# Dynamics of Rural Infrastructure and Ecosystems in Daurian Steppe

Dr. Anastasia Kirilyuk
(Forestry PhD program)

Committee members:

Dr. Zuzana Burivalova
Dr. Mutlu Ozdogan
Dr. Volker Radeloff
Dr. Richard Reading
Dr. Philip Townsend

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**Overall Introduction**

Humans face a global biodiversity crisis, and preserving remaining key habitats is crucial (Cui et al., 2022; *Kunming-Montreal Global Biodiversity Framework*, 2022). Climate change, habitat loss and fragmentation, and overexploitation are the most considerable direct determinants of biodiversity loss (Woodley et al., 2019). Historically, grasslands have experienced the highest levels of exploitation and disturbance relative to other ecosystems, resulting in only a few remaining intact grassland ecosystems (Oyunbileg et al., 2021; Scholtz & Twidwell, 2022; Smelyansky et al., 2015). The conventional approach for assessing the "health" of grassland ecosystems and the efficacy of nature conservation efforts has centered on overall biodiversity, fire disturbance, and the prevalence of plowing and overgrazing (Butterbach-Bahl et al., 2011; Hobohm et al., 2021; Hunter et al., 2018; Oparin & Oparina, 2012; Oyunbileg et al., 2021; Ronnenberg & Wesche, 2011; Schönbach et al., 2011). Maintaining key habitats in cross-border areas presents particular challenges due to socio-economic, cultural, legislative, and technological differences between neighboring countries (Mason et al., 2020; Yale University, 2003). Remote sensing provides an effective means of analyzing spatial data to assess conservation effectiveness, ecological risk, monitor land cover changes, and minimize transboundary differences.

Grassland ecosystems, characterized by interannual variability in high-quality pasture, have fostered the development of migrating ungulate-grassland systems (Morant et al., 2023; Nandintsetseg et al., 2019). These migrating ungulates play pivotal roles as "indicators" of ecosystem shifts, adapting to climate change and human activities while shaping vegetation structure and nutrient pathways as "ecological landscapers" (Hobbs, 1996; Morant et al., 2023; Sinclair, 2003). However, despite their ecological significance, most studies on temperate grassland ungulates have focused on their summer behavior, following greenness waves and applying NDVI as forage quality proxy, and overlooking crucial aspects of winter nutrition. Winter habitats often present nutritional challenges for ungulates, impacting neonatal survival and resilience to severe weather conditions, such as dzud events. Vegetation mapping using remote sensing technologies offers promising avenues for assessing forage quality in both winter and summer.

Linear infrastructure, such as roads and fencing, permeates most landscaps, exerting substantial impacts across social, economic, and environmental domains. Particularly, their influence on wildlife and ecosystems stands as a driver of global biodiversity loss, encompassing a spectrum of effects from habitat loss and isolation to increased human access and disturbance (Benítez-López et al., 2010; Jones et al., 2022; Woodroffe et al., 2014). Although often considered detrimental, both unpaved dirt roads and rural fences also present positive aspects for ecosystem and nature conservation, contributing to fire management and offering protection from poachers (McInturff et al., 2020; Yocom et al., 2019). In regions characterized by intensive agricultural practices and abundant wildlife, such as grasslands, the impacts of linear infrastructure are particularly pronounced (Guo et al., 2021; Jakes et al., 2018), Especially in cases where the formation of dirt roads is informal and fencing is unregulated, as in China-Mongolia-Russia Dauria grasslands. However, existing studies on the impact of dirt roads on microrelief and the mapping of linear infrastructure have been limited in scope or duration, necessitating novel mapping approaches to address these gaps (Buzzard et al., 2022). Furthermore, regions experiencing transformations, such as those resulting from changes in land use and economic activities, require extended time frames for analysis. In this context, declassified images obtained from reconnaissance satellites with high-resolution and high-quality imaging capabilities is a solution, extending a temporal span up to 50 years. Among them, Hexagon imagery stands out as one of the most promising options (Hammer et al., 2022).

Grassland ecosystems are shaped by the interaction between fire frequency and intensity and plant community composition and structure. With approximately 80% of global fires occurring in grasslands, including both wildfire and prescribed fire, understanding the intricate impacts of fire on these ecosystems is crucial for assessing their hydrological, ecological, and economic aspects (Bowman et al., 2009; Leys et al., 2018; Yan & Liu, 2021). The responses of various grassland types to fire vary, influenced by specific species assemblages and environmental conditions, resulting in a spectrum of reactions ranging from negative to positive (Dusaeva & Kalmykova, 2021; Stavi, 2019; Yan & Liu, 2021). Environmental factors such as climate, land use, and plant functional types play pivotal roles in shaping vegetation responses, with future successional pathways and productivity often diverging from previous vegetation types and fire cycles. Despite the importance of pre-fire conditions in influencing fire dynamics and post-fire ecosystem states, much of the existing research has focused primarily on post-fire factors over short spatial spans. I propose to delve deeper into pre-fire and during-fire conditions that contribute to increased fire occurrence, development, and severity. As climate warming and human activity continues to escalate, the frequency of grassland fires is expected to rise, underscoring the need for describing the long-term effects of fire on grasslands.

Utilizing remote sensing techniques and long-term ground data collected from the transboundary China-Mongolia-Russia Dauria grasslands, *my dissertation aims to investigate the dynamics of rural infrastructure and ecosystems in one of the last remaining intact grasslands globally*. Specifically, my study encompasses three main objectives:

*First*, to develop and validate a novel approach for evaluating the forage quality of ungulates in temperate grasslands. This involves mapping both winter and summer nutrition to enhance biogeographical models for ungulates, thereby contributing to a better understanding of their habitat and resource utilization patterns.

*Second*, to map changes in the network of unpaved dirt roads and rural fences across the Chinese-Mongolian-Russian Dauria ecoregion over a span of 50 years. By analyzing the temporal and spatial dynamics of these linear infrastructure elements, I aim to define their impacts on soil erosion in grassland ecosystems.

*Third*, to characterize the complex interplay of fire, climate, and primary plant community's productivity across a diverse range of grassland ecosystems, ranging from semi-desert to temperate regions. I aim to unravel the relationships between fire dynamics, environmental conditions, and vegetation responses, such as forage quantity and quality.

## Chapter 1: Mapping Winter and Summer Nutrition: A Novel Approach for Assessing Ungulate Forage Quality in Temperate Grasslands

### Introduction

Grassland ecosystems, characterized by substantial interannual variability in high-quality pasture, has led to the establishment of a nomadic ungulate-grassland system (Nandintsetseg et al., 2019). Migrating ungulates serve as an "indicators" of ecosystem shift (Environment Canada, 2011) as they are compelled to adapt to climate change and human activities and as "ecological landscapers" through modifying vegetation structure and alter pathways of nutrients (Hobbs, 1996; Morant et al., 2023; Nandintsetseg et al., 2019; Sinclair, 2003). They respond by altering migration routes, calving and wintering sites, which consequently impact their abundance and population structure, and spatial distribution (Berg et al., 2019; Malpeli, 2022; Weiskopf et al., 2019). Grassland ungulates have varying nutritional demands depending on their physical demands (Denryter et al., 2020; Olson, Murray, et al., 2010; Parker et al., 2009), which change during their life cycles. These demands are influenced by seasonal changes in climate and vegetation and are crucial for their survival, affecting their distribution and movements throughout the year (Anderson et al., 2010; Mueller et al., 2008a; Nandintsetseg et al., 2019; Naumann et al., 2017; Olson et al., 2010; Treydte et al., 2013). Movements and habitat choices are linked to changes in forage with unique nutritional properties (Anderson et al., 2010; Codron et al., 2007; John M., 1991; Mueller et al., 2008a; Naumann et al., 2017; Olson, et al., 2010; Prins & Beekman, 1989; Treydte et al., 2013).

Forage nutritional properties have two components: forage quantity (biomass) and forage quality, (calorie/minerals content) (Fryxell, 1991; Owen-Smith & Novellie, 1982). Nutrient availability to animals is influenced by factors that impact ingestion rates and digestive passage (which is called foraging efficiency) (Klop et al., 2007; Langvatn & Hanley, 1993; Owen-Smith & Novellie, 1982). These factors can differ among herbivore species, playing an important role in the distribution of both individual animals and populations of wild ungulates. However, most studies on temperate grassland ungulates have primarily focused on summer behavior (Codron et al., 2007; John M., 1991; Naumann et al., 2017; Olson et al., 2010; Prins & Beekman, 1989; Ryan et al., 2012; Treydte et al., 2013), overlooking crucial winter nutrition.

Forage nutrition are important for both winter and summer habitat of ungulates. Interannual variations in plant phenology, primarily caused by climatic variability particularly within continental climate ranges, influences nutrient contents (Westoby, 1974), leading to variations among different vegetation species or communities, and within the same species among seasons (Naumann et al., 2017). During the summer, forage conditions influence several critical aspects of ungulate ecology, including reproductive success, survival of juveniles and adults, as well as population recovery of large herbivores following disease outbreaks (Wagler et al., 2023). This is achieved through the accumulation of energetic reserves over the summer months. Conversely, winter habitats are often nutritional bottlenecks for ungulates. The nutritional quality and quantity available during the winter season influences neonatal survival

(Parker et al., 2009), as compromised body condition or fetal development may lead to early deaths (Roffe, 1993). Additionally, insufficient nutrition during winter can reduce resilience to severe winter conditions. Among natural calamities, the most fatal for ungulates are snowstorms, deep snow cover, and ice-crust, known as a dzud (Du et al., 2018; Dunlop, 2023). Dzud not only triggers migrations of wild ungulates but also leads to mass mortality (Geptner et al., 1988; Kaczensky et al., 2011; Kirilyuk & Lushchekina, 2017; Milner-Gulland & Lhagvasuren, 1998). For instance, the Mongolian gazelle disappeared from certain areas for several years, as observed in western Mongolia after the winter of 1935 to 1936 (Geptner et al., 1988). In such harsh winters, gazelles perish directly from hunger or fall victim to wolves. Weakened animals struggle to navigate through deep snow swiftly. Moreover, during migrations, ungulates often find themselves in unfamiliar conditions, such as forests or narrow valleys, making them easy prey for predators (Geptner et al., 1988; Kirilyuk & Lushchekina, 2017).

Vegetation mapping using field or airborne hyperspectral data can discern vegetation classes (Lang et al., 2021; Meng et al., 2022; Miao et al., 2022; Pöttker et al., 2023; Ran et al., 2019; Shi et al., 2022; Zhang et al., 2023) and various properties, including biomass (Beeri et al., 2007; Cho & Skidmore, 2009; Tucker, 1978), chlorophyll, leafwater (Green et al., 1998; Tucker, 1978), and foliar nutrient content (e.g. crude protein) (Beeri et al., 2007; Knyazikhin et al., 2013; Mutanga & Skidmore, 2004; Ollinger et al., 2002; Ryan et al., 2012; Skidmore et al., 2010). For instance, rangeland crude protein content and spectral indices measured by the Sentinel-2 satellite (Chabalala et al., 2020; Lugassi et al., 2019), Landsat (Pringle et al., 2021), and MODIS (Irisarri et al., 2022; Kawamura et al., 2005). However, this relationship, when based on satellite data, exhibits nonreliable irregularly associations with crude protein content (Kawamura et al., 2005; Lugassi et al., 2019). These associations seem to depend on factors such as the time scale, with analyses conducted among years (Kawamura et al., 2005) or within a single year (Ryan et al., 2012) yielding differing results. There is also a connection between the proportion of photosynthetic and non-photosynthetic vegetation and crude protein content (Evans, 1989; Field & Mooney, 1986; Pringle et al., 2021).

Vegetation indices like Normalized Difference Vegetation Index (NDVI) are commonly used as a proxy to assess forage quality (Ryan et al., 2012; Serrano et al., 2023). However, NDVI derived from red (665–680 nm) and NIR bands, along with MSAVI, SARVI, and NDWI, lack reliability in predicting grass/herb biomass annually (Cho & Skidmore, 2009; Lugassi et al., 2019; Moyer & Southeast, 2013; Ryan et al., 2012), and there is no strong relationship between NDVI and forage quality parameters such as crude protein, acid detergent fiber, and neutral detergent fiber (Montgomery et al., 2022). Moreover, vegetation indices, particularly NDVI, do not consistently perform well in ungulate biogeographical models (Gautam et al., 2018; Nandintsetseg et al., 2016; Said et al., 2003). NDVI may not adequately capture vegetation complexity and may not be suitable for ecosystems or species with distinct spectral responses or specific habitat requirements. Furthermore, relying solely on biomass, particularly in relatively homogeneous, arid ecosystems like steppes, which are prone to intermittent fires and human impact may lead to nonreliable results (Nandintsetseg et al., 2016).

Hence, my aim is to develop and test a novel approach for appraising the forage quality of ungulates in temperate grasslands utilizing remote sensing. I propose to map both winter and summer nutrition, contributing to the improvement of biogeographical models for ungulates.

My objectives are to (1) develop a novel approach for estimating winter crude protein concentration using freely available medium spatial resolution data, e.g., Sentinel-2 imagery; (2) show that in winter habitats, distribution map of plant communities substitutional to a map of concentration of crude protein; and incorporating biomass parameter will contribute positively to ungulates biogeographical models accuracy in areas with limited livestock pressure; and that (3) for summer habitats, the optimal predictors for spatial species distribution are biomass plus crude protein concentration, or biomass and plant community map.

## Materials and Methods

### *Study area*

The study area is the Daurian Steppe (known as Dauria) withing the border of the Amur Basin (Fig.1.1), vesting of 742,420 km$^2$ of comprising the Daurian Forest Steppe and Mongolian-Manchurian grassland (Olson & Dinerstein, 1998). Specifically, the study area covers the southeastern portion of Zabaykalsky Krai in Russia, region of Dornod Aimag, the northeastern Sukhbaatar and Khentii Aimag in Mongolia, and the northwestern parts of Inner Mongolia Province in China. This ecoregion represents a prime example of well-preserved, intact Eurasian steppe (Kirilyuk, 2021; Olson et al., 2010; Scholtz & Twidwell, 2022; Simonov et al., 2013). The study area is transitional temperate continental grassland located on the border of boreal forest on the north and semi-desert grassland ecosystems in the south, primarily locating at elevations ranging from 600 to 800 meters above sea level, and characterizing by vast plains and undulating terrain. It is subject to an ultra-continental climate, characterized by severely cold winter temperatures (with average January temperatures dropping to -25°C in the Russian part). The spring season is typically cold, windy, and dry, while the majority of rainfall occurs during the latter half of summer when temperatures reach their peak. The presence of open areas exposed to spring-summer winds and the fine granular composition of chestnut soils make them susceptible to erosion.

### *Mongolian Gazelle Ecology*

Further data on the ecology of the Mongolian gazelle, encompassing foraging behavior and spatial-temporal distribution, is summarized using published research from the Mongolian and Russian Dauria (Gibb et al., 2015; Imai et al., 2019, 2020; Kirilyuk, 2007, 2021; Kirilyuk, 2003; Kirilyuk & Lushchekina, 2017; Leimgruber et al., 2001; Lhagvasuren & Milner-Gulland, 1997; Mendgen et al., 2023; Miura et al., 2004; Mueller et al., 2008b; Odonkhuu et al., 2009; Olson et al., 2009, 2010, 2011; Olson et al., 2010), as well as unpublished data from the ongoing research project on Dzeren in the Daursky Reserve.

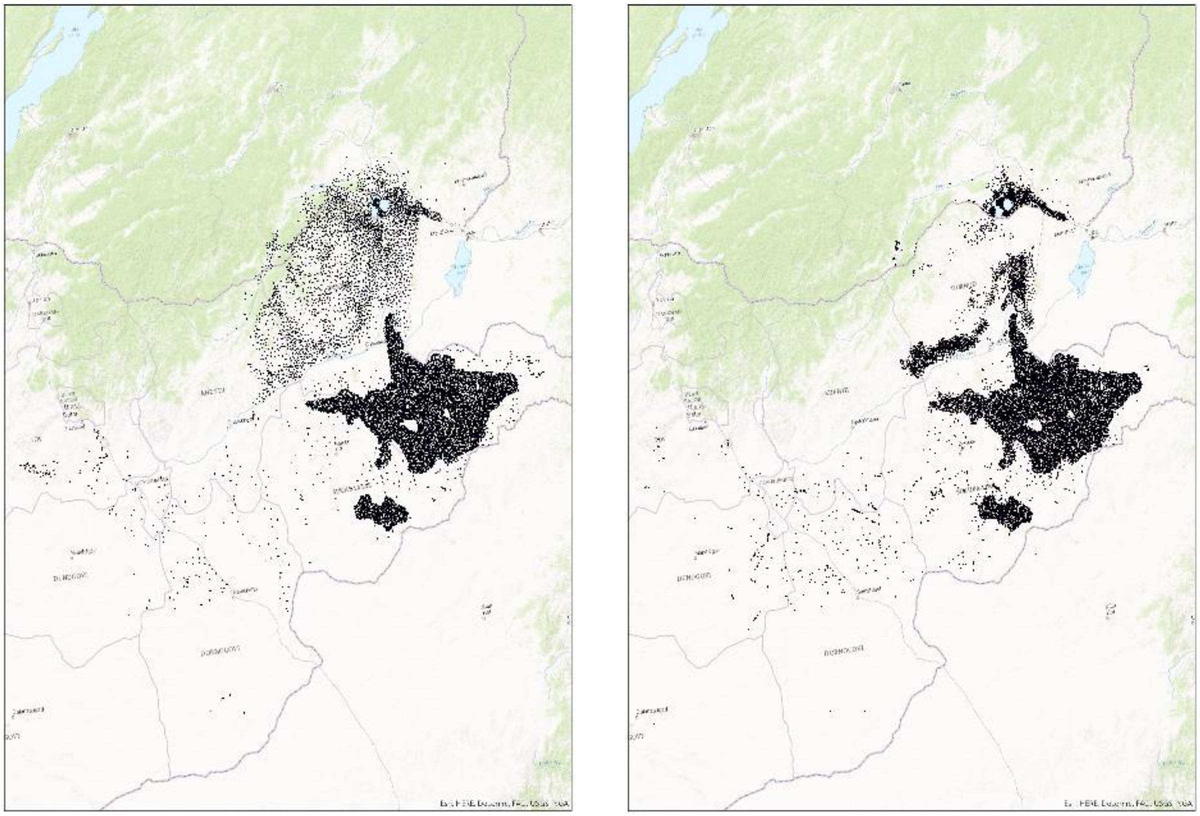
Dzeren, or Mongolian gazelles, consume a variety of plant species, including *Stipa sp., Siripa sp., Leymus chinensis, Koeleria sp., Potentilla sp., Allium sp., Artemisia sp., Caragana sp., Carex sp., Salsola sp., Cleistogenes sp., Serratula sp*., and others. They exhibit a nomadic grazing pattern to prevent pasture depletion, becoming more mobile with increased population density or diminished forage due to drought or overgrazing. During the growing season, they survive without watering places. They consume snow in winter or lick ice. In dry periods, watering places become necessary. The essential forage minerals for herbivores include calcium (Ca), phosphorus (P), potassium (K), especially for lactating females and growing young (Jiang et al., 2002; McNaughton, 1990; Olson et al., 2010)**.**

Female Mongolian gazelles prefer the edges of depressions, such as basins, ancient riverbeds, and gentle slopes of hills. These areas feature grass steppes dominated by *Leymus*, low-bunchgrass, and feather grass communities. Gazelles avoid more humid areas during the calving period. Adult males and one-year-olds split their summer stay, with males favoring rugged terrain and abundant forb vegetation. In winter, their habitat expands to explore various biotopes, including forb and *Filifolium* steppes and abandoned fields. Sedentary and migratory groups occupy diverse territories, avoiding water bodies, wetlands, rock massifs, and forest islands.

In Eastern Mongolia and the Russian Transbaikal region, summer territories with calving grounds remain consistent, expanding in autumn. Smaller groups consisting of one to two thousand individuals lead a relatively "sedentary" lifestyle, occupying a slightly larger territory in winter compared to summer and forgoing regular seasonal migrations. In contrast, larger groups comprising tens to hundreds of thousands of individuals largely vacate the summer territory and embark on long-distance migration routes during winter. Their winter habitat area is about ten times larger than their summer habitat. From year to year, the specific winter areas used tend to alternate, while the summer area undergoes minimal changes. The cumulative winter territory over many years serves as the group's habitat. There are zones of extreme winter displacement—areas that gazelles migrate to when highly unfavorable living conditions arise, particularly during heavy snowfall. Such areas are rarely utilized by antelopes, occurring no more than once every five to ten years and only in extreme circumstances. Studies suggest that 100-150 thousand hectares are necessary for a settled group of up to one thousand individuals for long-term stability.

*Mongolian Gazelle Data*

To test the species distribution model, I will utilize 12,213 “winter” (September–May) and 14,044 “summer” (June–August) gazelle encounter points or sites with gazelle excrement collected and provided by the specialists at the Daursky State Nature Biosphere Reserve 2000–2023 (Fig.1.1). The encounter point has an accuracy of 0.1 km and includes meetings of the gazelles themselves or their excrement.



A B

**Fig.1.1. Winter (A) and summer (B) encounter points of Mongolian Gazelle in Russia and Mongolia in 2000–2016, used to model the species' distribution.**

*Vegetation Classification*

I will create a map classifying the primary vegetation communities within the study area using 2023 Sentinel-2 imagery. This classification is based on field data research, encompassing approximately 300 plots of 100 $m^2$ each, applying the Random Forest algorithm (Meng et al., 2022) and spectral-temporal metrics (Frantz et al., 2023). It will focus on the permanent plots within the plant communities' dynamics monitoring network of the Daursky State Nature Biosphere Reserve, and the Mongolia-China-Russia Dauria International Protected Area transboundary ecosystem monitoring network, established in 2010. Geobotanical profiles were regularly measured until 2023 as part of these monitoring programs on lakes coast, in floodplains, and in steppe zones. The data collection methods used in this study are outlined in Gorunova et al. (2010) (Goryunova et al., 2010) and the internal Guidelines for Monitoring Ecosystems provided by the Daursky State Nature Biosphere Reserve.

The random forest (RF) classification algorithm will be employed for the classification of vegetation communities. RF has demonstrated high prediction accuracy in steppe classification (Meng et al., 2022). The hyperparameters of the RF algorithm, such as the number of estimators, maximum depth of the decision tree, and minimum leaf node samples, will be determined through a trial-and-error process (Yang et al., 2018). I will use the input data consisting of a training set and a validation set. The training set will be used to adjust the weights of each algorithm, while the validation set will help mitigate overfitting (Meng et al., 2022).

I will classify vegetation types into five primary classes based on the dominant species: 1 - "Sparse woody shrub", 2 - "Graminoids", 3 - "Filifolium-forb", 4 - "Artemisia", and 5 - "Halophytic meadow". Additionally, I will include three supplementary classes: "Forest" - 6, "Bareness" - 7, and "Water" - 8. Furthermore, I have conducted tests to ascertain if grassland vegetation community classes with similar spectral properties can be distinguished from one another. The data on vegetation community were gathered for 143 plots along three transects in 2019, along with 35 Landsat scenes (comprising 17 Landsat 7 and 18 Landsat 8, Level 2, Collection 2 data) merged by months using their median values. I performed a pairwise Wilcoxon rank sum test on the NDVI (and all six bands) values and the class variable, incorporating Bonferroni correction for multiple comparisons, and conducted the Dunn's test for post-hoc analysis of interactions between classes and months.

Class 5 is distinct from other classes. However, one has to interpret the results for class 5 (Halophytic meadow) cautiously. It appears that the presence of shallow water at the shoreline and the bottom of the lake in summer, along with the presence of salt marshes in general, could influence the reflectance of this class. Therefore, I will proceed with further interpretation of the results for classes 1-4: 1 - "Sparse woody shrub", 2 - "Graminoids", 3 - "Filifolium-forb", and 4 - "Artemisia". In terms of the application of NDVI, it may be useful in distinguishing between class 1 and 2, as well as class 1 and 4. These pairs of classes also exhibit distinguishable features across all spectra. Meanwhile, classes 1 and 3 differ primarily within SWIR1 and SWIR2. Classes 2 and 3 can be distinguished within the NIR and visible spectra, while it appears that classes 2 and 4 are not distinguishable. Classes 3 and 4, however, can be in the NIR and visible spectra. The addition of more samples may enhance the distinction among these four classes. Additionally, it is important to note that I conducted these tests for only one year, and the characteristics of each class may vary in different years, depending on different conditions. Furthermore, incorporating interactions with months can enhance the distinction of classes. NDVI values of all classes vary within the year, particularly, classes 1 and 3 show variation between each month of the year, as do classes 2 and 4. I observed similar trends across all six spectra.

*Image acquisition*

I will use a medium-resolution data from Environmental Mapping and Analysis Program (EnMap) imagery, and Sentinel-2 (the Copernicus Programme by the European Space Agency) imagery. EnMAP observes spectral ranges between 418.2 and 2445.5 nm with 224 bands and a ground instantaneous field-of-view of 30 x 30 m over a swath width of 30 km (Storch et al., 2023). The Sentinel-2 mission has a wide swath of 290 km field of view. The 13 spectral bands (443–2190 nm) of Sentinel-2 images have a spatial resolution of 10 m (four visible and near-infrared bands), 20 m (six red edge and shortwave infrared bands) and 60 m (three atmospheric correction bands) (Table .1.1) (ESA, 2014; Phiri et al., 2020). I will utilize Level 2A products, which entail atmospheric correction of orthorectified imagery.

**Table 1.1 Characteristics of ESA Sentinel-2A and -2B satellite images** (ESA, 2014)

| | | **Sentinel-2A, 2015** | | **Sentinel-2B, 2017** | |
|---|---|---|---|---|---|
| **Spatial Resolution (m)** | **Bands** | **Central wavelength (nm)** | **Bandwidth (nm)** | **Central Wavelength (nm)** | **Bandwidth (nm)** |
| **10** | Band 2 - Blue | 492.4 | 66 | 492.1 | 66 |
| | Band 3 - Green | 559.8 | 36 | 559 | 36 |
| | Band 4 - Red | 664.6 | 31 | 664.9 | 31 |
| | Band 8 - NIR | 832.8 | 106 | 832.9 | 106 |
| **20** | Band 6 - Red edge | 740.5 | 15 | 739.1 | 15 |
| | Band 7 - Red edge | 782.8 | 20 | 779.7 | 20 |
| | Band 8A - Narrow NIR | 864.7 | 21 | 864 | 22 |
| | Band 11 - SWIR | 1613.7 | 91 | 1610.4 | 94 |
| | Band 12 - SWIR | 2202.4 | 175 | 2185.7 | 185 |
| **60** | Band 1 - Coastal aerosol | 442.7 | 21 | 442.2 | 21 |
| | Band 9 - Water vapour | 945.1 | 20 | 943.2 | 21 |
| | Band 10 – SWIR (Cirrus) | 1373.5 | 31 | 1376.9 | 30 |

*Vegetation Data and Spectral Measurements*

Satellite-derived photosynthetic activity approximated by spectral vegetation indices ("greenness"), will be used as proxy for summer productivity. To minimize soil background reflectance in areas where grassland vegetation may be sparse, I will utilize the 2-band Enhanced Vegetation Index (EVI2) (Huang et al., 2019), derived from Sentinel-2. To estimate winter vegetation dry biomass, I will utilize the Gross Dry Matter Productivity product provided by Copernicus (Copernicus, 2024), which is derived globally from 10-day observations of Sentinel-3 (OLCI, PROBA-V) since 2014. This data is available at a spatial resolution of 300 meters. If the spatial resolution of the Copernicus product is insufficient to address my study question, I will utilize spectral indices directly characterize dry matter absorption, derived from Sentinel-2, such as cellulose absorption index (Nagler et al., 2003), or dry matter indices (Cheng et al., 2017).

For lab spectral measurements of four biochemical macronutrients: nitrogen (N), calcium (Ca), phosphorus (P), and potassium (K), I will use the ASD FieldSpec (ASD Inc., Boulder, CO, USA) (Chlus, 2020). Due to field sampling conditions and the presence of water in fresh leaves, which can obscure molecular absorption features (Chlus, 2020), I will use dried and ground foliar samples (20-mesh, 833 μm) for spectroscopic estimation of foliar biochemistry, following Serbin et al. (2014) (Serbin et al., 2014). All grassland samples will be categorized into two conditional seasons: summer (May-September) and winter (October-April). Vegetation samples (10 g dry matter per sample) were collected during fieldwork on 100 plots of 30 x 30 and 100 x 100m in 2023 (refer to Fig. 1.2), and additional collections are planned for 2024. Samples are collected across the Mongolian part of the study area, representing approximately 20 species. Upon collecting, leaf samples are placed in paper bags and air dried.

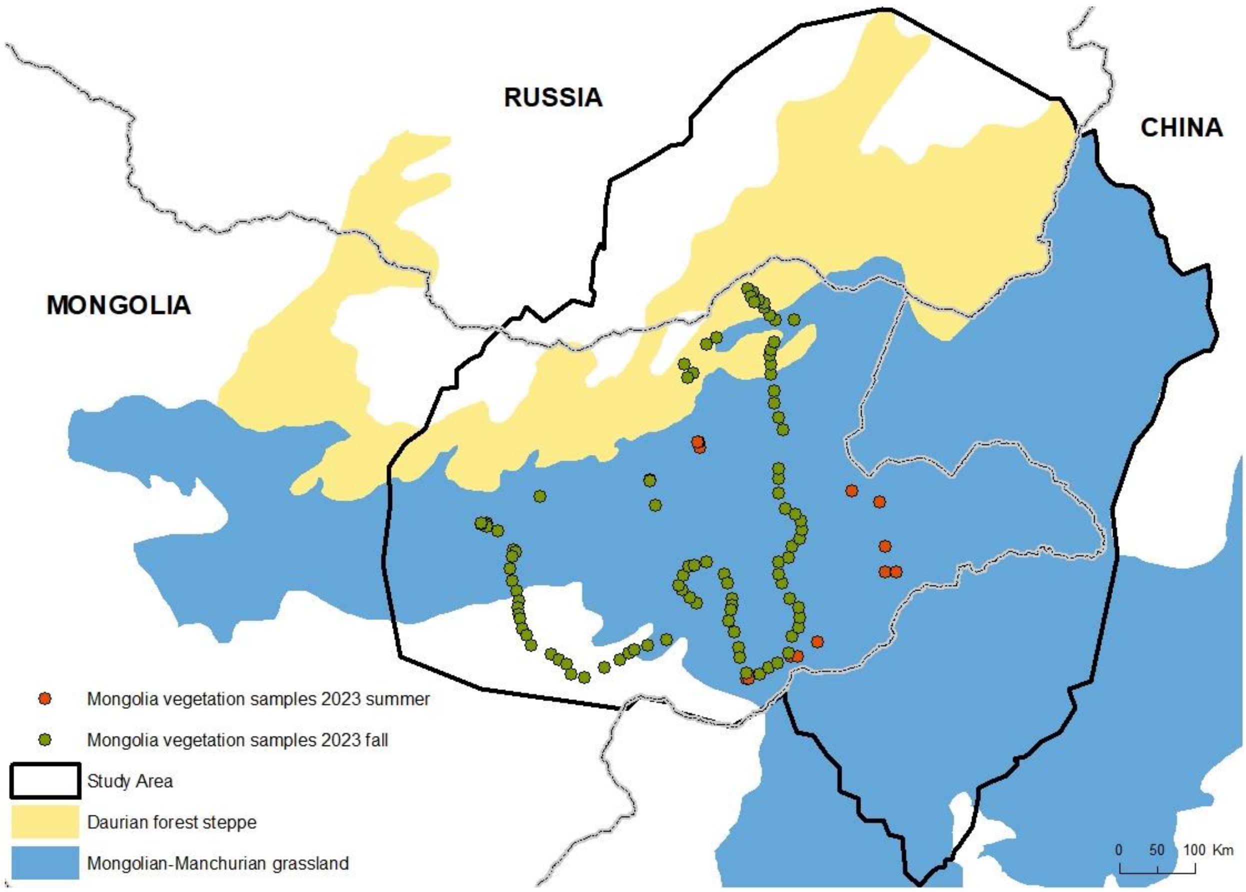



**Fig. 1.2. Study Area and vegetation samples collected during summer and fall in Mongolia, 2023.**

Following the method described by Wang et al. (2020) (Wang et al., 2020), I will calculate the community weighted means (CWMs) of traits using the averages of the leaf traits of each species, firstly finding the individual-level traits, then averaging leaf traits from multiple samples to species level traits, and then aggregating them using fraction cover by species to derive CWMs of traits. Furthermore, I will compare the lab results on summer vegetation nutrition with those from 2000-2002 field work presented by Olson et al. (2010).

I will utilize laboratory reflectance measurements of dried and ground leaves and extend these reflectance features to remote sensing data of a hyperspectral imagery of EnMap, and subsequent 13 bands spectra data from Sentinel-2 imagery. To predict leaf traits (specifically nitrogen, calcium, phosphorus, and potassium) from dry spectral results, following the methodology outlined by Wang et al. (2020), I will develop Partial Least Squares Regression

(PLSR) models (Singh et al., 2015) to estimate community-weighted traits based on EnMap imagery reflectance. I will delineate polygons for each plot and utilize them to extract spectra from images, subsequently averaging the spectra within each plot to obtain a mean reflectance per plot. For model development and mapping purposes I will eliminate the noisy and atmospheric absorption bands and remain spectral regions spanning 418.59–1335.04 nm, 1460.23–1770.72 nm, and 1986.06–2396.71 nm (Wang et al., 2020).

*Species Distribution Modeling.*

To demonstrate the variation in the improvement and integration of forage quality and quantity metrics into seasonal biogeographical models, I will run and test several models. Addressing my research questions involves examining the winter habitat concentration map of crude protein in relation to the distribution map of plant communities and determining how incorporating the biomass parameter contributes to the accuracy of ungulate biogeographical models. For summer habitats, I will explore whether the optimal predictors for spatial species distribution are biomass plus crude protein concentration or biomass and the plant community map. I will run three models, including all three parameters (distribution map of plant communities, crude protein, and biomass), the combination of distribution map of plant communities and biomass, and the combination of crude protein and biomass. Subsequently, I will test for any statistical differences between these models.

For a more in-depth analysis of possible and optimal summer and winter habitats in relation to forage quality and quantity metrics, particularly using the Mongolian Gazelle as an example, I will apply generalized linear models (McCullagh, 1984) for Species Distribution Models (SDM, biomod2 package). Totally, 9 parameters will be used to model gazelle habitats, identified by previous research (Table 1.2): vegetation nutrition qualities: crude protein concentration for the main vegetation communities, steepness of slopes and rough terrain, Dynamic Habitat Indices, fraction of the territory covered with woody vegetation, frequency of fires, Winter-Habitat Index, livestock density, Human footprint indexes (distance to settlements, and distance to main roads), and distance to water source.

I will split zones for the study area based on counting efforts over a 10-year period:

- With more than 10 end-to-end route counts - coefficient: 1.
- With 3-9 end-to-end route counts - coefficient: 0.5.
- With 2 or fewer end-to-end route counts - coefficient: 0.1.

The modeling will be conducted separately for the wet years (2000-2008), the dry years (2001-2017), and the wet years (2018-2023), with additional considerations for the year 2023 (need to add points).

**Table 1.2 Parameters used to model the Mongolian Gazelle habitats**

| N | Parameter | Rationale | Data |
|---|---|---|---|
| 1 | Vegetation nutrition qualities | Seasonal movements of gazelles correlate with changes in phytomass in the steppes of Eastern Mongolia (V. Kirilyuk et al., 2012; Leimgruber et al., 2001; Miura et al., 2004). Dzeren preferred sites with higher NDVI, at least during the dry phase of the moisture cycle covered by the studies. | See methods section. |
| 2 | Steepness of slopes and rough terrain | Dzeren does not use strongly rugged mountainous terrain and steep slopes as regular habitats, preferring flat or hilly terrain (Kirilyuk, V.E., in press). | COP-DEM_GLO-30, Copernicus DEM - Global and European Digital Elevation Model. https://spacedata.copernicus.eu/collections /copernicus-digital-elevation-model |
| 3 | Dynamic Habitat Indices | | DHI will be calculated for MODIS. |
| 4 | Fraction of the territory covered with woody vegetation | Dzeren can enter sparse valley forests only in certain snowy winters, in other cases they avoid such territories (Kirilyuk, V.E., in press). | MODIS Vegetation Continuous Fields (VCF). |
| 5 | Frequency of fires | Distribution of gazelles may be due to spring and autumn fires in the steppe: as a rule, animals avoid recently burned areas (Kirilyuk, V.E., in press). | The frequency of spring and autumn fires of 2000-2023 will be obtained through Chapter 3 and Daursky Reserve wildfires dataset. |
| 6 | Winter-Habitat Index | Dzeren prefers areas with low snow cover (<7-8 cm) for winter habitats (Lhagvasuren & Milner-Gulland, 1997) (Kirilyuk, V.E., in press). | |
| 7 | Livestock density | Overgrazing. Gaps in the spatial distribution of Dzeren are primarily limited to settlements and areas with dense livestock camps. | Official open statistical reports and databases of Mongolia, Russia and China. |
| 8 | Human Footprint Indexes (settlements, | Dzeren avoids settlements in Mongolia and does not usually approach at a distance of <5-15 km from them. In Russia, this distance is much less and is <1.5-2.5 km | |

| N | Parameter | Rationale | Data |
|---|---|---|---|
| | and roads sensity) | (Kirilyuk, V.E., in press). Road density is a good indicator not only for the disturbance factor, habitats fragmentation, but also for hunting pressure assessment (as an indicator of accessibility). | |
| 9 | Distance to water source | During the snowless dry periods of spring and autumn when the grass is dry and there is no snow, watering places become necessary. | |

**Expected results**

- I will map the primary vegetation communities in the selected study area, showing their distribution based on Sentinel-2 data for 2023.
- I will map the crude protein and mineral concentrations for classified vegetation communities and analyze their changes to assess differences between the summer and winter seasons.
- The changes in crude protein and mineral concentration among seasons will be quantified and analyzed spatially across the study area over 11 years.
- To validate the detected changes in crude protein and mineral concentration using hyperspectral images, I will compare them with the results obtained from lab tests on samples collected for summer and winter habitats in Mongolia.
- Accuracy measures and error matrices, including overall accuracy and precision, will be presented in tabular form for evaluation and comparison of all maps.
- To enhance seasonal biogeographical models, I will run and assess various models, examining summer and winter habitats in relation to forage quality and quantity metrics.
- To evaluate the utility of the created maps in biogeographical models, I will conduct a species distribution model for the Mongolian Gazelle.
- I will create maps of optimal and potential habitats for the Mongolian gazelle during summer and winter based on spring and fall encounter surveys conducted between 2000 and 2023. These maps will provide valuable insights into the species' habitat requirements and usage patterns, incorporating new data on vegetation composition and forage nutritional quality.
- I will identify the limiting factors that influence the suitability of potential habitats for the Mongolian gazelle, including climate conditions, environmental features, livestock pressure, and road density.

**Significance and contributions**

*Mapping Techniques Advancement.* The innovative use of advanced mapping techniques for mapping foliar nutritional traits, including hyperspectral imagery, represents an important advancement in the field, offering the opportunity to directly map forage quality. Moreover, the validation process, comparing hyperspectral images with lab test results, ensures the accuracy of mapping and detecting changes in vegetation quality.

*Forage Seasonal Dynamics*. The comprehensive mapping of vegetation communities, coupled with the assessment of their nutritional quality, provides crucial insights into forage dynamics in the homogeneous semi-dry grasslands across different seasons. Specifically, I will define how the concentrations of crude protein and minerals within the same vegetation communities can vary across seasons.

*Ecological and Conservation Contributions.* Testing the created maps on a species distribution model enhances understanding of nutritional quality and quantity traits in habitats during different seasons for modeling species habitats and distribution.

*Mongolian Gazelle Conservation Contributions.* Findings will inform conservation efforts for Dzeren and help protect its habitats. The research contributes to the purpose of conserving UNESCO World Nature Heritage Sites. The Dauria International Protected Area (Daursky State Nature Biosphere Reserve and Mongol-Daguur Strictly Protected Area are parts of the World Heritage Site "Landscapes of Dauria") preserves one of the last most intact and remaining continuous grasslands on Earth (Scholtz & Twidwell, 2022). Moreover, I will share my results with the relevant authorities in China, Mongolia, and Russia, integrated into the management plans of the Dauria International Protected Area.

In summary, the research advances mapping techniques and contributes to understanding and preserving not only grassland ecosystems but also holds significance for ecological research and conservation strategies, providing a pathway for sustainable land use planning globally.

## Chapter 2. Rural Infrastructure Dynamics: Mapping Changes in Unpaved Roads and Fences Over 50 Years in Daurian Grasslands

### Introduction

Linear infrastructure like road and fencing is a nearly omnipresent. The impact of unpaved dirt roads and rural fences is substantial across various domains, encompassing social, economic, and environmental aspects. Impacts of roads, fences, and other linear infrastructure on wildlife and ecosystems are one of the major drivers of global biodiversity loss. Impacts encompass habitat loss, isolation, barrier effects, intrusion of edge effects, microrelief and microclimate changes, road/fence mortality, increased human access/disturbance by roads, and fire ignition (Barrientos et al., 2021; Benítez-López et al., 2010; Berger, 2004; Cozzi et al., 2013; Harrington & Conover, 2006; Holt et al., 2021; Jones et al., 2022; Lee & Power, 2013; McInturff et al., 2020; Narayanaraj & Wimberly, 2012; Richard et al., 2000; Ricotta et al., 2018; Zhou et al., 2023). This concern is particularly heightened in areas with intensive agricultural use and abundant wildlife, such as grasslands (Guo et al., 2021; Jakes et al., 2018; Jones et al., 2019; Kinugasa & Oda, 2014; Lee & Power, 2013; Linnell et al., 2016; Liu et al., 2022; Løvschal et al., 2017, 2022; Woodroffe et al., 2014; Zhou et al., 2023). However, there are some positive aspects of both dirt roads and fences for ecosystem and nature conservation. Dirt roads contribute to fire management, facilitate animal access to new areas, promote the growth of certain plant species along road edges, and in snowy regions, animals may use roads to avoid deep snow, ensuring easier transport, and use road ravines as water and snow sources or as daily shelter in open landscapes (Bruggeman et al., 2007; Daoutis & Lempesi, 2023; Katuwal et al., 2016; Narayanaraj & Wimberly, 2011; Thompson et al., 2021; Yocom et al., 2019). Fences also play a role in conservation by protecting certain species from poachers and mitigating human-wildlife conflicts (McInturff et al., 2020; Woodroffe et al., 2014).

Although unpaved roads pose a potentially lower threat to wildlife disturbance and mortality compared to paved roads, their extensive network has profound ecological implications. In regions such as Mongolia, northwestern China, and southeastern Siberia, where intensive agricultural practices are prevalent, an extensive network of dirt roads is found in rural areas. In these areas, the proliferation of dirt roads contributes to alterations in landscapes, including soil properties, soil compaction, increased soil erosion, shifts in plant composition and hydrological behavior of landscapes, changes in microrelief, and habitat fragmentation (Benítez-López et al., 2010; Farias et al., 2021; Guo et al., 2021; Kinugasa & Oda, 2014; Lee & Power, 2013; Farias et al., 2019; Mendgen et al., 2023; Richard et al., 2000; Zhou et al., 2023). Thus, in northwest China dirt roads intensify soil wind erosion, enhancing the susceptibility of the surrounding environment to erosion (Zhou et al., 2023). These issues are exacerbated by the aridization of the climate and intensified cattle husbandry. Furthermore, vehicle tracks on unpaved road surfaces severely depletes plant seed banks, resulting in a slower restoration of vegetation cover (Kinugasa & Oda, 2014).

Drawing parallels with roads that have advanced science for public safety and wildlife conservation, rural fences play a similarly influential role. These structures introduce unique barriers and hazards for wildlife but have received less attention (Jakes et al., 2018; McInturff et al., 2020). Fences, much like dirt roads, are typically unregulated and are constructed and maintained largely by private landholders. Wildlife-fence interactions has been confined to local spatial scales, often concentrating on single species, particularly ungulates or at-risk species (Cozzi et al., 2013; Ricotta et al., 2018), and usually driven by observed mortalities and barriers to known migrations (e.g., (Jones et al., 2019)).

The study of an impact of dirt roads on microrelief as well as linear infrastructure as fences and mapping them have been mostly limited by short durations or small geographic scopes. Precise mapping of fences is challenging, hindering research and conservation efforts (Buzzard et al., 2022; Jakes et al., 2018; Liu et al., 2022; Poor et al., 2014). Gaps in scientific understanding of landscape-roads and wildlife-fence interactions underscore the necessity for novel mapping approaches. Furthermore, in regions undergoing transformations, such as the collapse of the Soviet Union, resulting in changes in land use and economic activities lead to subsequent changes of linear infrastructures. Dauria, located within China, Mongolia, and Russia, is a subject to such changes. The region is a highly diverse transitional area from boreal forest in the north to temperate continental grassland in the south, characterized by different socio-economic and nature conservation practices and policies. Hence, this diversity makes Dauria a good study area. However, remote sensing data cover only a little over 30 years, limiting the detection of changes in land use and linear infrastructure caused by socio-economic and political transformations. There is a need to extend the time frame for analysis. The images taken by American spy satellites in the 1960s and '70s offer a chance to acquire land use data from preceding decades (Bailey & Peebles, 1998; Hammer et al., 2022; Pressel, 2014). I propose utilizing the capabilities of spy satellites, like Hexagon, to extend the time frame over 50 years and expand study areas larger than it was done in previous research, encompassing diverse landscapes from semi-desert to forest-steppe.

High-resolution satellite imagery with a resolution of less than 5 meters traces its origins to the early 1960s with the launch of the first Corona spy satellites, followed by Gambit (KH-7) and Hexagon (Bailey & Peebles, 1998; Pressel, 2014). The Hexagon KH-9 satellites, deployed during the Cold War, were U.S. reconnaissance satellites designed for returning photographic film to Earth. Over 19 missions between 1971-1986, these satellites captured images of 877 million square miles of the Earth's surface. The primary objective of Hexagon was wide-area search, achieved through two cameras, designated KH-9 (Hammer et al., 2022; Maurer & Rupper, 2015; Pressel, 2014). These "optical bar cameras" spun on their axes, creating overlapping images for large panoramic pictures. From an altitude of 80-100 miles, the highest ground resolution achieved by the main cameras of the satellite was 0.61 m (Haines, 1997). Some missions also included a separate mapping camera at the front of the satellite, providing precise maps. Hexagon satellite imagery may not be as widely utilized for various studies as Corona imagery, as it has been declassified in 2011 (vs 1995 and 2002 for Corona and Gambit, respectively). However, it holds valuable information about the environment and better coverage of the proposed study area, which might be essential for mapping roads and fences. In other ways, Hexagon surpassed the achievements of earlier programs, offering higher resolution (maximum of 1.8 vs 0.6 m) and more fruitful results, including cloud-free photography (Hammer et al., 2022).

There are three methods for mapping roads: digitization, object-based methods and artificial intelligence-based (AI-based) methods. Traditional road detection methods rely on expert knowledge for manually designing features, often utilizing image segmentation-derived object features and object-based automatic road extraction methods (Brooks et al., 2017; Hinz & Baumgartner, 2003; Li et al., 2016; Pan et al., 2019; Song & Civco, 2004; Valero et al., 2010). Digitization for a small area is typically more accurate but is time-consuming on a larger scale. On the other hand, recently techniques such as U-net AI and post-AI models, enable fully automated road detection, offering increased promise, accuracy, and reduced time and labor requirements. Artificial intelligence-based road detection methods include fuzzy logic, artificial neural network (ANN), adaptive network fuzzy inference system (ANFIS), and deep learning (DL) (Botelho et al., 2022; Bugday, 2018; Karila et al., 2017; Lu et al., 2019, 2021; Mohammadzadeh & Zoej, 2010; Mokhtarzade & Zoej, 2007). Depending on the task, different resolutions of remote sensing data, primarily medium resolution like Sentinel and Landsat, are utilized for road mapping.

Unlike a pixel-based road surface, fences possess a vertical structure and their objects are challenging to distinguish from remote sensing data, thus limiting available mapping methods. Manual digitization using high-resolution imagery remains one of the most accurate methods for fence mapping (Buzzard et al., 2022; Løvschal et al., 2017, 2022; Seward et al., 2012). Another approach involves using predictive spatial models as a proxy for fence locations, relying on spatially-proxy fence line data such as land tenure and ownership or vegetation cover difference to extract fences through identifying boundary between pastures/fields (Buzzard et al., 2022; Liu et al., 2022; Poor et al., 2014). However, these approaches require a comprehensive study of the territory, ground truth surveys, access to state archives, and input from experts. Such methods hold promise for territories where predictions are feasible, as such as the USA, where there is a general understanding of what should be fenced off (Buzzard et al., 2022; Poor et al., 2014). However, in areas with scattered vegetation, where vegetation cover on fenced and unfenced area do not differ a lot to be easily distinguished, lacking fencing regulations and cadastral data on fences, this technique proves less effective as fences remain practically invisible for it. I assume that U-net AI and post-AI models might be effective for fence mapping as well, therefore, in the current research, I will test AI based method similar to roads for fence detection using high-resolution images.

The global expansion of road networks and fencing is evident (Barrientos et al., 2021). The widespread proliferation and density of fencing infrastructure is driven by from the expansion and intensification of anthropogenic land use, along with the escalation of wildlife-human and conservation conflicts (e.g., (Linnell et al., 2016; Løvschal et al., 2017, 2022)). This trend is also likely to be observed in the agricultural regions of grasslands in East Asia, particularly in Mongolia, northwestern China, and southeastern Siberia. However, I presume fencing density to be uneven there, influenced by disparate socio-economic situations and policies. The trend with unpaved roads remains unknown; and I assume that the change of unpaved roads network in such rural areas is probably less obvious and more complex and needs additional research.

Therefore, my goal is to map changes in the network of unpaved dirt roads and rural fences for the grasslands of the Chinese-Mongolian-Russian Dauria ecoregion over 50 years. Particularly, I aim to (1) map dirt roads and understand if there is their effect on forming microrelief, specifically, soil erosion and the appearance of ravines; (2) develop a novel approach for mapping fences, utilizing available high-resolution data like Hexagon and Planet imagery and to compare their contribution and accuracy; and (3) investigate if there are any temporal and spatial-related changes of fencing and dirt roads densities, and are there country impacts and how they differ within agricultural practices and policies of crop and livestock husbandry.

## Materials and Methods

*Study area.*

The study area encompasses the Daurian Steppe, also referred to as Dauria, located within the Amur Basin (Fig. 2.1), covering approximately 742,420 km$^2$. This region consists of the Daurian Forest Steppe and Mongolian-Manchurian grassland (Olson & Dinerstein, 1998). Within this expansive area, six study sites will be identified, with their specific size and location to be determined at a later stage. Specifically, the study area covers the southeastern portion of Zabaykalsky Krai in Russia, region of Dornod Aimag, the northeastern Sukhbaatar and Khentii Aimag in Mongolia, and the northwestern parts of Inner Mongolia Province in China. This ecoregion represents a prime example of well-preserved, intact Eurasian steppe (Kirilyuk, 2021; Olson et al., 2010; Scholtz & Twidwell, 2022; Simonov et al., 2013).

The study area is transitional temperate continental grassland located on the border of boreal forest on the north and semi-desert grassland ecosystems in the south, primarily locating at elevations ranging from 600 to 800 meters above sea level, and characterizing by vast plains and undulating terrain. It is subject to an ultra-continental climate, characterized by severely cold winter temperatures (with average January temperatures dropping to -25°C in the Russian part). The spring season is typically cold, windy, and dry, while the majority of rainfall occurs during the latter half of summer when temperatures reach their peak. The presence of open areas exposed to spring-summer winds and the fine granular composition of chestnut soils make them susceptible to erosion.

The Dauria is also vital for the wellbeing of nomadic herders and local communities who directly depend on its resources. During the Soviet period in Russia, the steppe zones were extensively used for grazing and crops cultivating, but the intensity has now reduced to a moderate level. In China, the grazing intensity is also relatively moderate. However, in Mongolia, the intensity of sheep and livestock grazing is increasing last two decades. Additionally, the study area faces exploitation for crop production, hay harvesting, mining activities, and relatively limited tourism (Kirilyuk et al., 2013; Simonov & Dahmer, 2008; Simonov & Kirilyuk, 2020; Tan et al., 2023).

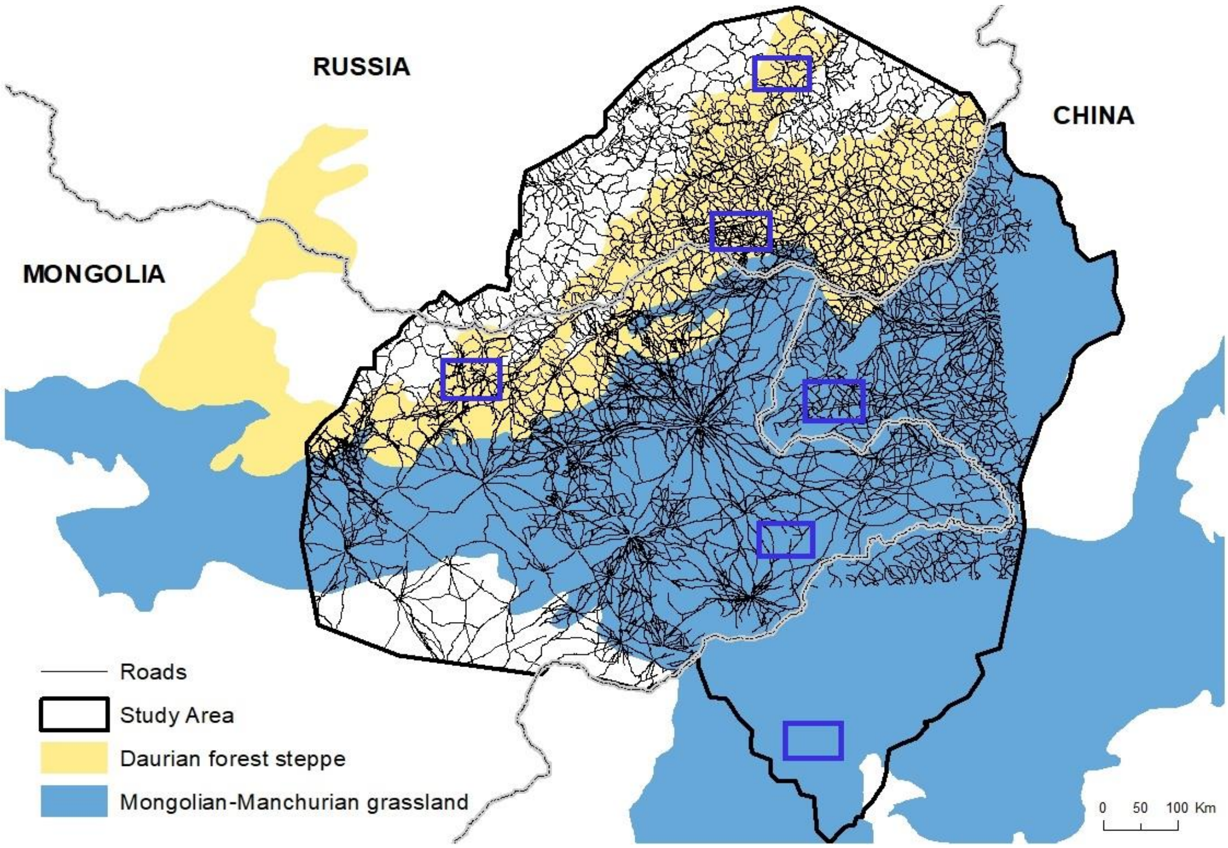



**Fig. 2.1. Roads network in the study area, including paved and unpaved roads. There are different roads network and geometry between three countries. Dark blue rectangles – study sites. Source: see methods section.**

The study area has diverse road network and geometries (i.e., radial, mosaic) (Fig. 2.1). Often dirt roads run parallel to paved roads. Crop fields in Mongolia and Russia are usually not fenced, as well as private land plots. However, in Chinese part of the study area, the network of fences around private land plots is quite extensive (Liu et al., 2022). In Mongolia and the Russian part of the study area, fences consist of wooden posts (10-20 cm in diameter) spaced approximately three meters apart and connected by multiple rows of barbed wire. These fences can be easily visible in high-resolution pictures, especially during the winter when their shadows are prominent due to the sun's low angle in the south (Fig. 2.2). In China, fence posts are typically made of iron with a smaller diameter (round 5 cm), making them hard to distinguish in high-resolution satellite images. However, the taller vegetation growing beneath the fence might be clearly visible (Fig. 2.2).

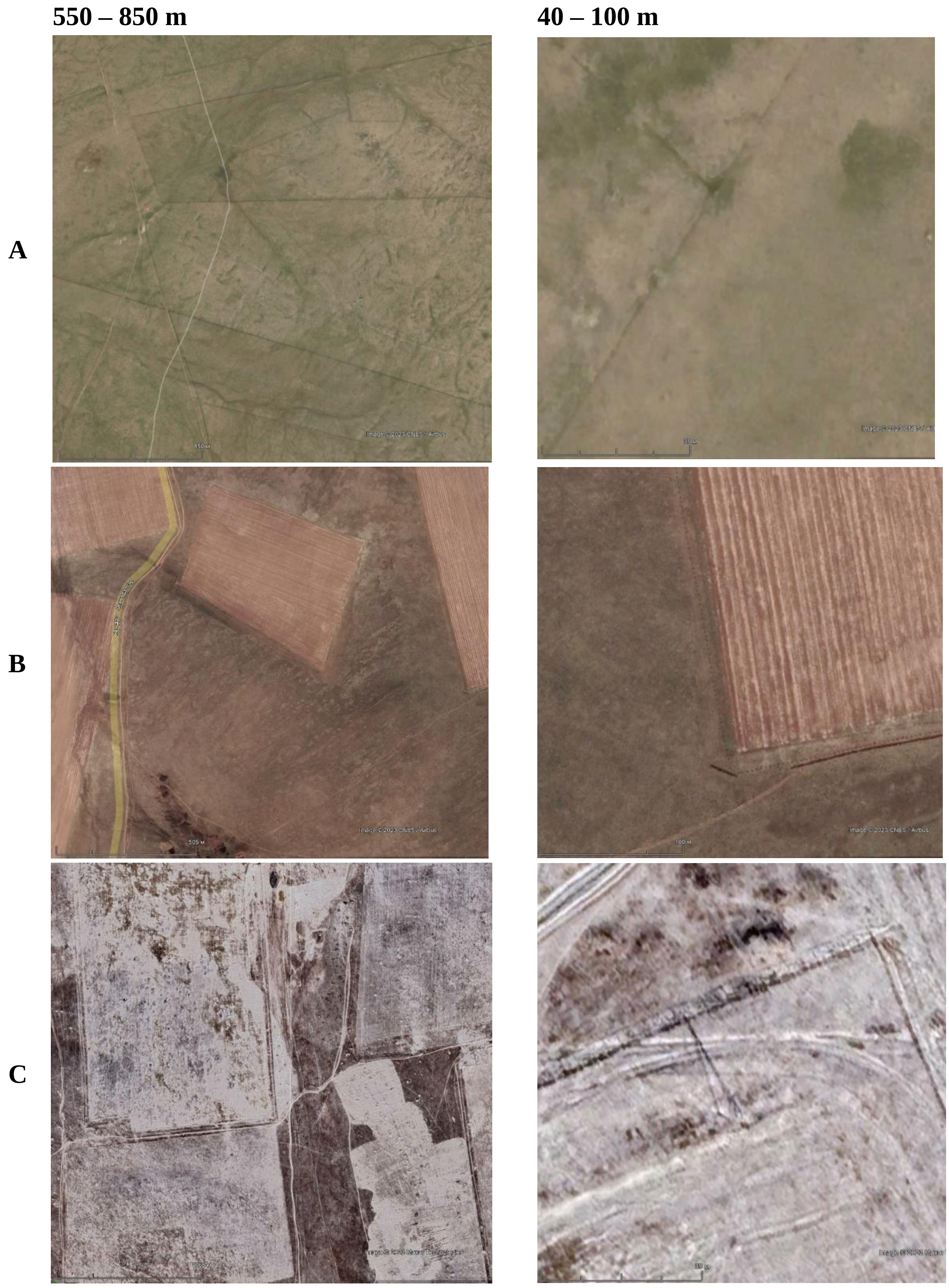



**Fig. 2.2. High-resolution imagery of fenced area across three countries and three seasons with different scale resolution: A – China, B - Mongolia, and C – Russia. Source: Google Earth Pro.**

*Data*

I will use high-resolution imagery of Hexagon (source: Earthexplorer.usgs.gov) and Planet (source: planet.com/explorer) to map roads and fences for picked 2 years: median of 1971/1972 (fig. 2.3) and 2023, respectively. Both datasets originate from satellite images captured through Earth observation and are presented in raster format. For orthorectifying the Hexagon images, I will follow the Corona georectification approach developed by Nita et al. (2018) (Nita et al., 2018). I will use SkySat Collect Product by Planet, particularly Ortho Panchromatic assets. These images are orthorectified, calibrated, super-resolved (0.50m), panchromatic-only with Top of Atmosphere (at-sensor) radiance correction.

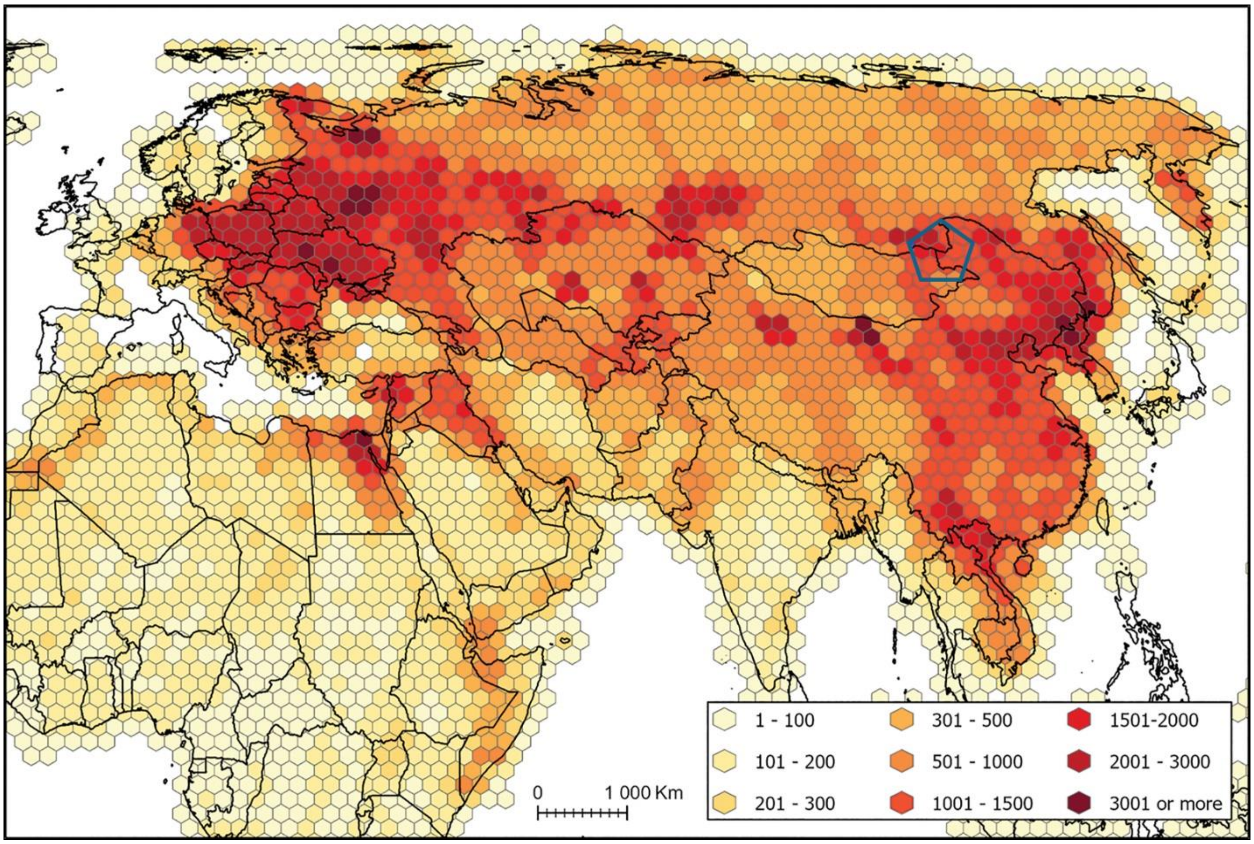



**Fig. 2.3. Hexagon coverage of North Africa and Eurasia. Blue pentagon – the study area location. Source:** (Hammer et al., 2022)**.**

The road layer includes various road types such as highways, primary roads, secondary roads, tertiary roads, and local roads, encompassing both paved and unpaved surfaces. It is a composite derived from the official national road layers for each country sourced from the Global Roads Inventory Project (GRIP) dataset (Meijer et al., 2018). Digitization from high-resolution Google Earth imagery and military topo maps at a scale of 100 meters contributes to the overall composition of the road layer. Additionally, the fence layer will be created through digitization using high-resolution Google Earth imagery.

To compare and define country effect on roads and fences density I will use freely available the European Space Agency World Cover dataset to capture land cover information (Zanaga, 2021), derived from Earth observation satellite images. Official open statistical reports and databases from Mongolia, Russia, and China will be sources for obtaining socio-economic features, including: human population, gross domestic product (GDP) per capita, and the agricultural workforce.

*Data Preparation, U-net Model, and Accuracy Assessment.*

Conceptually, I will apply two detection models, one for roads and another for fences. However, if the fence detection model fails, I will employ a different approach: running a model for detecting artificial linear structures and subsequently eliminating any detected roads from it. What remains will be as a proxy of the presence of fence structures.

At the preprocessing stage, I will apply a cloud mask using the Google Earth Engine, with a cloud cover rate of less than or equal to 10%. Imageries for each year will be merged by their median values.

I will train a modified U-Net road detection model following Botelho et al. (2022) (Botelho et al., 2022). Using Hexagon and Planet satellite imagery selected based on location, date, bands, and cloud cover (less than 10%), I will create a sample dataset for the AI algorithm. This dataset will be generated by digitizing fences and national road layers, rasterizing them into a binary image, and intersecting them with image chips of 256 × 256 pixels along with satellite imagery median values. We will break down the satellite imagery and road/fence raster into 256 × 256 grid cells within the study area to boost training speed.

The sample dataset will be randomly divided into training (80%), validation (10%), and test (10%) sets. Here, the training set is for model fitting, the validation set refines and assesses the model during training, and the test set evaluates the final model performance. I will use the validation and test datasets to conduct pixel-wise accuracy analyses, measuring precision, recall, and F1-Score. Precision assesses the correctness of positive results compared to the model's total positive predictions, while recall gauges how many true positives the model identifies relative to all actual positives. F1-Score combines precision and recall, providing a balanced measure of the model's performance.

Finally, I will convert the collected information into the TFRecord format for size reduction and integration with the TensorFlow AI library. I'll implement a post-AI processing workflow to rectify classification errors, automate road and fence vectorization, connect isolated road and fence segments, and calculate over time change detection. For the dirt roads layer, I will mask out the paved roads.

*Ravine Erosion Detection.*

Because Hexagon data is a grayscale image with potential ambiguity in pixel values due to varying levels of brightness, I will use image brightness property to detect ravine erosion (Kim et al., 2004). I will apply the same approach for panchromatic images of Planet data. I will perform detection of brighter areas only within the 300-meter buffer zone created around the roads, followed by a comparison of the results over a span of 50 years.

*Statistical Analyses.*

I will employ logistic regression to examine the connection between soil erosion (presence/absence) and dirt roads across various terrains (slope and topography) and climate conditions (temperature and precipitation). I will compare the impact of using different remote sensing data sources on the accuracy of analysis.

To assess changes in density of rural dirt roads and fences over time and space, I will utilize a generalized linear mixed model (GLMM). The GLMM will have hierarchical structure and consider variables such as:

- Country level: China, Mongolia, and Russia.
- Time level: 1971/1972 and 2023.
- Land cover
- Socio-economic features from three countries per administrative units, including: human population, gross domestic product (GDP) per capita, and the agricultural workforce.

**Expected results**

I will map rural dirt road and fences in the selected study area, showing their distribution and density based on Hexagon and Planet data for two year of 1971/1972 and 2023. I will map microrelief changes, identifying areas of bare soil and the emergence of ravines, to assess if there are any new objects between 1971/1972 and 2023 that correlate with the presence of dirt roads. The changes in the linear structures' density will be quantified and analyzed spatially across the study area over 50 years.

To validate the detected changes in rural dirt road and fences density, I will compare them with visually assess changes using high-resolution images. Accuracy measures and error matrices, including overall accuracy, and precision, will be presented in tabular form for evaluation and comparison of all maps.

Notably, I anticipate detecting changes of roads and fences density and network geometry along the croplands, particularly after the Soviet Union collapse. To visualize these results, I will create maps depicting dirt roads and fences density and geometry changes between 1971 and 2023. Furthermore, I will identify the primary social-economic drivers of roads and fences density changes, assessing if is there any difference between China, Mongolia and Russia part of the study area.

**Significance and contribution**

My findings of linear infrastructure shifts derived from over 50 years will make several important contributions to the fields of ecology, environmental science, and land-use planning and aid in anticipating future changes.

*Mapping Techniques Advancement.* Mapping long-time changes in roads and fences, the development of a novel approach for mapping rural fences, utilizing high-resolution data like Hexagon and Planet imagery and AI based models, contributes to the advancement of mapping techniques. The comparison of different mapping approaches provides insights into their accuracy and efficiency, potentially influencing future mapping insights.

*Temporal and Spatial Understanding.* Investigating temporal and spatial-related aspects of fencing and dirt roads offers valuable insights into how these structures change over time and space. Understanding country-specific impacts and variations within agricultural practices and policies enhances our knowledge of the broader socio-environmental context.

*Effects on Microrelief.* The exploration of dirt roads' effects on microrelief, soil erosion and the appearance of ravines, addresses a critical gap in our understanding of the ecological consequences of linear infrastructure within different grassland landscapes (from semi-desert to forest-steppe).

*Ecological and Conservation Contributions.* Maps of rural roads and fences contribute to the development of effective conservation strategies; for policymakers, land managers, and conservationists to make informed decisions that balance development and environmental conservation. In particular, it will contribute to the Russian national strategy of Mongolian gazelle conservation and the Dauria International Protected Area conservation action plan. In general, the research addresses global concerns related to extending of linear infrastructure's network in areas with intensive agricultural use and abundant wildlife, such as grasslands in East Asia. The findings may have implications for regions facing similar challenges, contributing to a broader understanding of sustainable land development.

In summary, this research advances mapping technologies, enhances our understanding of the dynamic relationships between linear infrastructure and ecosystems, and provides valuable information for sustainable land-use planning and conservation practices. The findings have the potential to shape future research agendas, influence policy decisions, and contribute to the ongoing discourse on balancing human development with environmental preservation.

## Chapter 3. Long-term Changes of Grassland Plant Community's Productivity: Unraveling the Interplay of Fire, Climate, and Landscape Factors Across China, Mongolia, and Russia

### Introduction

Changes in plant community composition and structure can both influence and be influenced by fire frequency and intensity, thereby affecting the hydrological, ecological, and economic aspects of grassland ecosystems (Bowman et al., 2009; Capitanio & Carcaillet, 2008; De Luis et al., 2006; Dubinin et al., 2011; Yan & Liu, 2021). Approximately 80% of global fires occur in grasslands (Leys et al., 2018), including wildfire and prescribed fire, and exhibiting variations in burn area, severity, frequency, and season. Understanding the impacts of fire on ecosystems requires consideration of specific fire patterns and environmental features. Environmental factors, such as climate and land use (Bradstock et al., 2010), alongside with plant functional type and spatial attributes (Alstad & Damschen, 2016), shape vegetation responses and future successional pathways (Keane et al., 2004; Li et al., 2013), which may diverge from previous vegetation type and fire cycles (De Luis et al., 2006; Kirkman et al., 2014; Maestre et al., 2009). Hence, post-fire ecosystem states might evolve during recovery, emphasizing the importance of long-term monitoring. Pre-fire conditions also influence plant communities and fires dynamics, yet most grassland fires studies have predominantly concentrated on post-fire factors and over short spatial spans.

Various pre-fire and during-fire conditions contribute to an increased likelihood of fire occurrence, development, and severity. Pre-fire abiotic factors include geographical location, terrain characteristics, weather, including wind strength and direction, precipitation and its annual distribution, high temperatures (Bradstock et al., 2010; Cansler & McKenzie, 2014; Ellis et al., 2022; Wang et al., 2023), and human presence and activity (Nagy et al., 2018). Biotic conditions involve the presence and abundance of herbivores, vegetation type and arrangement, and the accumulation of dry combustible material (grass thatch) (Dubinin et al., 2011; Ellis et al., 2022). Combustible material in grasslands is more porous than forest litter, allowing for higher oxygen flow and faster convective heat transfer (Smelyansky et al., 2015). This contributes to the rapid spread of grassland fires, such, in dry, windless conditions, a steppe fire can reach velocity of 80–85 km per day, corresponding to an average of 50–60 m/min, faster than tall grass litter fire in forest-grasslands (up to 6 m/min) (Burasov, 2006; Grishin et al., 2010; Na et al., 2018). The fire velocity is linearly related to wind velocity (Burasov, 2006; Cheney et al., 1993, 1998; Grishin et al., 2010; Khanmohammadi et al., 2022) and can reach much higher speed under strong winds. In the Askania-Nova Nature Reserve (Kherson region of Ukraine), fire has a velocity of about 180 m/min (Gavrilenko, 2005). Fire velocity, spread and intensity is also positively correlated with the surface slope (Asylbaev, 2013; Khanmohammadi et al., 2022; Filkov et al., 2011). Hence, on an incline, fire spreads more rapidly; and an elevation change from 0 to 20° leads to a 2-3 times acceleration in fire velocity. Therefore, pre-fire and post-fire conditions are both important in understanding the changes caused by fires (Ellsworth & Kauffman, 2017; Werner et al., 2022).

Wildfire impacts vary depending on the site and context, leading to diverse effects on vegetation communities, soil, post-fire grazing, and ecosystems functioning (Smelyansky et al., 2015; Stavi, 2019; Yan & Liu, 2021). Grassland fires typically cause fluctuations within the existing vegetation community, altering aspects such as projective cover, abundance, dominance, and vitality of specific species (Gordijn & O'Connor, 2021; Kandalova, 2007; Koerner & Collins, 2014; Li et al., 2013). Intense and frequent grassland fires may induce more profound changes, pyrogenic succession, especially with annual burning. Particularly, in semi-arid grasslands, such successions favor the spread of more drought-adapted communities due to rising soil temperatures and decreased humidity in the upper layers of the burned soil during the growing season (Ansley et al., 2010; Badmaeva et al., 2010; Kandalova, 2007; Prober et al., 2008), akin to successions caused by ungulate overgrazing (Dechinperlii et al., 2022; Huang et al., 2018). In ecotones, where grassland interfaces with desert, shrub or forest communities, fires can trigger radical community transformations. Woody vegetation has rapidly replaced grasslands in many arid and semiarid regions worldwide (Maestre et al., 2009; Sala & Maestre, 2014). Nonetheless, opposite observations exist. For example, in the Dauria steppe, Russia, six severe fires prompted the replacement of island pine forest with steppe community (Saraeva, 2012). In the Grassland–Shrubland Ecotone in New Mexico, USA, changes in soil carbon and nitrogen redistribution, soil water content due to fire can result in increased grass coverage compared to shrubs (Wang et al., 2019). The deep thermal burn of soil resulting from high severity, intensity and large area fires and the deeper frozen soil in such burnt areas can lead to frost and thermal damage to roots and seeds of some plant species (Saraeva, 2012; Schimmel & Granstrom, 1996). Not deeply rooted grasses, moss, and lichen cover may completely disappear, as can rare plant species growing in small patches (Heim et al., 2021; Roth, 2016). Therefore, the effects of wildfires on vegetation dynamics and arrangement may differ based on conditions both before and after the fire, as well as the location and features of ecosystems. These effects can result in further changes in soil water content, carbon and nitrogen redistribution, and forage quantity and quality.

The timing, seasonality and frequency of fires are also an important factors influencing its impacts, in addition to the prevailing pre-fire and post-fire abiotic and biotic conditions (Dusaeva & Kalmykova, 2021; Stavi, 2019). The effect of seasonality influences vegetation transitions, changes in projective cover and phytomass, and is dependent on the severity and frequency of fire, as well as plant composition (Ansley et al., 2010; Owens et al., 2002; Smelyansky et al., 2015). Winter or early spring fires, occurring before or at the beginning of growing season, are usually less destructive as the soil retains moisture. Summer fires may lead to decreased projective cover, total phytomass, average height, and plant community complexity. Experimental fires in meadow steppes of the Russian southwestern Transbaikalia show varying effects based on timing. A March fire increased community phytomass by 29–80%, an April fire had a less pronounced effect (2–53% increase), and a May fire caused 10–40% decrease in phytomass compared to the control (Imeskenova et al., 2011). Annual net primary production is also lower in summer burns in tallgrass prairie in eastern Nebraska, United States (Dickson et al., 2019). However, this phenomenon can differ. Repeating growing season fires in mesquite/mixed acacia shrublands in Texas, United States, do not change plant community composition (Owens et al., 2002), while in in the savanna-type forest-steppe in the Russian Dauria summer fire may maintain the savanna-type system and prevent intense fires in the following years (Daursky Reserve Annual Scientific Report, 2006 -2021).

The effects of burning frequency on vegetation responses are also complex, varying with seasonality, location, and external conditions. In tall grasslands in South Africa, burn season and frequency interaction does not affect forb species richness (Fynn et al., 2004), while it leads to differences in grass species composition in tallgrass prairie areas in eastern Nebraska, United States (Dickson et al., 2019) and mountain grassland, South Africa (Munyai et al., 2023). More frequent burns increase plant diversity in mesic grassland in South Africa (Kirkman et al., 2014) and in northern Illinois tallgrass prairies (Bowles et al., 2003; Bowles and Jones, 2013), but reduce it in mesic grassland in Kansas, United States (Kirkman et al., 2014) and in steppes of Dauria, South Russia (Tkachuk & Denisova, 2015). Generally, in grasslands burned annually, both species diversity and nitrogen availability tend to be lower (Blair, 1997; Collins & Calabrese, 2012; Gordijn & O'Connor, 2021; Li et al., 2013). Additionally, annual fires may prevent the spread of woody vegetation in mesic grasslands (Twidwell et al., 2013) or exhibit hysteresis (Collins et al., 2021), meaning that the return to the pre-disturbance state is not immediate or linear and the trajectory of vegetation change differs depending on fire features.

The productivity of grasslands post-fire is typically evaluated in terms of biomass (phytomass, aboveground annual net primary production), subject to the intricate interplay of pre- and post-fire conditions and the effects thereof. In the short term, fires may boost post-fire biomass due to reduced competition for water and light, as well as increased accessibility of plant-assimilated nitrogen, potentially favoring more productive species or less nutrient-efficient plants (Dusaeva & Kalmykova, 2021; Stavi, 2019; Yan & Liu, 2021). However, the long-term effects of wildfires are multifaceted. In extensively grazed grasslands in the United States, fire frequency does not impact on aboveground productivity over the long term (Dickson et al., 2019; Li et al., 2013). Annual burning may lead to vegetal nitrogen loss (Blair, 1997). In ungrazed grasslands, fires decrease net productivity by shifting resources towards root productivity over aboveground biomass (Johnson & Matchett, 2001). Moreover, continuous fires in steppes exacerbated by livestock grazing can further diminish productivity, despite adequate nitrogen levels and other conducive conditions (Huang et al., 2018). Alterations in habitat modifications, plant communities and composition resulting from fires can disrupt foraging conditions for animals, habitat availability and even influence wildlife disease dynamics, leading to further ecosystem shifts (Albery et al., 2021; Kelly & Brotons, 2017; Smith, 2000; Westlake et al., 2020). However, current research often focuses on small areas, overlooking the broader impact of fire and its interaction with scale, seasonality, and frequency, in combination with organic nitrogen content, on both biomass quantity and forage quality (e.g., crude protein, mineral content).

The interaction between climate warming and grassland fires is complex and dynamic. Grassland ecosystems may vary in their vulnerability to climate-driven changes in fire regimes, depending on i.e., soil moisture, plant community composition, topography, and human land use. As climate warming continues (Kuai et al., 2023; Zhang et al., 2020), there is a growing need for understanding the long-term effects of fire to predict future ecosystem changes.

My aim is to investigate the long-term dynamics of grassland plant community's productivity by applying remote sensing, unraveling the interplay of fire, climate, and landscape factors across a broad region spanning semi-desert to temperate grasslands and forest-steppe in China, Mongolia, and Russia. My objectives are, using over 30-years Landsat time-series data, to (1) study the impact of precipitation, wind, and vegetation condition in the pre-fire period on the frequency and extent of fires; and (2) analyze forage quantity and quality responses within and among plant community to fire depending on frequency, extent, pre and post fire conditions.

**Materials and Methods**

*Study area*

The study area encompasses a vast region spanning three countries: China, Mongolia, and Russia, which includes the Daurian Forest Steppe and Mongolian-Manchurian Grassland ecoregions (D. Olson & Dinerstein, 1998). These ecoregions belong to the temperate grasslands, savannas, and shrublands biome, ranging from semi-desert areas in the Gobi Desert to the south to temperate grasslands in the north within the Mongolian-Manchurian grassland, and as a transition zone between the grasslands in the south and the forests of Siberia to the north within the Daurian forest steppe.

The study area lies within the Palearctic realm (or Eastern Eurasia realm), characterized by a hypercontinental dry-winter subarctic climate in the north (Dwc, according to the Köppen–Geiger climate classification), a very cold semi-arid climate (BSk) in its southwestern parts, and a humid continental climate in the extreme east (Dwa or Dwb). This region experiences warm summers and severe, windy and extremely dry winters, with fluctuations in temperatures between day and night, and decreasing rainfall from north to south and east to west. Nearly all precipitation occurs during the warmer months, typically between May and September, with an average range from 200 to 450 mm. This results in a highly intense cycling of nutrients during the short summer period, leading to the development of primarily nutrient-poor, shallow soils (Carpenter, 2000; European Commission, 2015; Kirilyuk et al., 2013; Simonov et al., 2013).

The Daurian forest steppe has a variety of vegetation types, including meadow steppe, herbaceous steppe, and sandy saltmarsh steppe, dominated by sedges (genus *Carex*) and grasses (family *Poaceae*). Feather grass species like *Stipa krylovii* and *S. baicalensis*, *Leymus chinensis*, and *Artemisia frigida* are prevalent in these steppe communities, often accompanied by *Achnatherum* species containing halophytic elements such as *Limonium aureum*, *Saussurea amara*, and *Iris lactea*. Salt-dependent plants and reed beds fringe the shores of lakes in the area. Forested areas primarily consist of Asian black birch (*Betula dahurica*), Scots pine (*Pinus sylvestris subsp. krylovii*), and Siberian larch (*Larix sibirica*), with European aspen groves occurring in certain mountainous regions (Kirilyuk et al., 2013; Simonov et al., 2013).

In the Mongolian-Manchurian grassland, dominant species include feather grasses such as *Stipa baicalensis*, *S. capillata*, and *S. grandis,* along with *Festuca ovina*, *Aneurolepidium chinense, Filifolium sibiricum*, and *Cleistogenes squarrosa*. Regions closer to the Gobi Desert feature desert steppe characterized by lower productivity, with dominant species including drought-resistant grasses like *Stipa gobica, S. breviflora*, and *S. glareosa*, as well as forbs such as *Reaumuria soongolica, Hippolytia trifida*, and *Ajania fruticosa*, along with small, spiny shrubs well-adapted to arid conditions like *Caragana microphylla, Ephedra equisetina*, and *E. sinica*. Other plant communities in the area include *Kalidium gracile* in saline soil areas and salt marshes dominated by *Scirpus rufus, S. planifolium, Ranunculus cymbalaria,* and *Phragmites communis* (Carpenter, 2000; Oyunbileg et al., 2021).

Within the study area, both large and small fires have occurred, with some areas experiencing multiple instances of burning during the study period. The highest frequency of fires occurs in April and May, coinciding with the dry and windy spring season characterized by low temperatures and large daily temperature fluctuations. During this period, the majority of phytomass in the steppes consists of highly flammable dry grasses. In the study area more than half of all fires are caused by humans, including "controlled" burns (Kazato & Soyollham, 2022; Li et al., 2023; Smelyansky et al., 2015; Wang et al., 2023). In the south of Russian part of the study area, approximately 60% of steppe fires are attributed to negligent fire management practices; 30% of fires result from equipment malfunction on dirt roads, mainly due to worn-out tractors without spark arresters on their exhaust pipes. Additionally, 2-5% of fires are ignited along railway and from falling power lines, while approximately 1% are ignited by lightning (natural caused fires) (Daursky Reserve Annual Scientific Report, 2006-2021). Burning of wasteland (48.6%) and religious rituals (15.3%) comprise the primary causes of grassland fires in northern China (Wang et al., 2023).

During the Soviet period in Russia, the steppe zones were extensively used for grazing and crops cultivation, but the intensity is now at a moderate level. In China, the grazing intensity is also relatively moderate. However, in Mongolia, the intensity of sheep and livestock grazing has increased over the last two decades. Additionally, the study area faces exploitation for crop production, hay harvesting, mining activities, and relatively limited tourism (Fig. 3.1) (Kirilyuk et al., 2013; Simonov & Dahmer, 2008; Simonov & Kirilyuk, 2020; Tan et al., 2023).

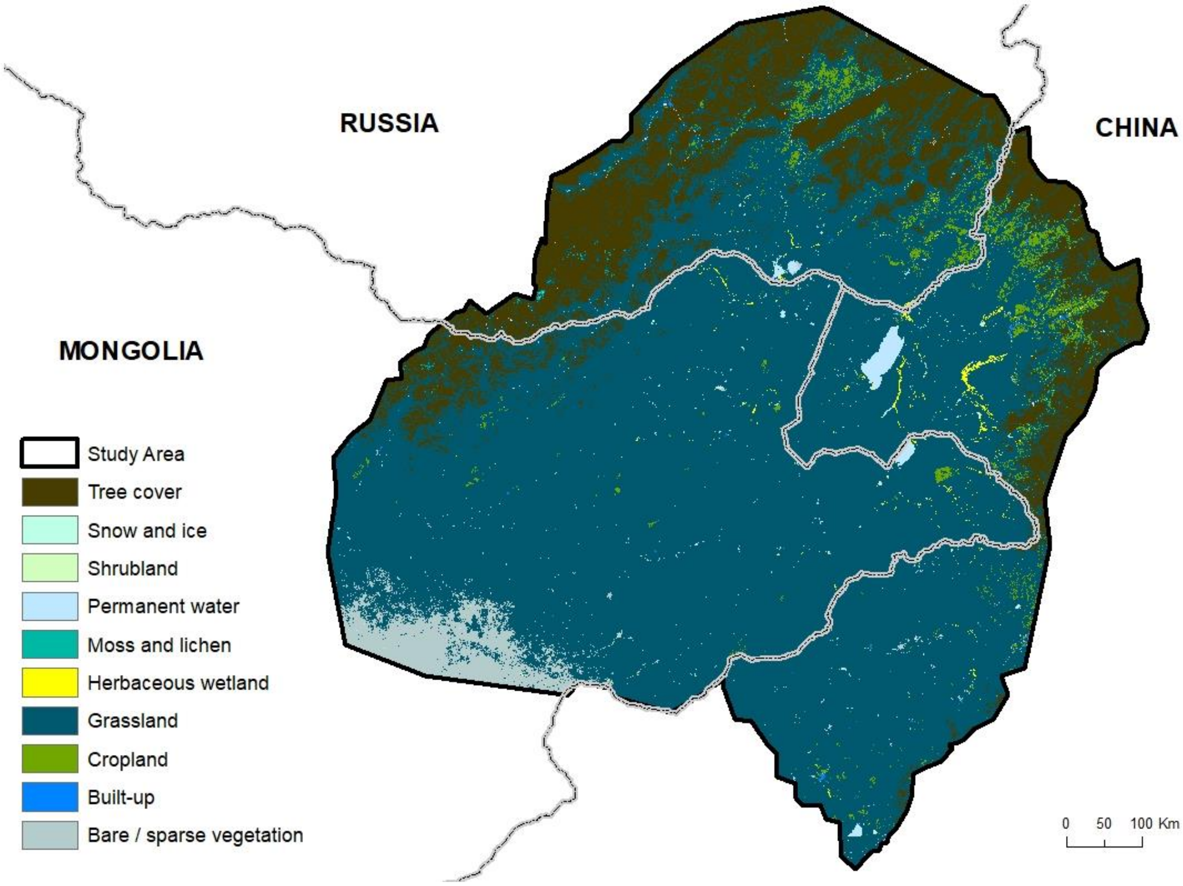



**Fig. 3.1. Study area land cover map. ESA WorldCover 10 m 2021 v200 (Zanaga et al., 2022)**

*Vegetation Classification and Forage Quality Data*

I will utilize plant communities and forage quality (crude protein, calcium (Ca), phosphorus (P), and potassium (K) concentration) annual maps acquired from the chapter titled "Mapping Winter and Summer Nutrition: A Novel Approach for Assessing Ungulate Forage Quality in Temperate Grasslands". I will use maps derived from 30-m Landsat time series (TM, ETM+, and OLI) for 1988-2023 (Level 2, Collection 2 data) from the US Geological Survey (USGS). If it is methodologically impossible to generate maps of forage quality using Landsat data, then I will create maps derived from Sentinel-2 imagery and narrow the time span to 11 years.

*Fires Mapping*

I will utilize fire maps generated by the fire mapping project of USGS, of which I am a part, leveraging historical data from Landsat and Sentinel-2 imagery. The methodology will involve implementing the gradient boosting regression model, following the approach outlined in Hawbaker et al.(Hawbaker et al., 2017, 2020).

*Modeling*

As my data consist of spatially autocorrelated time series satellite image data, I will use a Remote PARTS model (Ives et al., 2021). Conceptually, I will categorize the models into two research streams: one focusing on plant community responses and the other on fire occurrence.

Both directions will involve analyzing the dynamics of change, encompassing shifts in vegetation type (classes) and concentrations of crude protein and minerals, as well as the intervals between fires and the extent of fire-affected areas, respectively.

In examining the occurrence of fires, I will consider pre-fire and during-fire states of weather parameters and vegetation factors, such as biomass and plant communities. Specifically, the model of "the first fire" will incorporate weather conditions, initial vegetation type, and biomass. Subsequent models will include the years between the first and second fire (and subsequent fires) as response variables, with weather conditions, vegetation type, and biomass of each year after a fire (i.e., between fires) serving as independent variables.

For assessing forage quality response within and among plant community, I will develop a model that includes weather conditions, fire frequency and area, biomass, and vegetation type, using Remote PARTS time-series analysis. The same approach I will apply for analyzes of vegetation type productivity (biomass) and the extent of fire-affected areas.

My analyses will be conducted across the three countries to assess potential country-level effects. Models consider variables at a pixel size of 30 x 30 meters, including:

- Country level: China, Mongolia, and Russia.
- Weather: Standardized Precipitation Evapotranspiration Index and maximum wind velocity.
- Fire features: frequency and distance to the nearest fire border.
- Vegetation features: dominant species' plant communities, biomass, and forage quality (crude protein and mineral concentration).

**Expected results**

- I will analyze the temporal and spatial changes of forage quantity and quality among and within dominant species' community dynamics based on an annual fire map derived from Landsat imagery spanning over 30 years. This analysis will focus on areas burned at different frequencies and extents, as well as on pre- and post-fire weather conditions.
- I will produce maps providing the primary vegetation communities productivity within the study area, delineating pre-fire and post-fire succession stages.
- I will assess the impact of precipitation, wind, and vegetation conditions both before the fire and during fire on the frequency and extent of fires.
- I will investigate whether there is a country-level effect on the spatial and temporal changes of forage quantity and quality of dominant species' community and on the occurrence and extent of fires.

**Significance and contribution**

My research aims to fill knowledge gaps regarding the combined influence of weather, fire frequency, and extent on plant community dynamics and structure in the semi-arid and temperate grasslands of Asia. Particularly, my findings contribute to:

*Modeling Techniques Advancement*. The innovative utilization of advanced modeling techniques, such as Remote PARTS, to comprehend spatially autocorrelated changes in plant community responses to fire and weather, including long-term analyses, represents an important advancement in the field of spatial statistical analyses and modeling. Furthermore, the comparison of the obtained results with field experimental findings, conducted by specialists from the Daursky Biosphere Reserve, ensures the accuracy of detecting changes in plant communities under various fire disturbances.

*Addressing Forage Quality*. By analyzing temporal and spatial changes in forage quality and quantity, I will show how, and whether it may change among dominant species' communities and within them, depending on different fires and weather conditions.

*Addressing Climate Change*. By investigating the dynamics of grassland plant communities, my study provides how these ecosystems respond to fire events in the context of changing climate conditions.

*Management and Conservation Practices*. By studying the impacts of precipitation, wind, vegetation condition, and fire frequency, as well as country effect on plant communities and forage quality, my research provides information for developing strategies to mitigate fire risks and enhance ecosystem resilience in grassland regions. Additionally, understanding the responses of plant communities and forage quality to fire events is essential for promoting sustainable resource management practices in grassland ecosystems.

The research contributes to the conservation objectives of UNESCO World Natural Heritage Sites and aligns with the mission of UNESCO's Man and the Biosphere (MAB) programme. Particularly, the Daursky State Nature Biosphere Reserve and the Mongol-Daguur Strictly Protected Area are integral components of the World Heritage Site "Landscapes of Dauria," protecting one of the last remaining continuous grasslands on Earth (Scholtz & Twidwell, 2022). Additionally, the Chinese-Mongolian-Russian Dauria International Protected Area encompasses three protected areas that are part of the MAB programme, promoting innovative approaches to sustainable development, including fire management. Furthermore, I intend to share my findings with relevant authorities in China, Mongolia, and Russia, facilitating their integration into the management plans of the Dauria International Protected Area.

Overall, my study comprises an important analysis of the long-term changes of grassland plant community’s productivity in response to fire regimes, leveraging remote sensing technology to provide insights for addressing the challenges posed by climate change, anthropogenic pressure and fire disturbances in grassland ecosystems.

**Overall Significance**

Land-use changes, shifts in climate, pollution, habitat fragmentation, and infrastructure development play crucial roles in shaping ecosystems, biodiversity, and human well-being. Steppe biomes are particularly vulnerable to these pressures due to inadequate protection and conflicts between nature/land management and conservation objectives. Understanding the processes of land cover change is therefore essential to address evolving conditions and mitigate environmental damage, which often impacts local communities as well. It is imperative to focus on changes in forage quantity and quality, rural linear infrastructure such as dirt roads and fences, and the disturbance caused by fires. Understanding the root causes and varied impacts of these factors is essential for developing effective strategies in nature conservation and sustainable development. The maps and codes that I develop will be made freely available, and the adoption of new techniques to minimize labor input will facilitate widespread use. My proposed research will contribute to science from three perspectives.

*The main methodological contribution* is to develop an approach utilizing hyperspectral imagery and spectrometry techniques for mapping foliar nutritional traits for large areas and extended time spans. This represents an important advancement in the field, offering the opportunity to directly map forage quality. I will validate results, comparing hyperspectral images with lab spectrometry results, to ensure the accuracy of mapping and detecting changes in vegetation quality. I will map long-term changes in roads and fences, developing a novel approach for mapping rural fences using high-resolution data from reconnaissance satellites like Hexagon and current satellite imagery from Planet, along with AI-based models. I will also determine whether high-resolution multi-band Planet imagery can be combined with Hexagon imagery. Furthermore, I will utilize advanced modeling techniques, such as Remote PARTS, to comprehend spatially autocorrelated changes in plant community responses to fire and weather, including long-term analyses, representing an important advancement in the field of spatial statistical analyses and modeling. Lastly, comparing the obtained results with field experiments conducted by specialists from the Daursky Biosphere Reserve will ensure the accuracy of detecting changes in plant communities under various fire disturbances.

My research will *contribute several scientific insights* into the nutritional quality of grasslands, focusing on forage dynamics in homogeneous semi-dry grasslands across summer and winter, influenced by weather fluctuations and disturbances from fires. I will explore variations in nutrient concentrations within the same plant communities across winter and summer, and assess how these variations may occur among dominant species' communities and within them, depending on different fire events and weather conditions. Additionally, I will apply my findings to develop a species distribution model for the Mongolian gazelle, generating maps of its optimal and potential habitats during both summer and winter. This will offer novel insights into the species' habitat preferences and utilization patterns, as well as identify the limiting factors that impact the suitability of potential habitats for the Mongolian gazelle. These factors include climate conditions, environmental features, livestock presence, and road density. Moreover, I will investigate the effects of dirt roads on microrelief, soil erosion, and the formation of ravines, examining their ecological implications across various grassland landscapes, ranging from semi-desert to forest-steppe environments.

*Conservation Contributions*. I will enhance understanding of how remote sensing data can be applied to land management and conservation efforts to reduce biodiversity loss and natural resource degradation. By analyzing the long-term and vast area impacts of precipitation, wind, vegetation condition, and fire frequency, as well as the influence of different countries on plant communities and forage quality, my research offers insights for developing strategies to mitigate fire risks and enhance ecosystem resilience in grassland regions. Moreover, to refine seasonal biogeographical models, I will evaluate various models, focusing on summer and winter habitats concerning forage quality and quantity metrics. My findings will guide conservation efforts for Dzeren and contribute to the Russian national strategy for Mongolian gazelle conservation and the conservation action plan of the Chinese-Mongolian-Russian Dauria International Protected Area. Additionally, my research will address global concerns related to the expansion of linear infrastructure networks in areas with intensive agricultural use and abundant wildlife, such as grasslands in East Asia. The implications of my findings may extend to regions facing similar challenges, thus enriching our understanding of sustainable land development on a broader scale.

The last but not least, *my research has a practical contribution*. Thus, it contributes to the conservation objectives of UNESCO World Natural Heritage Sites and aligns with the mission of UNESCO's Man and the Biosphere (MAB) programme. Particularly, the Daursky State Nature Biosphere Reserve and the Mongol-Daguur Strictly Protected Area are integral components of the World Heritage Site "Landscapes of Dauria," protecting one of the last remaining continuous grasslands on Earth (Scholtz & Twidwell, 2022). Additionally, the Chinese-Mongolian-Russian Dauria International Protected Area encompasses three protected areas that are part of the MAB programme, promoting innovative approaches to sustainable development, including fire management. Furthermore, I will share my findings with relevant NGOs, such as the Wildlife Conservation Society (WCS), World Wildlife Fund (WWF), Wildlife Science and Conservation Center of Mongolia (WSCC), authorities in China, Mongolia, and Russia, facilitating their integration into the management plans, including of the Chinese-Mongolia-Russian Dauria International Protected Area.

**Proposed journals for publication:**

Chapter 1: Mapping Winter and Summer Nutrition: A Novel Approach for Assessing Ungulate Forage Quality in Temperate Grasslands - ***Journal of Applied Ecology / Ecological Applications / Biological Conservation.***

Chapter 2. Rural Infrastructure Dynamics: Mapping Changes in Unpaved Roads and Fences Over 50 Years in Daurian Grasslands – ***Remote Sensing of Environment / International Journal of Remote Sensing / Ecological Indicators.***

Chapter 3. Long-term Changes of Grassland Plant Community's Productivity: Unraveling the Interplay of Fire, Climate, and Landscape Factors Across China, Mongolia, and Russia – ***Landscape Ecology / Conservation Biology / Journal of Environmental Management.***

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