). The linear trendline is for visualization purposes only. (b) Average annual precipitation (blue) and average annual relative humidity (green) across the study region (Harris et al., 2014; Hersbach et al., 2018). (c) Annual grazing demand of grazing livestock in the study region. The energy equivalent was calculated using annual national statistics bulletins (KazStat, 2019), the 2006 agricultural census (KazStat, 2008), and recommended intake values (Zhazylbekov et al., 2008). See Hankerson and others (2019) for calculations. (d) Average annual temperature and average annual growing degree days (Harris et al., 2014; Wouters, 2021).

3.3.2 Spatial trends in burned area

Across the Kazakh steppe, the most frequently burned areas occurred across the middle and northeast of the study area, bordering the predominately crop-producing region in the northcentral (Figure 3-3). Of the grassland in the study area over the 19-year study period, 42% burned at least once, 21% at least twice, 10% at least three times, and 4% four or more times.

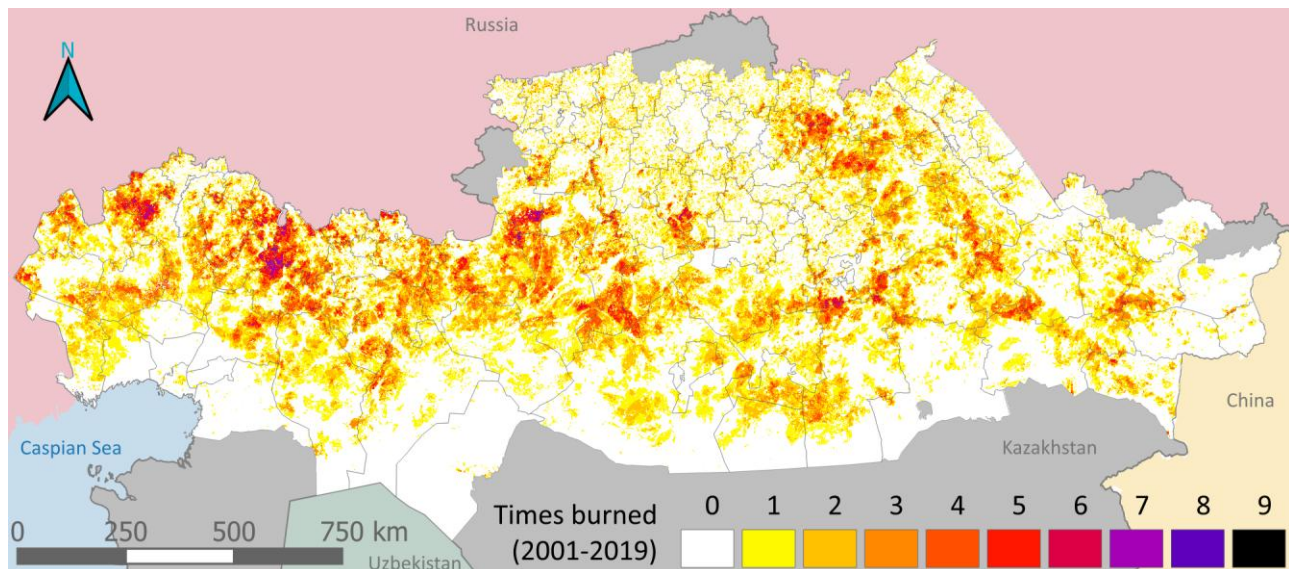


Figure 3-3. Frequency of fires (measured as the number of years with burned area) across the study area from 2001-2019. Only burns on grasslands are shown. Gray area shows the rest of Kazakhstan, with neighboring countries (GADM, 2018).

3.3.3 Analyses of determinants in fire patterns and trends

We first tested our assumption of restricting the area of interest to grasslands available for pasture. We tested three different scenarios, first where grazing demand can be spread across all land types, second where grazing demand can only be spread across grasslands and croplands (grazing is known to occur on croplands (Coughenour et al., 2008)), and third where grazing demand can only be spread across grasslands. Using grasslands only for the distribution of grazing demand had the highest R^2 values (Table 3-1. Marginal and conditional R^2 values for model results of three different land use masks with and without a one-year lag of burned area with respect to grazing demand (Nakagawa & Schielzeth, 2013).). We then examined the lag effect of the variables, to determine whether burned area is more a result of the conditions in the current year or in the previous year. Applying a one-year lag of burned area with respect to precipitation, temperature, relative humidity, growing degree days or combinations of them did not increase the models' R^2 value. However, applying a one-year lag of burned area with respect to grazing demand increased the R^2 value by approximately 0.2. This makes sense considering that the livestock statistics were reported "at end of year". Therefore, we chose to use the climatic variables of the current year in combination with the previous year's grazing demand, which has precedent in similar regions (Dubinin et al., 2011).

Table 3-1. Marginal and conditional R^2 values for model results of three different land use masks with and without a one-year lag of burned area with respect to grazing demand (Nakagawa & Schielzeth, 2013).

Set of variables	Marginal R^2	Conditional R^2
Grazing on all land types	0.157	0.369
Grazing on grasslands and croplands	0.215	0.424
Grazing on grasslands	0.295	0.522
Grazing on all land types with lag	0.327	0.526
Grazing on grasslands and croplands with lag	0.404	0.612
Grazing on grasslands with lag	0.505	0.749

We then fitted the GLMMs with all possible combinations of grazing demand and climate variable combinations as predictors, and the proportion burned area per grid cell as the response variable (over 16000 models were analyzed, a complete list can be provided upon request). An analysis of R^2 values produced the highest values when burned area was a function of the previous year's grazing demand. Figure 3-4 plots the normalized values of precipitation, temperature, relative humidity, growing degree days, and grazing demand (previous year) against the proportion burned in a given district and year. For each set of climate variables, we chose the best-performing single-variable model according to AIC. Interestingly, longer time periods explained burned area better, either the annual average for temperature, or the fire season values for precipitation and relative humidity.

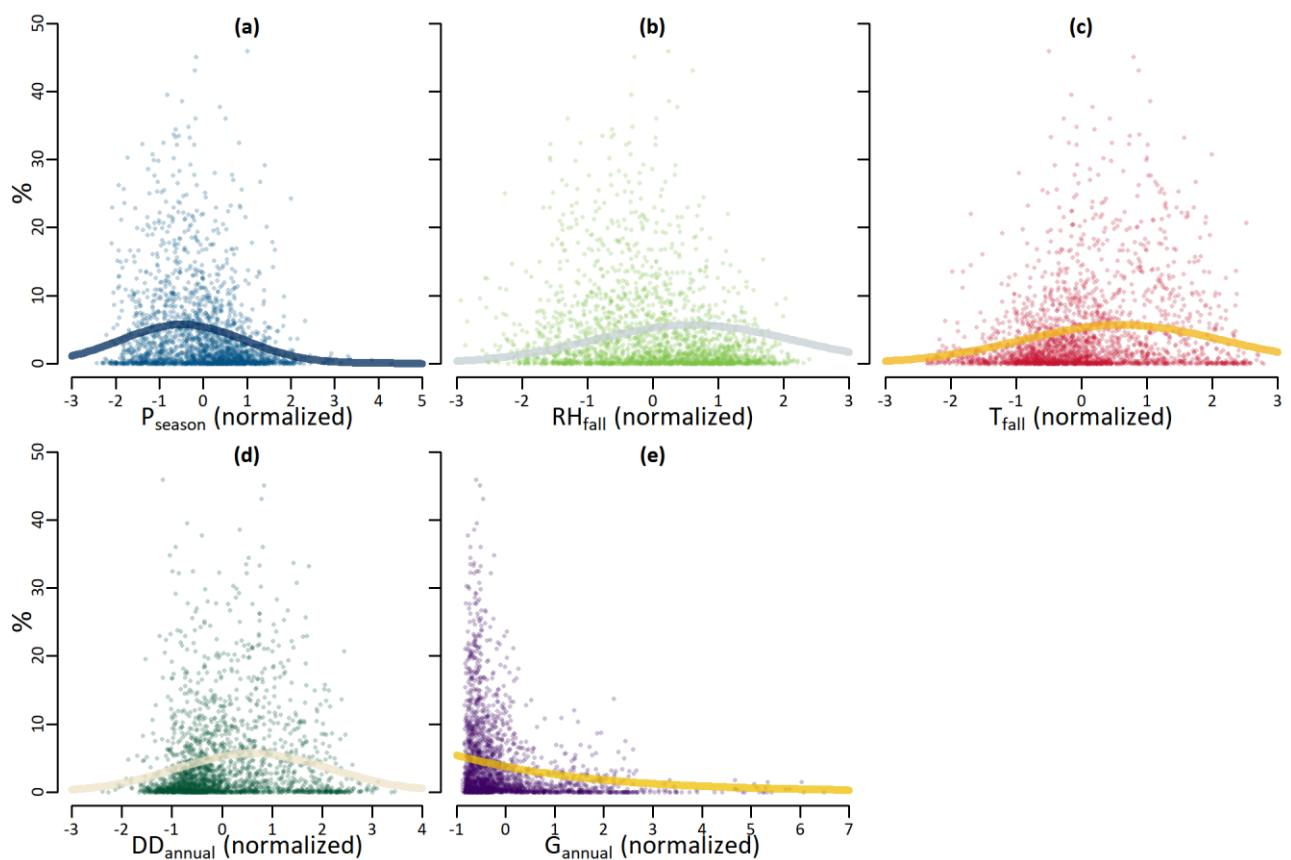
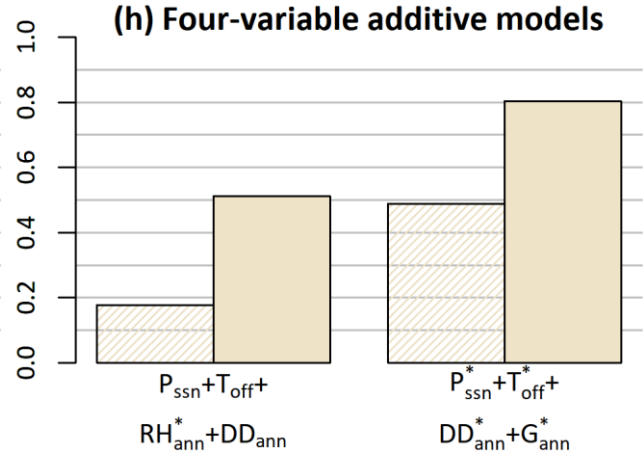
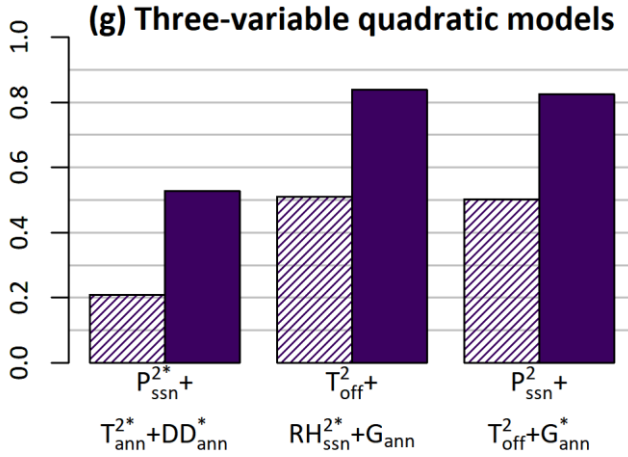
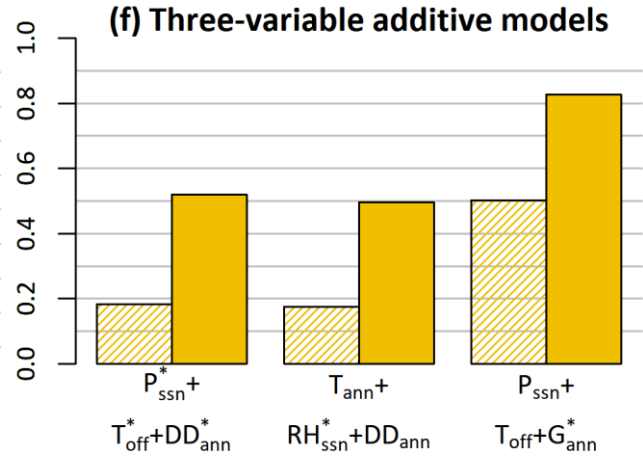
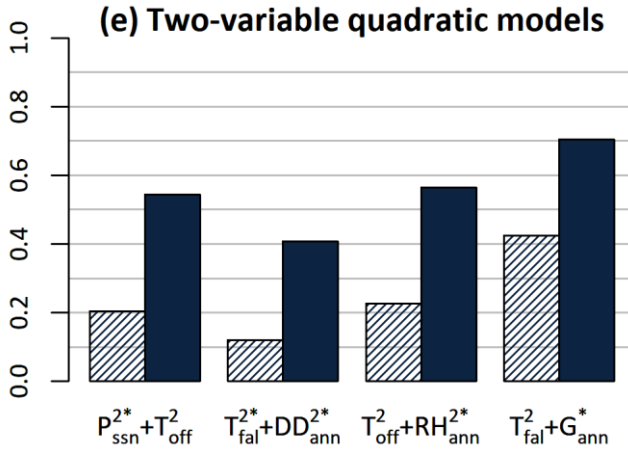
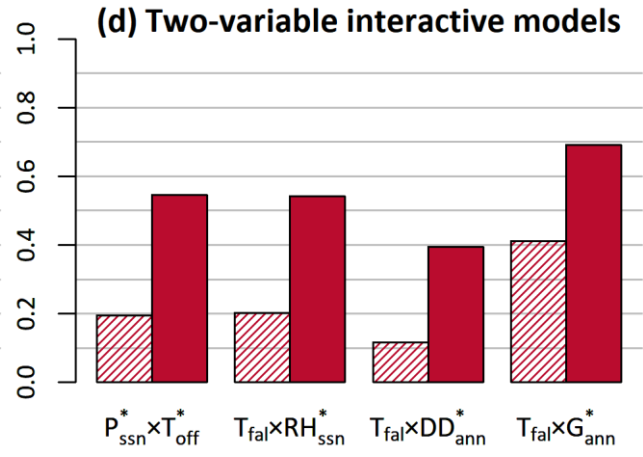
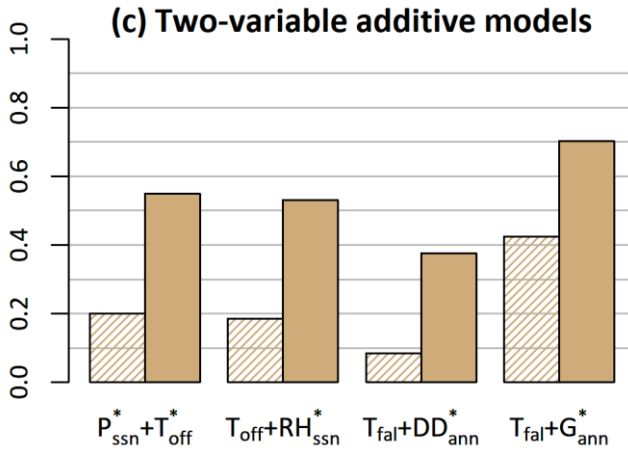
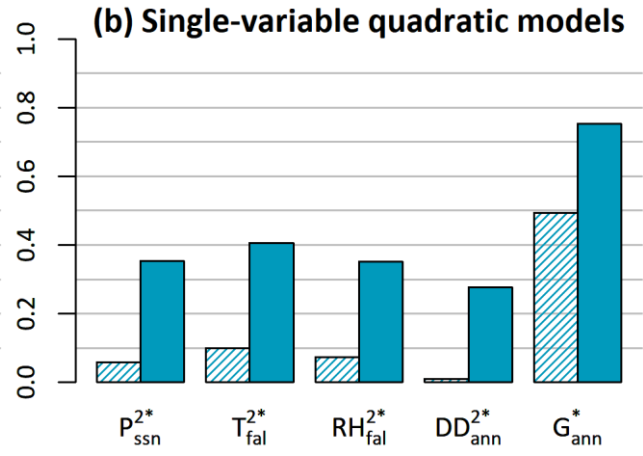
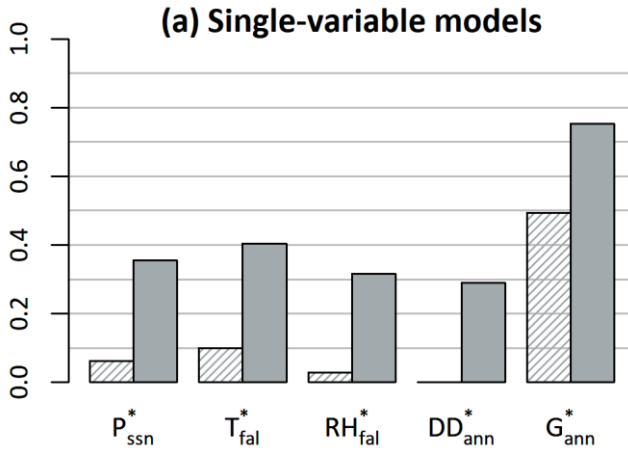


Figure 3-4. Burned area of a district-year with fitted binomial regression for normalized values of (a) fire season precipitation (P), (b) average fall relative humidity (RH), (c) average fall temperature (T), (d) annual growing degree days (DD), and (e) annual grazing demand (G).

We found that any model that included grazing demand greatly increased both marginal and conditional R^2 values compared to models without that variable (Figure 3-5). The best combination of solely climatic variables was the interaction between summer precipitation and fall relative humidity combined with annual temperature interacted with growing degree days (Figure 3-5k). However, whenever grazing demand was combined with at least two other variables, the R^2 values were routinely better than any model with solely climatic variables.



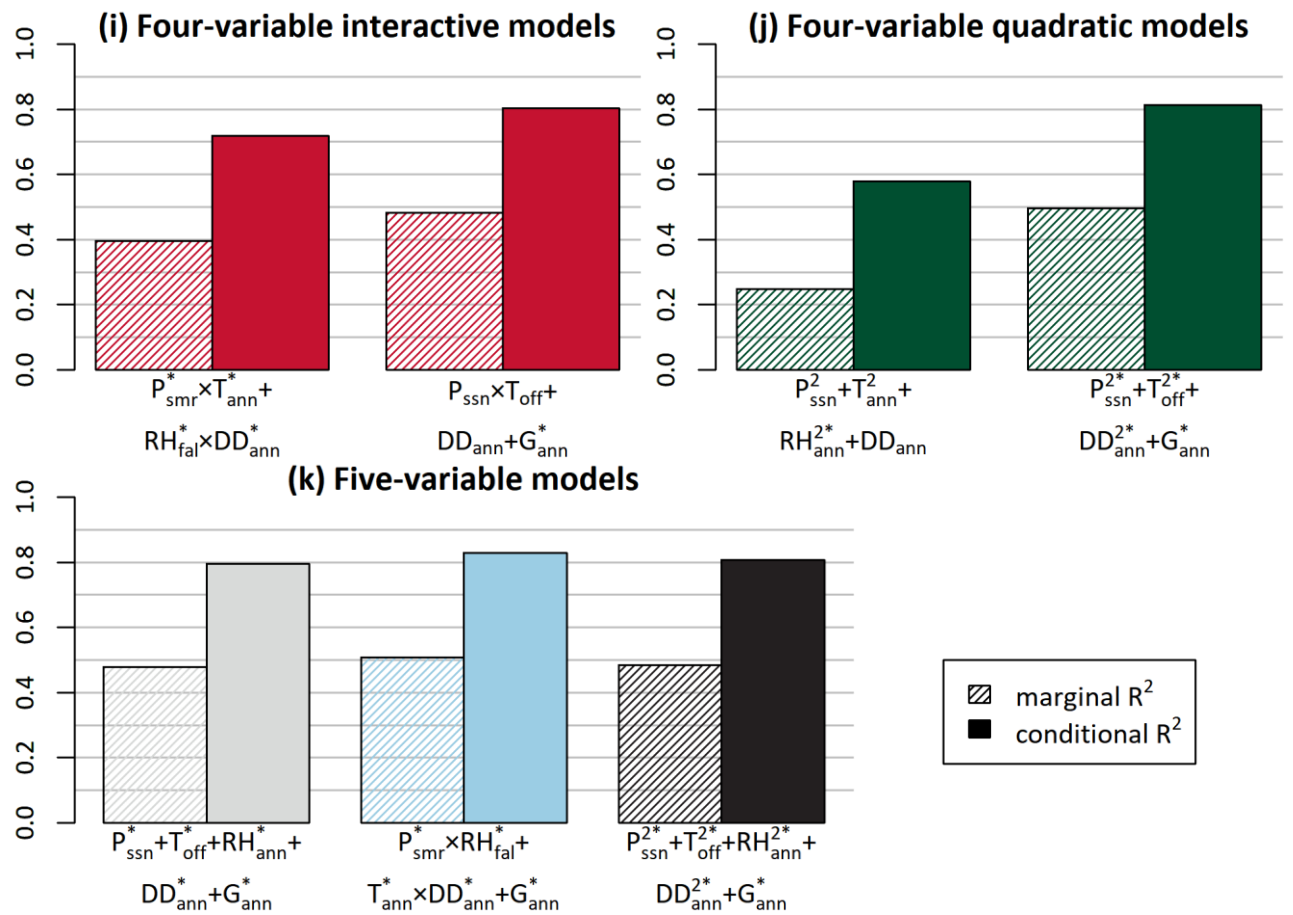


Figure 3-5. Marginal and conditional R^2 for increasingly complex models. Asterisks are applied to the best model of its type for each climate and grazing variable. For example (h) has only two graphs, the first is the best-performing four-variable additive model that has relative humidity in it, the second graph is shared among every other variable as their best-performing four-variable additive model. The overall best-performing model (by AIC value) is the five-variable model including interacting summer precipitation & fall relative humidity, interacting annual temperature & growing degree days, and grazing demand (k). ann=annual, ssn=fire season, off=fire off-season, spr=spring, smr=summer, fal=fall, win=winter.

3.3.4 Regional analyses

We evaluated each of the eight ecoregions in the study area separately to determine possible variations in burned area determinants (two ecoregions, the Junggar Basin semi-desert and the Emin Valley steppe, encompass only a single district, and were therefore not analyzed). Per ecoregion, both the best set of predictive variables (determined by AIC) and the model with the highest conditional R^2 was determined (Table 3-2).

The R^2 values varied substantially between ecoregions (cf. Figure 3-). The Kazakh steppe ecoregion has the largest number of districts, but only moderate R^2 values, with a quadratic model produced the highest R^2 values. The Kazakh upland steppe covers only three districts and encompasses predominately crop-producing regions, where the burned area is small. Here an interactive model produced the highest R^2 values, though conditional R^2 is the lowest of any ecoregion. The Kazakh semi-desert is the second-largest ecoregion and exhibited a high degree of variation and uncertainty. However, accounting for spatial distribution through inclusion of random effects (districts) greatly increased the conditional R^2 with a quadratic model. The Pontic steppe was the only ecoregion without temperature in its best R^2 model. The Caspian lowland desert was the only ecoregion without precipitation in its best R^2 model, and had the

highest R^2 values of any ecoregion. The Altai steppe and semi-desert is the second smallest ecoregion and did not have grazing demand in its best R^2 model. Relative humidity was the only variable found in every ecoregion's best R^2 model. Notably, the best predictive power (valuated by AIC) was obtained by including all variables in all ecoregions, with the two most well-represented ecoregions (Kazakh steppe and Kazakh semi-desert) having the best associated R^2 values.

The ecoregions can be split roughly into two groups, the “wet” group—Kazakh steppe, Kazakh upland steppe, and Altai steppe and semi-desert—and the “dry” group—Kazakh semi-desert, Pontic steppe, and Caspian lowland desert. The “dry” group are situated in the south and west of the study area, and share a number of characteristics, including many of the lowest precipitation and highest temperature values. In these, burned area shows a stronger relationship with spring, summer, and fire season climate variables. The “wet” group are in the north and east of the study area and have the highest precipitation and lowest temperature values. In these, winter and spring climate variables are more common in the best-performing R^2 models. These groups also share the type of predictive model (AIC), with the “wet” group preferring interactive models and the “dry” group preferring quadratic. Perhaps most notably, when analyzing on the scale of ecoregions, the seasonality of climate variables are revealed as many more of the shorter time periods (spring, summer, fall, and winter) appear in the best-performing models.

Table 3-2. Models with the lowest AIC value and the highest conditional R^2 for each ecoregion.

Ecoregion	No districts	Value	Best-performing model	R^2_m, R^2_c
Kazakh steppe	73	AIC	$P_{ssn} * RH_{fal}, T_{off} * DD_{ann}, G_{ann}$	0.39, 0.60
		R^2_c	$P_{win}^2, T_{spr}^2, RH_{smr}^2, DD_{ann}, G_{ann}$	0.54, 0.75
Kazakh upland steppe	3	AIC	$P_{win} * RH_{ssn}, T_{ann} * DD_{ann}, G_{ann}$	0.42, 0.46
		R^2_c	$P_{win} * DD_{ann}, T_{smr} * RH_{fal}, G_{ann}$	0.47, 0.64
Altai steppe & semi-desert	6	AIC	$P_{spr} * DD_{ann}, T_{win} * RH_{off}, G_{ann}$	0.28, 0.37
		R^2_c	$P_{spr}^2, T_{win}^2, RH_{ann}$	0.47, 0.81
Kazakh semi-desert	24	AIC	$P_{ssn}^2, T_{off}^2, RH_{ssn}^2, DD_{ann}^2, G_{ann}$	0.23, 0.67
		R^2_c	$P_{ssn}^2, T_{ann}, RH_{ssn}^2, G_{ann}$	0.26, 0.74
Pontic steppe	8	AIC	$P_{smr}^2, T_{smr}^2, RH_{fal}^2, DD_{ann}^2, G_{ann}$	0.22, 0.52
		R^2_c	$P_{smr} * RH_{spr}, G_{ann}$	0.60, 0.80
Caspian lowland desert	8	AIC	$P_{smr}^2, T_{off}^2, RH_{fal}^2, DD_{ann}^2, G_{ann}$	0.26, 0.53
		R^2_c	$T_{smr}^2, RH_{spr}^2, DD_{ann}, G_{ann}$	0.50, 0.97

3.4 Discussion

Climate factors and grazing both have been shown to be important determinants of fire patterns and trends, but their relative importance has often been elusive. Understanding their roles is key as climate change progresses. Making use of the natural experiment of rapid, widespread, and spatially heterogeneous declines in livestock numbers in the steppes of post-Soviet Kazakhstan, a global fire hotspot (Archibald et al., 2013; Hantson et al., 2013), we assessed the relative importance of changes in grazing demand and climate variables on burned area at unprecedented spatial and temporal detail. Our analyses yield three major insights. First, fire regimes changed markedly, with exceptionally high frequency and extent of fires in the 2000s followed by a decline in the 2010s, corroborating earlier findings for smaller

subregions and from other parts of the post-Soviet sphere (Dara, Baumann, Hölzel, et al., 2020; Dubinin et al., 2010; Hao et al., 2021). Second, there was a strong negative association between grazing demand and burned area, suggesting that restoring grazing regimes—either with domestic livestock or natural grazers—can suppress burning in Eurasian steppes. Third, changing livestock grazing demand after the breakdown of the Soviet Union explained fire dynamics better than both broad-scale climate patterns and inter-annual climate variation, highlighting the importance of grazing and, more generally, the need for better data on grazing pressure in grasslands.

Answering our first research question, we found that burned area extent varied greatly from year to year (Figure 3-2a). Linear regression showed an average decrease in burned area of 3,670 km²/year from 2001-2019. As percent change (about -5.4%), this is well above the global trend of about -1.6% over the same time period (Zheng et al., 2021). We also found that the most frequently burned areas are located predominantly along the border between the Kazakh steppe and the Kazakh semi-desert, as well as in the Pontic steppe (cf. Figure 3- & Figure 3-3). This agrees with the median fire return interval for this region found by Archibald and others (2013), which extends westward across the Southern Federal District of Russia (Dubinin et al., 2010).

The negative association between grazing and fire in our study area is in line with Dara and others (2020), who found fire occurrence to be correlated with livestock presence in a subset of our study area. Similarly Dubinin and others (2011) found livestock population to be negatively associated with burned area in a region adjacent to our study area. We also find agreement with Hao and others (2021), who looked at a similar time period across a large area in northern Eurasia and found grazing demand to be strongly correlated with declining burned area. Importantly, we go beyond prior work in that the relationship between fire and grazing has neither been studied across a broad range of environmental conditions and natural vegetation zones while using high-resolution data on grazing demand and fire activities, nor across such a length of time while using sub-annual data.

Our most important finding was that fire was more strongly related to grazing than climate factors. We have shown that grazing demand is strongly, and negatively, correlated with burned area (Figure 3-4), and can be used alone or in cohort with climate variables to produce a robust model (Figure 3-5). Indeed, as grazing demand has steadily increased over the period 2001-2019, burned area has become less variable and generally smaller. While we did not measure forage quantity or quality, our findings corroborate the linkages between large grazers and fire occurrence (Reid et al., 2022).

We identified trade-offs between conservation, fire suppression, and livestock production, which can inform policy makers and local governments looking to optimize the allocation of resources assigned to fire prevention and control. The results corroborate that livestock grazing can be used to mitigate fire occurrence on temperate grasslands, which more broadly can support mitigation of greenhouse gas

emissions from fire and promote production from grazing livestock in regions with large grassland resources at lower environmental costs. This is timely for Kazakhstan and the former Soviet Union in general as they start to release carbon that had been sequestered in the years immediately following the dissolution of the Soviet Union (Schierhorn et al., 2019).

A few limitations need mentioning. First, there were several variables that may have added explanatory value. Topography, wind patterns, fuel continuity, and access to ignition sources are all unaccounted-for variables that also determine fire frequency and extent (IAFC & NFPA, 2019). Our intent was not to create a definitive model for ranking fire drivers, but rather to investigate the rank of grazing demand in comparison to some of the most important climatic variables (Oliveira et al., 2012). Second, the MODIS burned area product may not capture all burned areas, especially small burns. However, small burns are not characteristic of our study area, and indeed, temperate grasslands and xeric shrublands (the biomes of our study area) are among the most highly accurate biomes in terms of burned area estimates (Boschetti et al., 2019). Third, despite our use of district-level statistics, our spatial representation of grazing demand remains a coarse aggregation, with no way to definitively allocate livestock within the district (Hankerson et al., 2019). Finally, small sample sizes reduced the goodness-of-fit for some ecoregions, even when including all variables and quadratic terms (Table 3-2). Some ecoregions, especially in eastern Kazakhstan (cf. Figure 3-), are small, isolated, and unique, not lending themselves well to analyses at the district level. Larger ecoregions, however, produced robust results.

Our work also has major policy implications. As much of the steppe is too arid for profitable crop production, livestock grazing has little competition from other land uses for Kazakhstan's grassland resources (Fetzel, Havlík, Herrero, & Erb, 2017), a bias which may strengthen under continuing climate change (Weindl et al., 2015). Additionally, Kazakhstan is not considered a priority area for climate change mitigation and adaptation (Bonilla-Cedrez et al., 2023), suggesting that it is a suitable candidate for livestock expansion. As a predominately pastoralist society, the mitigation of fire occurrence on the Kazakh steppe could at least in part be achieved through the management of grazing practices, providing that livestock numbers continue to grow in order for large-scale reduction of fuel loads, possibly with the help of targeted governmental programs. Any program implemented by the government would have to take into account the vast differences in grazing practices between large agricultural enterprises with tens or hundreds of thousands of animals, medium-sized private farms—which are the fastest growing farm type—and small households with a handful of animals, which is where the majority of grazing livestock in Kazakhstan are still raised, but whom are rarely able to take advantage of any of the government's current support programs (Kerven et al., 2021).

Despite a potential revival of livestock husbandry in the steppes of Kazakhstan, inevitably there will also be large areas where livestock grazing remains infeasible (e.g., too remote, too marginal) or prohibited (e.g., inside protected areas) (Dara, Baumann, Freitag, et al., 2020; Kamp et al., 2016; Kerven et al., 2016). These

areas provide opportunities for trophic rewilding, that is, restoring populations of natural grazers, such as saiga antelopes, goitered gazelles, kulan, wild horses, or wild camels (Bakker & Svenning, 2018; IPBES, 2018; Perino et al., 2019). This would make a major contribution to conservation, given the currently imperiled status of some of these species (Rosen Michel & Röttger, 2014). It would also help in achieving Target 2 of the recently agreed upon Convention on Biological Diversity goals: restoration of at least 30% of the world's degraded areas by 2030 (UNEP, 2022). At the same time, such trophic rewilding has the potential to reduce fire activity, improve carbon storage and thus mitigate climate change in a range of ways (Johnson et al., 2018; Sandom et al., 2020).

3.5 Conclusion

Human-induced changes in fire regimes at the global scale pose challenges to ecosystem health and biodiversity, as natural fire regimes become rare. As we venture further into the Anthropocene, we must recognize, analyze, and respond to the critical role that fire plays in shaping ecosystems (Kelly et al., 2020). While more widespread and intense fires are dangerous to people and infrastructure, blindly intensifying grazing pressure in the world's grasslands without consideration for carrying capacity and ecosystem services ultimately endangers the people depending on grasslands for their livelihood and sustenance (Qi et al., 2017). With functional populations of native grazers having largely disappeared from many grasslands, the choice of animal species used to intensify grazing pressure, as well as the land use change itself, will have ramifications for carbon emissions (Rolinski et al., 2021). Our research provides the framework needed to begin restoring the balance between grazing and fire, offering an opportunity to maintain the world's grasslands while mitigating the inherent dangers of fire.

3.6 Acknowledgements

We thank Norbert Hölzel for his insights into relationships between fire and grasslands, and Max Hofmann for his expertise in R coding. This work was partially funded by the Volkswagen Foundation (project BALTRAK, grant project number A112025).

Chapter 4:

The other red meat: environmental and nutritional advantages of horsemeat over beef and other meats

Nature Food, 2025, submitted

Brett R. Hankerson, Daniel Müller

Abstract

Beef is the most environmentally unfriendly meat. Horsemeat could reduce or even replace beef as the red meat of choice. Nutritionally, horsemeat contains higher protein, iron, and amino acids, and lower fat and cholesterol. Emissions-wise, horses produce far less methane per kilogram meat. Horses do require more total area, but less cropland. Horses are also more mobile, hardier, and can graze year-round, making more marginal and distant pastures available for longer periods. Horsemeat is not only a viable option, but perhaps a preferable one in the face of the global need to reduce the environmental impacts of meat production.

4.1 Introduction

Globally, meat consumption has increased almost six-fold over the last 60 years (FAO, 2024). Figure 4-1 shows the evolution of meat consumption since 1961. Poultry—primarily chicken—has seen an exponential rise in consumption, passing pork in recent years to become the most popular meat. However, the four-legged meats have all increased as well in a more linear fashion. In 1960, beef was the most-consumed meat, but was surpassed by pork in the 1980s and by poultry in the 1990s, and has seen a decline in per capita consumption since the 1970s (FAO, 2024). As meat consumption has increased worldwide, livestock production has correspondingly grown, and the economic, environmental, ethical, and health ramifications have become increasingly important, with much debate as to how to confront changing diets and the rising demand for meat and animal products. While livestock production has a secure future as a source of nutrients and livelihoods, consumption in high-income countries is unhealthily high, and the environmental footprint must be reduced (Parlasca & Qaim, 2022).

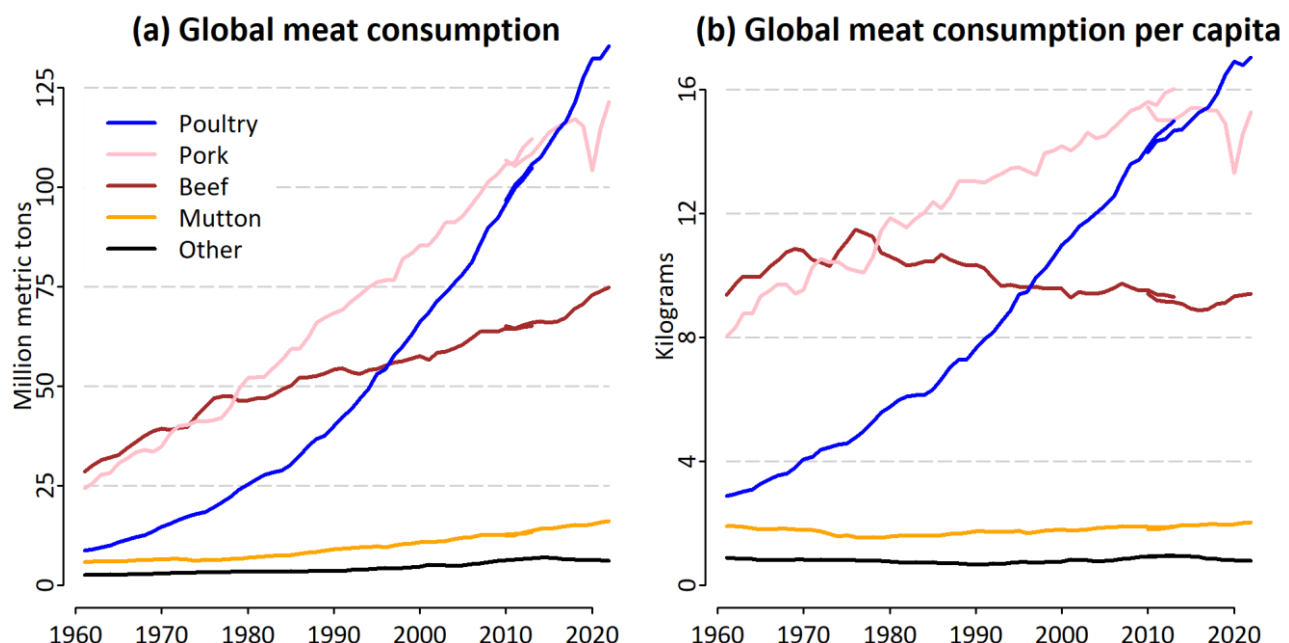


Figure 4-1: Global annual meat consumption from 1961-2022 (FAO, 2024). (a) Total meat consumption and (b) per capita. Line segments indicate the “old methodology” (1961-2013) and the “new methodology” (2010-2022) (FAO, 2022). Mutton includes goatmeat.

Almost every type of meat is considered taboo in some religion or culture (Schwabe, 1979). Hinduism prohibits the slaughtering of cattle, while Islam and Judaism prohibit the consumption of pork. Chicken is taboo in Tibet and some African cultures (Zaraska, 2016). While not always forbidden by religion, most of the less popular meats are subject to regional cultural taboos (Schwabe, 1979). Horsemeat is a somewhat unique example in that the taboos surrounding its consumption vary dramatically between nations that otherwise share similar cultures (Leteux, 2012). In the United State (US), horsemeat consumption is extremely taboo, where the banning of federal funding for mandatory slaughterhouse inspection makes it effectively illegal (Forrest, 2017). However, horsemeat is relatively common in both Mexico and Canada (especially French Canada), and a thriving market exists for the transportation and slaughter of horses from

the US (Stanciu, 2015). In Europe, the acceptance of horsemeat is nearly on a case-by-case basis (Gade, 2000). In broad strokes, English-speaking countries eschew horsemeat while French- and Italian-speaking countries embrace it (Leteux, 2012). Germanic countries are ambivalent, with Nordic countries leaning approbative, especially Iceland (Belaunzaran et al., 2015). Iberian and Slavic countries typically avoid horsemeat, with the notable exceptions of Croatia, Slovenia, and northwestern Spain (Dobranić et al., 2008; Insausti et al., 2021). Central Asia and Mongolia are the most conspicuous examples of horsemeat consumers, where the people revere both the animal and the dish. Indeed, the national dish of both Kazakhstan and Kyrgyzstan—*beshbarmak*—is commonly made with horsemeat, and the horsemeat-sausage *kazy* is a staple of any butcher shop (Sturød et al., 2020). They also share a love for the traditional drink of fermented mare milk (Willekes, 2013). Meanwhile, China is its own microcosm, where horsemeat is eschewed in some provinces while being a famous dish in others (Stanciu et al., 2013). Japan considers horsemeat a delicacy (Smil, 2002), while Australia, a former British colony, generally shares the US and Britain’s distaste for horsemeat, though they produce quite a bit for export (Leteux, 2012). Horses are fairly rare in Africa, but many cultures view horsemeat as a delicacy (Stanciu, 2015). Countries in South America generally abstain from eating horsemeat, although Argentina and Brazil—like Australia—produce quite a bit for export (Jaskari et al., 2015; Stanciu, 2015).

The first human interaction with horses was likely during the late Pleistocene Epoch, more than ten thousand years ago, and consisted of humans hunting horses for food (Clutton-Brock, 1992). Evidence for horse domestication goes as far back as 3500 BC, probably on the Eurasian steppe and probably—at least at first—to provide a stable source of food (Levine, 2005; Librado et al., 2021; Vilà et al., 2001; Warmuth et al., 2012). Thus began the most important, productive, and varied human-animal relationship in human history. Food, clothing, draft power, transportation, cavalry, musical instruments, sports, entertainment, and pets are just a few of the services horses have provided for over the years (Willekes, 2013). In western culture, the taboo surrounding hippophagy (the consumption of horsemeat) can be traced to 732 A.D., when Pope Gregory III banned the consumption of horsemeat, likely in an attempt to stamp out pagan rituals in northern Europe (Mann, 1914). Its banning didn’t eliminate its consumption, but horsemeat didn’t officially return to European cuisine until Denmark legalized its sale in 1841 (Jastrzębska et al., 2019)—though it was famously consumed in France during the French Revolution in the 1790s and the Napoleonic Wars in the early 1800s (Stanciu, 2015). The Siege of Paris in 1870-71 further ingrained hippophagy in French culture and cuisine (Leteux, 2012).

The European “horse-gate” scandal of 2013 reiterated the stigma that many nationalities have towards horsemeat consumption. In January of 2013 products claiming to be beef were found to contain significant amounts of horsemeat, prompting a European-wide investigation, a systematic review, and systemic changes in meat-sourcing control (Elliott, 2014). Although the larger issue was the lack of oversight in the meat supply chain, the fact that it was horsemeat drew the public’s attention. While this has instigated a

flurry of scientific articles relating to the detection of horsemeat in consumer goods (Barbarossa et al., 2016; Barnett et al., 2016; Boyacı et al., 2014; Brooks et al., 2017; Kamruzzaman et al., 2015; Madichie & Yamoah, 2017), some have explored the deeper undercurrents and externalities of the scandal (Abbots & Coles, 2013; Ibrahim & Howarth, 2016; Jaskari et al., 2015; Stanciu, 2015), while others have taken advantage of the public interest to explore the potential benefits of introducing horsemeat into the global diet (Balji et al., 2019; Belaunzaran et al., 2015; Lorenzo et al., 2017; Lorenzo et al., 2014; Marino et al., 2022).

We seek to identify and outline the most pressing issues and uncertainties regarding the natural potential for raising horses for meat, particularly in comparison with beef. It is well documented that beef production has one of the highest per-unit environmental impacts. What is the environmental impact of horsemeat production? Could horsemeat production replace beef production practically, and what would that mean for production systems? Overcoming cultural taboos, could horsemeat replace beef on the table, both perceptually and nutritionally?

4.2 Nutrition

If compared to the “big four” of beef, chicken, pork, and lamb, horsemeat nutritionally most resembles chicken (generally perceived as the healthiest of the four) (Farrell, 2013; Kennedy et al., 2004), with similar levels of calories, protein, and fat, in addition to lower levels of cholesterol (only pork has lower) (Geyer & Lawler, 2013). In taste and texture, however, horsemeat most resembles beef (Lamy et al., 2023). Figure 4-2 shows a comparison of selected “red meats”. Note that compared to beef, horsemeat has higher protein, lower fat, a higher percentage of polyunsaturated fat, lower cholesterol, and more essential amino acids (Paleari et al., 2003). Horsemeat is also a better source of vitamin A (Lee et al., 2007), iron (Del Bò et al., 2013), and magnesium, while containing less sodium (Lorenzo et al., 2014).

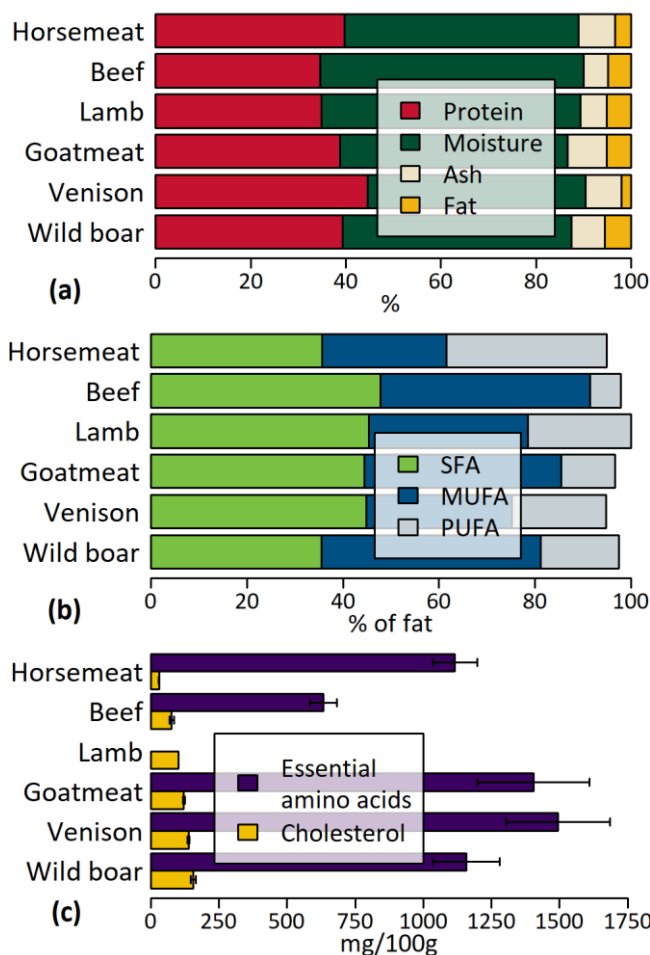


Figure 4-2: Selected properties of beef and its less popular substitutes. All data from Paleari et al. (2003) except lamb, from Paleari et al. (2006). (a) Physical composition of the meat. (b) Fatty acids composition, SFA—saturated fatty acids, MUFA—monounsaturated fatty acids, PUFA—polyunsaturated fatty acids. (c) Essential amino acids (not calculated for lamb) and cholesterol levels, with standard error. Meats were cured, fermented, and dried in a rigorously consistent manner following the traditional preparation of 'bresaola', an Italian dried-meat product.

4.3 Land use

Feed-use efficiency is an important indicator of the environmental impact of meat production. A number of indicators can be used, which highlight different footprints. Feed conversion ratio measures all feed intake (as dry matter) to mass of product (meat), energy conversion ratio measures energy intake to energy in product, protein conversion ratio measures protein intake to protein in product, and nitrogen use efficiency measures the percent of nitrogen intake retained in the product (Hou et al., 2016). For conversion ratios, lower is better, while for use efficiencies, higher is better. In the relatively intensive production systems of the EU, non-dairy cattle (i.e. beef cattle) have conversion ratios 4-7 times higher than pork or chicken, while having a nitrogen use efficiency 3-4 times less (Hou et al., 2016). Similar differences in feed conversion ratios were found in the US (Mekonnen et al., 2019). However, beef cattle obtain the majority of their intake requirement through grazing and forage (around 80% in the EU & US), energy sources that are not in direct competition with human-edible feed, whereas pork and chicken receive almost exclusively human-edible feed (Hou et al., 2016; Mekonnen et al., 2019). Thus, there is a niche that beef fills, providing human-

edible food (meat) from land otherwise not capable of producing human-edible food (or at economically infeasible levels) (van Zanten et al., 2018).

Figure 4-3 shows the 2015 distribution of cattle and horses, along with the shaded outline of four biomes that are commonly grazed (Dinerstein et al., 2017): Temperate broadleaf and mixed forests (eastern US, Europe, and East Asia), tropical and subtropical grasslands, savannas, and shrublands (Brazil, Africa, and northern Australia), temperate grasslands, savannas, and shrublands (central US, Argentina and across Eurasia), and montane grasslands and shrublands (the Andes, East Africa and the Tibetan Plateau).

Obviously, this is not a perfect representation of areas to target for expansion, for example there are heavily wooded areas in the temperate broadleaf and mixed forests not suited for grazing, and montane grasslands range from the lush Ethiopian grasslands to the frigid and barren eastern Himalayan alpine shrub. Likewise, some eligible regions are excluded from this map: The Aravalli west thorn scrub forests in Pakistan are very heavily grazed, but many other regions in the deserts and xeric shrublands biome are devoid of livestock. The shaded area covers nearly 50 million km², or about one third of the land surface. It is estimated that livestock production currently utilizes about 33 million km² for pasture (X. Xu et al., 2021).

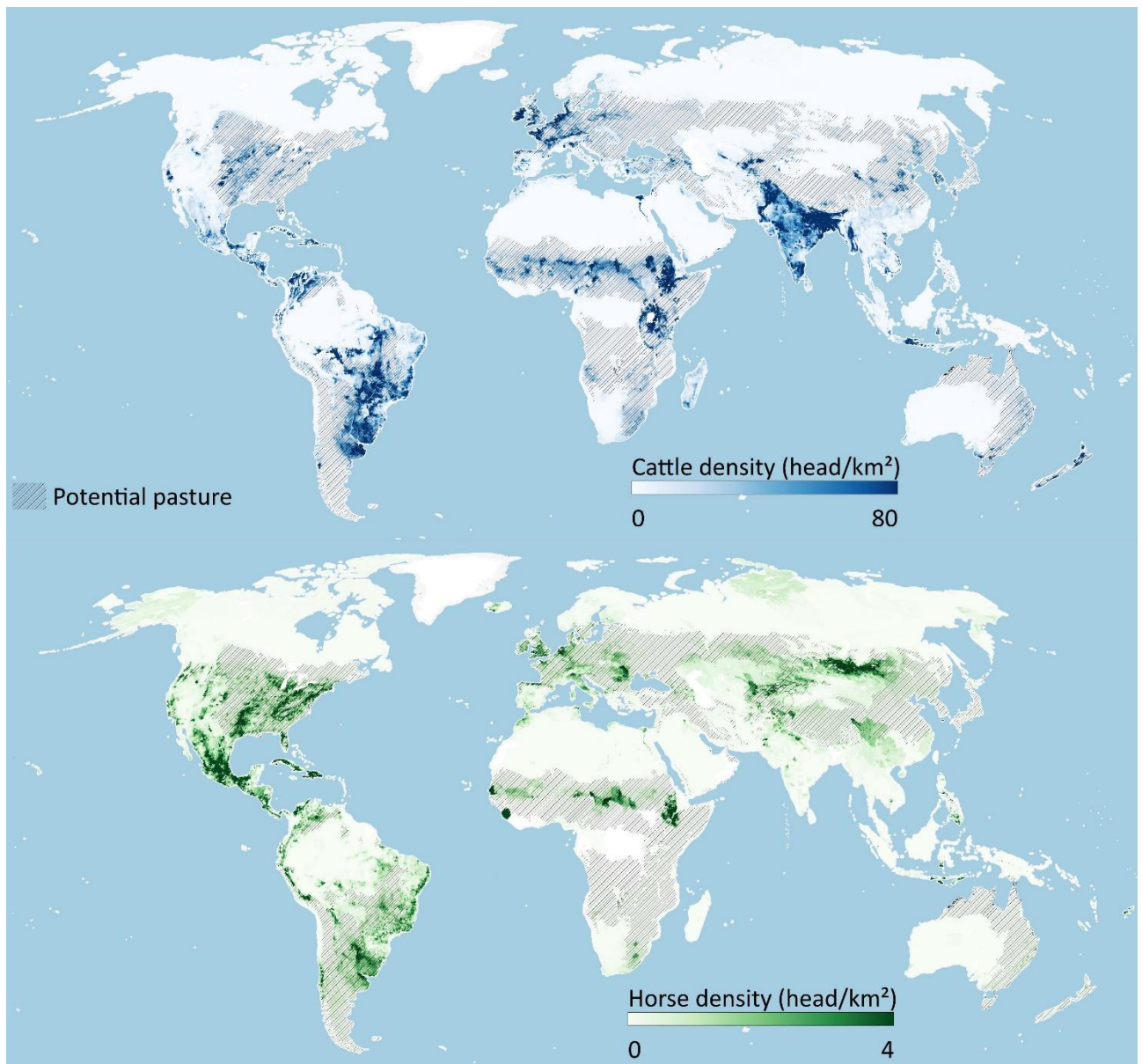


Figure 4-3: The Gridded Livestock of the World for cattle and horses (Gilbert et al., 2022a, 2022b). Shaded areas are broad, variegated biomes that may have desirable characteristics for horse grazing (Dinerstein et al., 2017).

Some of the potential grazing land in Figure 4-3 is currently being used as cropland. Livestock production uses about 20% of the 16 million km² of global croplands for feed (FAO, 2024; X. Xu et al., 2021). Additionally, feed production consumes about 20% of agricultural blue water use (mainly irrigation) (Heinke et al., 2020). Horses can graze on the same land that cattle do, as well as more marginal and distant pastures due to their greater mobility, sturdiness, and the higher proportion of grass in their diet (Cymbaluk, 1994; National Research Council, 1981; Willekes, 2013). Moreover, studies have shown that introducing human-edible cereals during finishing can even be wasteful economically and harmful to horses' welfare (Raspa et al., 2021). Their ability to dig through snow and break ice with their hooves are skills that cattle lack and allow horses to graze year-round at latitudes and altitudes where cattle need to be sheltered and fed entirely with feed and fodder (Gudmundsson & Dyrmondsson, 1994).

4.4 Greenhouse gas emissions

Livestock produce approximately 21% of human-induced carbon dioxide-equivalent (CO₂e) GHG emissions (X. Xu et al., 2021). Methane (CH₄) is by far the largest source of livestock GHG emissions, and cattle are by far the largest contributors to methane production, accounting for 77% of all non-CO₂ emissions from livestock production. The amount of methane released to produce a kilogram of beef varies greatly depending on the production system and region, with intensive systems in developed nations producing the fewest GHGs per kg protein and extensive systems in developing countries producing the most, especially in arid regions (Herrero, Havlík, et al., 2013). Dairy beef emits about 25% less CO₂e GHG than traditional beef cow/calf systems (Nguyen et al., 2010).

Greenhouse gas emissions from livestock depend on management practices. Horses are also hindgut fermenters, meaning that they produce substantially less methane than foregut fermenters (such as cattle, sheep, and goats) (Hristov et al., 2013). Horses emit an estimated 18 kg methane per head per year through enteric fermentation (Crutzen et al., 1986). Cattle are treated to more regionalized precision, with dairy cattle ranging from 46 kg/head/year in Africa and the Middle East to 128 kg/head/year in North America. Other cattle (mainly beef cattle) range from 27 kg/head/year in the Indian Subcontinent to 60 kg/head/year in Oceania (Dong et al., 2006). In 2021, average global methane emissions (enteric fermentation plus manure management) from dairy cattle were 74.7 kg/head/year, other cattle 45.4 kg/head/year, and horses 19.5 kg/head/year (FAO, 2023a).

While both are predominately grazing species, cattle and horses differ in important meat-producing aspects such as average daily gain (ADG), live weight at slaughter (LWS), and dressing percentage (DP%), which is a measure of meat yield as a percent of LWS. Calves up to 16 months typically have higher ADG than foals (López et al., 2019). After 16 months, however, horses overtake cattle in ADG, and by three years are more massive than cattle (Sarriés & Beriain, 2005). In addition to the increased LWS, DP% is also higher for horses, around 65%, vs. around 55% for cattle (Coyne et al., 2019; He et al., 2005). Moreover, DP% in horses increases with age, while for cattle it decreases (Janiak et al., 2017; Mantovani et al., 2014). This leads the difference in emissions per kg meat to be even greater than per head. In Kazakhstan, horses and cattle raised for meat are slaughtered at similar ages, with horses slightly outweighing cattle. In 2022, the average cattle LWS was 339 kg, while the average horse was 347 kg (KazStat, 2023). With an average age of 18 months, methane emissions per kg meat were almost three times higher for beef (0.37 kg/kg) compared to horsemeat (0.13 kg/kg).

4.5 Secondary sources of horsemeat

The practice of slaughtering horses that have reached the end of their useful life in a sector other than meat production are often unfit for human consumption. Racehorses, especially, have been given many substances that are illegal to administer to animals meant for human consumption (Anderson, 2015).

Horses are classified as companion animals by the American Federal Drug Administration, meaning all drugs approved for pets can be administered. Several of these are banned for food-producing animals, and poor oversight of the horse slaughter industry has led to many horses entering the human food market that shouldn't have (Weber et al., 2023). Nevertheless, the market for horses from the non-food sector could be structured and expanded such that properly documented horsemeat therefrom could safely enter the human food chain (Saastamoinen, 2015).

4.6 Other horse products

A discussion of horse production would not be complete without mentioning kumys (*airag* in Mongolian), a drink made from fermented mare milk. Historically produced from Hungary to China, kumys remains a popular dairy product in Mongolia, Central Asia, and neighboring Russian provinces (Langlois, 2011). Fresh mare milk is similar to human milk and is an option for infants allergic to cow milk (Malacarne et al., 2002). However, its very similarity to human milk, low fat content, and inability to make cheese severely limits mare milk's ability to replace cow milk in the general public (Langlois, 2011). Kumys, on the other hand, is often produced concomitantly with horsemeat, and competes with kefir (fermented cow, goat, or sheep milk) in the regions where it is popular. Considered an "acquired taste", kumys nevertheless has been gaining in popularity outside its traditional home due to its purported health benefits (Singh & Shah, 2017), and could accompany expanding horsemeat production (Askarov et al., 2020).

4.7 Outlook

Besides overcoming the tremendous taboo surrounding horsemeat consumption, there remains another, more tangible hurdle. Horses require more grazing land per kg meat because they are less efficient digesters than cattle, especially of higher-fiber diets (Chenost et al., 1985). While access to more pastures for longer periods helps to mitigate the additional land demand, the transition from beef to horsemeat would necessarily coincide with a decrease in red meat consumption. This is a trend that is already being realized and is encouraged from both a health and an environmental standpoint (Smil, 2014). Indeed, reduction in meat—particularly bovine meat—consumption is useful and important to avoid crossing several planetary boundaries (Parlasca & Qaim, 2022). Cropland freed from cattle feed production can be used to further mitigate the additional land demand through high-quality hay and pasture, and further land sparing could occur through upcycling of agricultural byproducts in animal feed (Govoni et al., 2023).

There is currently a paucity of scientific literature concerning horses raised for meat. Several knowledge gaps need to be explored and given the same rigorous treatment that beef production has received over the last century. How to optimize horses' diet for meat production—what, if at all, would feedlot production look like? How to reorganize cropland production, as a shift to horsemeat production would free up a lot of land previously used for cattle feed—should we use it to feed horses, other livestock, grow food, biofuel, or increase natural conservation? How different production systems affect GHG emissions—

could horse emissions be reduced even further with higher-energy grain supplements? How to conserve and preserve biodiversity and ecosystem services on marginal pastures—what fraction of Figure 4-3 is acceptable for expansion? Animal welfare has been an increasingly important aspect of livestock production, with cattle, poultry, and pork receiving the lion’s share of attention. For example, customers are willing to pay premiums for “cage-free” eggs or “grass-fed” beef. Horses raised for meat have recently also been treated with studies on welfare indicators (Raspa et al., 2020).

While we have elaborated on the environmental benefits of converting beef production to horsemeat, for many consumers, the battle will be fought on the dinner table. Horsemeat is substantially more healthy than beef, with a taste and texture similar, if not even superior to beef (Jaskari et al., 2015). On top of extolling the health benefits, premium-quality horsemeat could also improve its market share by better presentation and advertising. Besides the well-known sausages and dried meats in hippophagic regions, raw horsemeat could be graded by cut in the same way that beef is, increasing the value and desirability of better cuts. Restaurants that introduce and prepare horsemeat as gourmet could do much to help overcome the negative stigma that horsemeat has in many countries.

We have explored the potentials and externalities of expanding horsemeat production while reducing beef production. In a novel approach, we have combined social aspects (public perception, religious taboos), environmental aspects (land and water use, GHG emissions), production aspects (feed requirements, grazing patterns), nutritional aspects, and animal welfare. Our goal was to create a holistic and realistic analysis of horsemeat production, to define the state of the art and provide a possible, partial solution to the problem of livestock’s long shadow (Steinfeld et al., 2006).

Chapter 5: Synthesis

5.1 Summary

The overarching goal of this thesis was to advance the knowledge and understanding of land use—especially pastureland use—and livestock production in Kazakhstan. Several facets were explored that contribute to knowledge gaps in the relationship between livestock productivity, grazing patterns, ecological functions of grasslands, and environmental footprints of meat production. Kazakhstan was chosen as the study area for a number of reasons: 1) it contains huge tracts of uninterrupted grazing land; 2) it has significant herds of four different grazing livestock species; 3) those herds have seen dramatic rises and falls in populations over a short and recent time period; 4) is at risk of desertification and other climate change-related effects; and 5) has potential to increase meat production without taking land away from crop production.

5.1.1 Research questions and answers

5.1.1.1 Question I: Where, and to what extent, could increases in Kazakh livestock production take place?

Chapter 2 developed a model to distribute grazing demand across Kazakhstan's vast grassland resources. Much of Kazakhstan was found to be ungrazed or grazed at very low intensities. However, there is ample evidence for localized overgrazing around settlements across the country, and extensive, proliferant overgrazing likely occurs in the south and southeast, corresponding to the highest livestock densities and despite high grassland productivity. In the areas of low-intensity grazing, large increases in livestock production could take place without changing the current state of pastoralism. With repaired and improved infrastructure, however, Kazakhstan could increase meat and dairy production by an order of magnitude. Improvement projects are well underway in the northcentral, where fodder crop production supports large agricultural enterprises and feedlot-style beef and especially dairy. An area of interest for potential expansion that has not begun to be tapped is in the northwest, West Kazakhstan and Aktobe Oblasts. Beef and dairy cattle understandably attract the most attention, but Kazakhstan has the capacity and pathways to further vitalize the sectors of other grazers: sheep, goats, horses, and camels are all economically significant and each could step up if global demand for cattle products were to wane due to concerns over the environmental footprint of cattle.

5.1.1.2 Question II: To what extent are livestock in Kazakhstan actors in fire regimes?

Chapter 3 utilized binomial generalized linear mixed-effects models to analyze the correlation that grazing demand has on burned area extent. The magnitude of this correlation was then compared to other common predictors of burned area extent: precipitation, humidity, temperature, and growing degree days. The climate variables were further stratified into seasonal values, as fire is ephemeral and often driven by temporary, extreme conditions, and all possible combinations of these variables were analyzed to determine a best fit. Additive, interactive, and quadratic models were considered, however the best

performing models always included grazing demand. Grazing demand is strongly, and negatively, correlated to burned area extent. While this is logical and not in itself earth-shattering, the magnitude of correlation was surprising, a small increase in grazing demand corresponded to a large decrease in burned area extent. Besides the obvious conclusion that increasing livestock numbers can mitigate fire occurrence, this research suggests the efficacy of rotational grazing as a way to drastically reduce the risk of wildfire without needing to increase herd size. Improved infrastructure and incentivizing programs could be used in local mitigation schemes. As far as targeting livestock for expansion, horses are most mobile and would be best-suited to forming traveling fire-prevention bands.

5.1.1.3 Question III: Is there a path to sustainable livestock development in Kazakhstan?

Chapter 4 concerns the large, growing, and detrimental impact beef and dairy cattle have on the environment. The biological processes that allow cattle to be energy-efficient digesters of grasses also emit more greenhouse gases (GHGs) per kilogram of product than any other mainstream meat or dairy source. The potential of one of mankind's very first domesticated meat sources that has only relatively recently fallen out of favor was explored as an alternative to beef: horsemeat. Nutritionally, horsemeat is superior to beef in every measureable way: more protein, less fat, better fat, and more essential amino acids. Texturally, horsemeat is more similar to beef than any other red meat, and when raised for meat is sweeter and tenderer. Environmentally, horsemeat production is more of a mixed bag compared to beef production. Horses are hindgut fermenters, and therefore by nature emit fewer GHGs per kilogram of product than cattle, but they are less efficient digesters, requiring far more energy input in the form of grass than cattle do, which means a larger land use footprint. On the positive side, this land requirement can be satisfied using marginal grasslands not suitable for crop production, but the more marginal the land the less productive it is and the more land is required. Simply based on the land requirement, horsemeat is unable to replace beef kilogram-for-kilogram. A reduction in meat consumption or a shift to other meats is also required.

5.2 Insights

Together, Chapters 2-4 offer several cross-cutting insights into the recent history and modern state of livestock production in Kazakhstan, environmental interactions, and potential for further development. First, as discovered in Chapter 2, much of Kazakhstan is ungrazed or grazed at low intensities. Livestock numbers plummeted after the Soviet Union dissolved in the early 1990s, leaving distant pastures and stations abandoned. Since the launch of the MODIS satellites in 1999 and 2002 there has been a continuous record of burned area extent, and Chapter 3 shows a strong correlation between livestock grazing and burned area extent. The high variability of burned area in Kazakhstan in the 2000s coincides with the decrease in livestock numbers, suggesting that decreased grazing allowed variation in climatic factors to play a larger role in fire occurrence. Given the current low grazing intensities in the hotbed of Kazakhstan's

grassland fires, targeted increases in pasture use, either by increasing livestock numbers or by scheduled rotational grazing, can drastically reduce the threat of wildfire by removing a relatively small amount of fuel.

Second, based on the grazing map from Chapter 2, much grassland near human populations is at risk of overgrazing. Moreover, there are huge swaths of un- or underutilized pasture far from settlements, especially in western and central Kazakhstan. Utilizing this pasture is a difficult proposition under the current circumstances of decaying Soviet infrastructure: crumbling roads, dilapidated livestock stations, and failed wells. However, this barrier to expansion has made one assumption that need not be true: that cattle are the species to propagate. Cattle are dependent on human infrastructure, short distances to food and water, and are largely defenseless against apex predators and the bitter cold of Kazakh winters.

Introduced in Chapter 4, the idea of expanding horsemeat production has many positive attributes. In relation to Chapter 2, horses could be an immediate answer to utilizing distant pastures, as they can range much further than cattle, can defend themselves from predators, and are hardy enough to survive even the *dzhuts*—various extreme weather conditions causing mass die-offs—that repeatedly threaten grazers on the Eurasian steppe.

Third, in a grand cross-cut of Chapters 2, 3, and 4, employing a highly mobile, hardy species that requires very little cut-and-carry fodder to roam the fire-prone grasslands of the Kazakh steppe, dramatically reducing the risk of uncontrolled wildfire while utilizing grassland otherwise inaccessible for human food production is a powerful argument for the expansion of horse husbandry. There is strong emotion in many countries against the eating of horses, and in many others, horse is viewed as a lesser meat. However, Chapter 4 reveals that horsemeat is in fact superior to beef in almost every way: nutritionally, environmentally, and—perhaps most importantly—gastronomically. The potential for horsemeat operations to reduce or even supplant beef as the red meat of choice relies on the ability to (a) efficiently and sustainably utilize marginal grasslands and (b) change the majority of mindsets with tender, tasty slabs of high-quality “I can’t believe it’s not beef”.

5.3 Implications

There are two overarching, universal questions associated with changes in livestock production, agricultural production in general and indeed, with any kind of production: 1) how will the economy be affected, and 2) how will the environment be affected? Economic impacts of agricultural policies are extensively studied and forecasted before a policy is implemented, continuously analyzed during its effective period, and thoroughly evaluated after its conclusion. Comprehensive assessment always remains elusive, however, as real-world policy never occurs in a vacuum, and there is no “control variable”. Nevertheless, analysis has come a long way in the last half-century, as the framework for assessing agricultural policy developed (Josling, 1974), as computational power increased dramatically (Just & Antle, 1990), as statistical databases

became widely available and economies became globally integrated (van Tongeren et al., 2001), and as environmental goals joined economic goals as fundamental tenets of agricultural policy (Carpentier et al., 2015). Inasmuch as agriculture impacts the environment, agricultural policy forms the shape of its environmental footprint. Environmental policies to protect the environment are often at odds with agricultural policies designed to positively affect economic aspects, however there has been concerted effort among developed and developing nations in recent years to incorporate positive environmental impacts into agricultural policy (DeBoe, 2020). It was realized long ago that “reality is far too complex to allow generalizations about the environmental impacts of agricultural policies” (Just & Antle, 1990). Despite this, the state of the art continues to attempt generalization—albeit with many qualifications and caveats—often with actionable success (Kirchner et al., 2015). The application of the research in this dissertation has several compelling implications for developing agricultural policies that positively impact the environment.

Chapter 2 shows how merging disaggregated point and area statistics with gridded land use and productivity maps can inform policy makers of areas most capable of supporting additional livestock, and equally as important, areas to target for de-intensification—which could be achieved without overtly negative economic impacts by e.g. increasing fodder production. Finding synergy between increasing economic output and improving the environment is a fine line at best, but targeting areas that are underperforming—grasslands in Kazakhstan that saw a dramatic contraction in grazer numbers and now produce much more biomass energy than is consumed—presents a pragmatic solution with comparatively low environmental tradeoffs. Chapter 3 substantiates the importance of grazing patterns in determining burned area extent. In the Kazakh steppe between 2001 and 2019, extensive area burned as often as once every 3 or 4 years. With the knowledge that “a little bit of grazing goes a long way”, programs supporting the movement of grazers across fire-prone regions in response to compounding climate factors—i.e. shifting focus to areas that have been hot and dry—could effectively mitigate fire risk with little cost and potentially positive economic and environmental returns through diminished overgrazing and safeguarding more carbon-sequestering decomposition processes. Chapter 4 promotes the consideration of a paradigm shift in range livestock production that might (literally) be difficult for some to swallow. Whatever the arguments against red meat production and consumption—and they are extensive—the complete removal of red meat from the human diet is at best decades away. However, a shift in red meat production away from beef and towards horsemeat could upend many of the criticisms that plague beef production: methane emissions, crop feed production, concentrated feedlot operations. Dairy cattle are a completely different beast, as there is no known substitute for the quality, quantity, and efficiency of cow milk production. Beef will therefore necessarily continue to be provided by dairy bulls. The savings in GHG emissions by a substitution of horses for beef cattle could be the greatest environmental win in agriculture of this century.

5.4 Outlook

Kazakhstan stands in the nexus of a number of Sustainable Development Goals (SDGs) (United Nations, 2015). As a burgeoning economy and the ninth-largest country in the world, the directions that Kazakhstan pursues in the agricultural sector will have global consequences in the progress towards SDG 12: Responsible consumption and production, SDG 13: Climate action, and SDG 15: Life on land. In no uncertain terms, Kazakhstan plans to join the top 30 economies by 2050 (Nazarbayev, 2012). However, economic development is often at odds with environmental sustainability, and while Kazakhstan has made positive strides in eight of the seventeen SDGs, only one (SDG 1: No poverty) is on track to be achieved by 2030, and nearly a quarter of the indicators are worsening (Sachs et al., 2024). While Kazakhstan is by no means an undeveloped country, many sectors have a lot of room for development, and historically, closing this development gap involves tradeoffs with environmental health. Yet all is not doom and gloom. With regard to GHG emission, air pollution, land use, water use, and water pollution, Kazakhstan has achieved absolute economic decoupling, meaning that further economic development can be achieved while decreasing emissions and environmental footprints (UNEP, 2024). In 2016, 20% of the working population worked in agriculture, yet agriculture accounted for only 4.7% of national gross domestic product (GDP) (Tokbergenova et al., 2018). By 2021, employment in agriculture had dropped to 15% while the contribution to national GDP rose to 5.2% (Zhanaltay, 2023). This is indicative of consolidation (either vertical or horizontal), which brings with it efficiencies in production, but still requires a push in the right direction to develop resiliency and sustainability (Bulkhairova et al., 2024).

From 1961-2022, global GHG emissions from beef reduced in intensity from 44.8 to 30.1 kg CO₂e/kg (carbon dioxide equivalent) (FAO, 2025). By the time Kazakhstan enters the statistics (1992), global beef GHG emissions intensity was 35.1 kg CO₂e/kg. In the largest beef-producing countries since 1992, major gains in GHG efficiency were realized in China, Brazil, and Mexico (Figure 5-1), while the other countries stagnated (Australia) or saw modest improvement (Argentina, Russia, USA). Nevertheless, there are clearly gains still to be had. Brazil is more than two times less efficient with GHG emission than the USA or China.

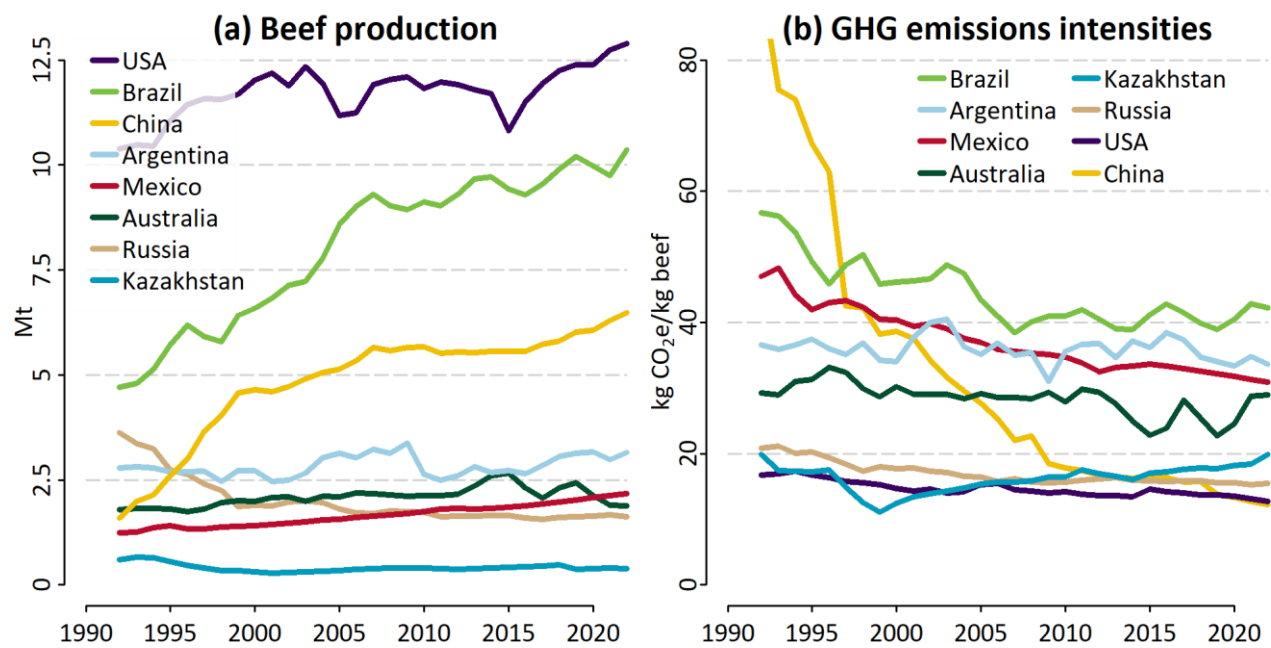


Figure 5-1: (a) Beef production of the seven largest beef-producing countries in 2022 and Kazakhstan, and (b) emissions intensities for beef of the same eight countries, 1992-2022 (FAO, 2025).

Kazakhstan has historically had very good emissions intensity numbers, and compares favorably against countries that are undergoing similar agricultural intensification (Schierhorn & Müller, 2020), however in recent years they have been climbing, increasing more than 50% from the low in 1999. Despite this recent increase, Kazakhstan (19.8 kg CO₂e/kg beef in 2022) remains well below the emissions intensity of several behemoths of beef production: Argentina, Australia, Brazil, and Mexico (33.6, 29, 42.2, and 30.9, respectively). Maintaining this environmental edge is a critical component arguing for the expansion of beef production in Kazakhstan.

5.5 Future

This dissertation explored three distinct but related questions concerning livestock production and pasture use in Kazakhstan. Obviously, that is not an exhaustive account of all aspects of animal agriculture. Many directions could be taken to expand this research in the quest for knowledge and improvement. The launch of higher resolution satellites has allowed the detection of smaller and smaller objects, and the methods developed in Chapter 2 could continue locating livestock with more certainty by incorporating remotely detected wells, livestock stations, pasture structures, agricultural enterprises, and even the animals themselves. Some of these aspects are already being pursued (Fernández et al., 2025). Higher resolution multispectral imagery could also lead to large-scale mapping of plant species composition, allowing more accurate estimations of biomass energy. Methods for this purpose are already being developed in anticipation of such imagery (Lopatin et al., 2017). This could also enhance the ability to detect dry matter accumulation, further aiding the identification of fire predisposition and improving on existing models (Kaduyu et al., 2022). Further expanding on the research in Chapter 3, the interaction of grazing with dry matter productivity, topology, climate, and shorter-term weather events could be explored in the ongoing

attempt to predict fire occurrence (Chang et al., 2023). Using grazers to reduce the risk of fire invites the development of a best-practices model: where, when, how long, and which livestock species to use (Ratcliff et al., 2022). While the focus has been on cattle as the range livestock of choice, horses are more mobile and more capable in a wider variety of terrain than cattle. There are many directions needed to explore the research started in Chapter 4, as a critical mass of research on horsemeat production is far from being realized. From the social sciences, research is needed to identify pathways for reintroducing horsemeat into many societies where it has fallen out of favor or even considered taboo (Ibrahim & Howarth, 2016). From an economic standpoint, a conversion from cattle to horse ranching has myriad ramifications, from animal health and nutrition requirements to infrastructure to land apportionment (Belaunzaran et al., 2015). The future of research into livestock production and pasture use is alive and well.

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Declaration

I declare that I have completed the thesis independently using only the aids and tools specified. I have not applied for a doctor's degree in the doctoral subject elsewhere and do not hold a corresponding doctor's degree. I have taken due note of the Faculty of Mathematics and Natural Sciences doctoral degree regulations, published in the Official Gazette of Humboldt-Universität zu Berlin № 42 on July 11th, 2018.

Brett Hankerson

Halle (Saale), 25.03.2025