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On behalf of
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Germany 2025

GREEN IS NOT ALWAYS GOOD:

Vegetation And Rangeland Health In The Tuul River Watershed

Central-Northern Mongolia

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1. STATE-OF-THE-ART

Temperate grasslands, i.e. pampas, prairies and particularly steppes are among the most threatened biomes (Henwood, 2010). Mongolia still hosts one of the finest grasslands of the planet, and has extraordinary importance as well as responsibility for the conservation of steppe ecosystems globally (Batsaikhan et al., 2014; Wesche et al., 2016). Ever since Mongolia entered market economy, degradation has been a major concern, and Mongolia became an important testbed for global rangeland ecology and grazing studies. The 1990s witnessed a strong increase in livestock numbers. These were partly driven by beneficial weather conditions in the otherwise rather challenging climate of the Mongolian steppe, and herds collapsed repeatedly afterwards, e.g. in summer droughts and extremely harsh winters in 2001 – 2002. This development led to an intense controversy about the relative importance of environmental (weather) and biotic (livestock) controls (Fernández-Giménez, 1999; Sasaki et al., 2008; Addison et al., 2012). Livestock numbers have, however, strongly increased in the last two decades reaching all time high values from 2015 onwards, and this was also caused by economic interests uncoupled from climatic conditions (e.g. Engler et al., 2021). It has now become increasingly clear that the country's typical steppes, i.e. transition zones between the southern drylands and the moister northern meadow and forest steppes, are particularly vulnerable to degradation by livestock (Khishigbayar et al., 2015; Ahlborn et al., 2020). The extent of degradation differs between the major vegetation types but also between regions within similar vegetation types, as shown by a recent review (Munkhzul et al., 2021) and by various results from remote sensing studies (Eckert et al., 2015; Fernández-Giménez et al., 2017; Meng et al., 2021). In addition, the steppes of eastern Mongolia remain still relatively intact because of their remoteness (Batsaikhan et al., 2014; Hilbig & Narantuya, 2016; Ma et al., 2024).

Surveilling vegetation dynamics over extended time periods is important to effectively monitor land cover changes, particularly land degradation driven by land use and climate change. Remote sensing offers comprehensive tools for monitoring temporal and spatial changes in vegetation. This has been demonstrated by numerous studies across diverse ecosystems, linking e.g. aboveground biomass, cover, and species richness (Camathias et al., 2013; Gao et al., 2020; Mutanga et al., 2023). However, it remains an important question how well vegetation structural characteristics and plant assemblages can actually be predicted by this data (Feilhauer & Schmidtlein, 2011). The current monitoring of vegetation changes through remote sensing primarily relies on vegetation cover or biomass related indices driven by transforming data from multiple spectral bands (Xue & Su, 2017). Examples include the Ratio Vegetation Index (RVI), Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI) or Net Primary Productivity (NPP). However, degradation manifests itself in various ways, and monitoring methods based solely on biomass or cover have certain limitations (Lyu et al., 2020). Field studies on degradation did, however, concentrate on different facets of rangeland health, with authors describing an increase in grazing weeds / unpalatable species rather than changes in standard indicators like richness or total cover (Khishigbayar et al., 2015), while others concentrate on changes in soil conditions (Yang et al., 2014; Wang & Wesche, 2016). This highlights the need to analyze degradation from the perspective of species composition, forage quality and soil conditions based on ground-truth data acquired in the field.

The Tuul watershed is a key landscape in the country's most densely populated region including half of the capital Ulaanbaatar, and its degradation is becoming a major concern (WWF, 2019). Land degradation is potentially increasing in the central part of Mongolia, i.e., the surroundings of Ulaanbaatar and the adjacent regions of the Tuul watershed, primarily driven by factors such as growing human settlements, intensive grazing around nomadic camps, mining activities, and the demands of power plants, all of which heavily rely on local water and land resources. Numerous studies have focused on the hydro-chemical properties of surface and ground water (Dalai & Ishiga, 2013;

Tsujimura et al., 2013), on isotopic and heavy metal contamination in water and soil (Munkhuu et al., 2019; Soyol-Erdene et al., 2019; Narangarvuu et al., 2023), as well as on impacts of climate change on land cover and hydrological processes using satellite data (Sukhbaatar et al., 2017; Dorjsuren et al., 2021). However, a comprehensive field-based study on the evaluation of vegetation and its degradation has not yet been conducted. The older report "Tuul River Basin, Integrated Water Management" (2012) had suggested that land use intensity ranges from distinct overgrazing near the major settlements to relatively intact conditions in its upper reaches. More precise and recent information is, however, needed to support evidence-based management and policy development. Here, we present new data from a field study of vegetation conditions in the Tuul watershed, contributing to a better understanding of steppe community composition in Mongolia's core region. We provide thereby also background information for standard remote sensing approaches relying essentially on estimates of cover or productivity.

Specifically, we addressed the following goals (numbers) and respective hypotheses (letters):

Table 1. Goals and hypothesis

Goal 1. Surveying vegetation of rangelands in the Tuul watershed:	a)	Degradation is widespread in the typical steppes of the lower reaches of the Tuul, extending from settlements far into the wider landscape.
	b)	Degradation involves a strong change in species composition towards a high share of grazing-tolerant species, while changes in species richness are less pronounced and vegetation cover may be even unaffected.
Goal 2. Surveying pastures apart from direct surface water influence and comparison with less intensively or non-grazed (fenced) plots:	a)	Fenced sites exhibit much higher biomass and thus carrying capacity, but plant species numbers are not necessarily higher under exclusion of grazing.
Goal 3. Assessment of forage availability:	a)	Forage availability in dry steppes is lower than in meadow steppes.
Goal 4. Analysis of soil nutrients, forage quality, and their relationship:	a)	Forage quality and soil nutrient availability are low in the typical steppes, and deteriorate under intensive grazing
Goal 5. Comparison of vegetation and biomass development over the course of the summer season (2 surveys):	a)	Vegetation cover and biomass represent high variation during the growing season depending on precipitation, although species richness does not.
Goal 6. Comparison with data on similar studies conducted by Senckenberg Görlitz and its respective network, with a focus on rangeland changes:	a)	Shifts in rangeland health are apparent when recent samples from the Tuul river are compared with historical samples, or with recent samples from the more intact eastern Mongolian steppe.
Goal 7. Introducing students of the respective National University of Mongolia to techniques for vegetation sampling and assessing pasture quality.		

2. MATERIAL AND METHODS

2.1 Study area

The study area is located in the central part of Mongolia, covering five provinces, including the capital city, Ulaanbaatar (UB; Fig. 1). The Tuul river, one of Mongolia's largest water courses, originates in the Khan Khentii mountain range, flows westerly through UB and central Mongolia before merging with the Orkhon River northwards (Udvaltsetseg & Khulan, 2012).

The Tuul catchment can be divided into three parts differing by their extent of urbanization and landform changes caused by human activities (Tuyagerel & Orkhonselenge, 2018; Fig. 2).

The upper section of the Tuul River features largely intact habitats, with protection afforded by the Khan Khentii Special Protected Area and Gorkhi-Terelj National Park, which are part of the taiga belt (Fig. 2a). The middle section, extending from Ulaanbaatar towards central Mongolia (Fig. 2 b,c), comprises forest and steppe zones, characterized by significant human settlements and a high impact of livestock grazing. The lower section lies within the forest-steppe belt and is marked by extensive gold mining operations and (partly growing) rural communities (Fig. 2d).

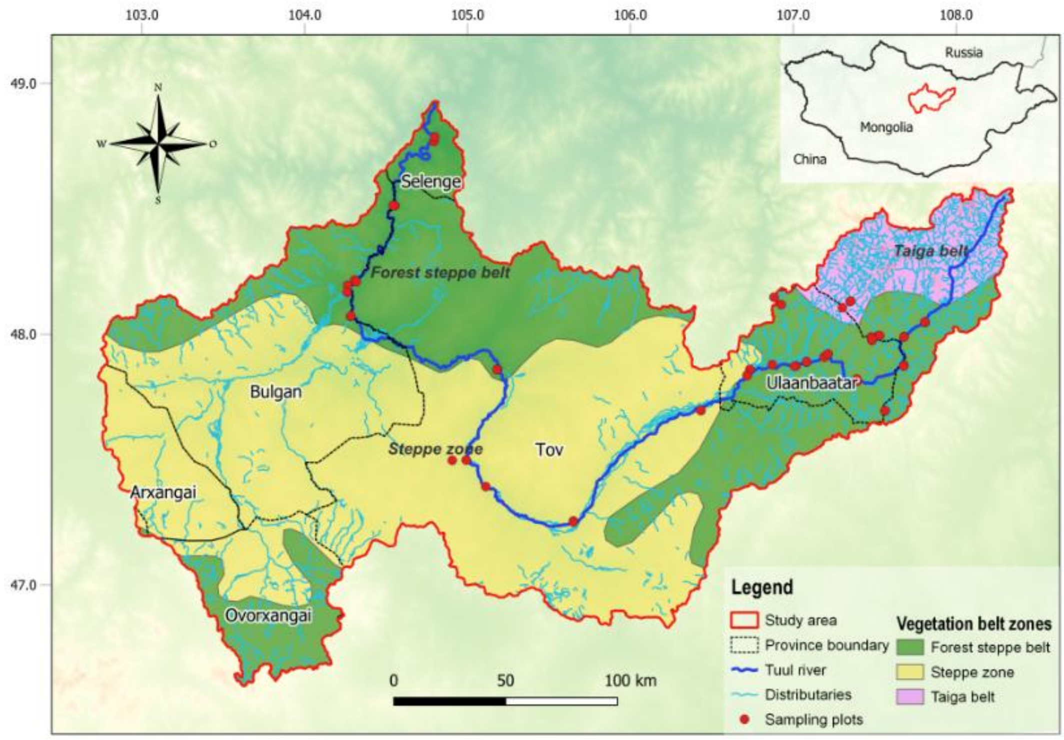

Figure 1. Study region with sampling locations within the Tuul river basin. The basin boundary and topography are based on a physiogeographic map

Source: The Institute of Geography and Geoecology of the Mongolian Academy of Science. Zonation of vegetation belts is according to Munkhzul et al. (2021).

Figure 2. Habitat types and associated land-use patterns of the Tuul watershed study area: a) upper, b and c) mid and d) lower Tuul region.

Source: Senckenberg Museum of Natural History Görlitz/ Oyundelger Khurelpurev

2.2 Ground data collection

To survey vegetation of watershed rangeland **(Goal 1)**, fieldwork was conducted from late June to early September 2024, covering 25 study sites along the Tuul River and three small tributaries (Selbe, Uliastai and Gachuurt rivers) in coordination with the hydrological team of the Institute of Geography and Geoecology (IGG) of Mongolia. Each site comprised a pair of vegetation plots: one in the floodplain and the other in the adjacent steppe. Additionally, four fenced sites of the IGG and one fenced site of the Mongolian University of Life Science were sampled to contrast grazed and ungrazed conditions **(Goal 2)**. Of those, ten sites were revisited, with surveys conducted in late June and late August to examine changes in vegetation conditions during summer **(Goal 5)**. In total, 83 vegetation plots were surveyed in the Tuul river basin (Appendix Table 1).

We recorded longitude, latitude and elevation for each plot in the field using a Garmin GPS.

At each plot, we demarcated one 10 m × 10 m vegetation plot, where we assessed plant community composition according to the Braun-Blanquet approach. We visually estimated i) percentage of cover of each plant species at a modified Londo scale (Londo, 1976), ii) cover of bare soil, stones and litter, and iii) cover of livestock droppings. We identified plant species directly in the field (Grubov, 2001), more critical specimens were collected and brought to herbaria of National University of Mongolia, Ulaanbaatar (UBU) and Herbarium Senckenbergianum Görlitz (GLM) for further identification and permanent curation. Taxonomy followed the most recent checklist (Baasanmunkh et al., 2022).

Furthermore, above-ground herbaceous biomass was harvested within a 1 m × 1 m quadrat aside to the vegetation plot by hand clipping to ground level for evaluating forage availability **(Goal 3)**. Biomass samples were oven-dried at 75°C for 48 h, then weighed in the laboratory. Analyses of forage quality, measuring crude protein, crude fat, and two different types of fiber content (i.e., acid detergent fiber 'ADF' and neutral detergent fiber 'NDF') were conducted at the School of Agriculture and Biotechnology, Mongolian University of Life Science (Goal 4). Digestible Dry matter (DDM) content indicating the portion of the dry matter in a biomass that is digested by animals at a specified level of feed intake, was estimated from the ADF content using the formular (Saha et al., 2010): %DDM = 88.9 – [0.779 × %ADF (on a dry matter basis)].

One mixed sample of top soil (0-5 cm depth), including fine roots and the humic layer was collected from each vegetation plot to analyze soil nutrient contents **(Goal 4)**. Mixed samples were air-dried and run through 2 mm sieve for further chemical analysis. Samples were transported to Germany and processed in the soil laboratory of Senckenberg Görlitz. Total concentrations of C and N were measured using a CN Analyzer (Vario Pyro Cube; Elementar, Langenselbold, DE). Content of inorganic C ($CaCO_3$) was determined with 10% HCl using a calcimeter with Scheibler's method (ON L 1084-99, 1999) to correctly derive soil organic carbon content. Plant available P was extracted following the Olsen P method (22 °C, 200 r/min for 30 min; Sims, 2000), then measured by ICP-OES (Varian 725-ES; Varian, Mulgrave, AU). Rest water content of air-dried soil was determined by drying a subsample 24 h at 105 °C, and rest water was used to correct concentrations of C, N and other nutrients.

2.3 Comparison with data on similar studies

There are no long-term monitoring plots in the project region that would allow for an assessment of decadal changes. We thus pursued three lines of evidence **(Goal 6)**:

A. Comparison with historical vegetation data, made available by Werner Hilbig (see Hilbig, 1990, 1995) as a reference for comparing temporal changes in plant species composition in central Mongolia, and in the cover of certain species, particularly those indicative of degradation.

B. Comparison with recent vegetation data from the Ba) MoreStep transect (see morestep.org) covering steppes from Mongolia's central to far eastern regions (see Jäschke et al., under review) and Bb) a transect from the TRAITS project covering steppes around Ulaanbaatar south to the Gobi Altay region south of Dalanzadgad (see Ahlborn et al., 2020, Oyundelger unpubl.)

C. Assessment of long-term trends in remote sensing data. For the assessment of long-term trends for a larger-scale patterns, we retrieved standard satellite imagery for a crude assessment of temporal trends in vegetation cover. We downloaded MODIS, Landsat 7 and 8 data as these provide the longest time series with comparable sensor technologies (we ignored NOAA AVHRR because of its coarse spatial resolution and older sensor technology). Data were extracted for the following periods: Landsat 7 data is available from 1999 to 2023, Landsat 8 data from 2013 to 2024, and MODIS from 2001 to 2024. We were not interested in absolute values but in relative temporal trends. For Landsat, all clear images (i.e., removing cloud pixels) from June 15 to August 15 of each year were used to calculate the maximum EVI & NDVI values. For MODIS, where there are much more images per time period available, mean values were calculated for each period of June 15 to August 15. We found that values correlated highly among platforms ($r < 0.78$) and thus presented only the longest continuous record, i.e., the MODIS data.

Students from the National University of Mongolia´s Biology Department participated in the some of the field trips to learn techniques to assess pasture quality **(Goal 7)**.

2.4 Data analyses

Carrying capacity was calculated based on directory of the NSO (2019), using Mongolian Sheep Units (MSU; 1 horse – 7 MSU, 1 cattle – 6 MSU, 1 camel – 5 MSU, 1 goat = 0.9 MSU and 1 sheep – 1 MSU), considering grazing days (167 days) and the daily forage consumption (1.6 kg per MSU) for the summer and autumn seasons in the mountain forest steppe zone.

Livestock data for the central region of Mongolia, where our study area is located, was obtained from the National Statistical Office of Mongolia (NSO, 2025). Numbers of different types of livestock were translated to sheep units (MSU) in accordance with the above mentioned directory (NSO, 2019). Furthermore, we examined correlations between NDVI value (MODIS) and livestock number (in MSU) between 2001 and 2024, i.e., the longest time period for which MODIS data is available.

For the comparison with recent studies conducted by Senckenberg Görlitz, we combined all (available) vegetation data in a large table. After checking for duplicates, we removed rare species, which are typically single specimens that could not be reliably identified due to their developmental stage. This resulted in a large table of 451 samples and 391 species, a subset of this table comprising data from typical steppes still comprised 154 samples. We used multivariate DCA ordination to plot patterns in overall species similarity (detrending by 26 segments, rare species down-weighted, species cover values log transformed log(x+1). Differences between datasets were tested for significance by permutation-based MANOVA (Bray-Curtis similarity metric).

We present mainly summary tables and raw data graphs. Statistical analyses and plotting were done in the R environment (R Core Team, 2024), correlations were estimated with the package *Hmisc* (Harrell Jr & Harrell Jr, 2019), multivariate analyses were conducted with *vegan* (Oksanen et al., 2007), and graphs were made with tools from *tidyverse*, namely *ggplot2, gridExtra, cowplot and ggpubr* (Wickham et al., 2019; Kassambara, 2023).

3. RESULTS

Goal 1 & 2: Surveying vegetation of riparian sites and pastures outside of direct surface water influence

In total, we encountered over 400 species of vascular plants, and collected ca. 200 specimens from the study region which were deposited at the herbaria GLM and UBU. In line with available maps (Fig. 1), we observed four distinct vegetation types during our survey: meadow steppe, dry steppe, forest steppe (i.e. forest, forest edge) and floodplain. We included only those few forest islands and forest edge sites that were located within fenced areas of the IGG, since our focus was on grassland vegetation. Therefore, analyses focused primarily on herbaceous vegetation types, in which the highest species richness (SR), vegetation cover (VC) and above-ground biomass (AGB) were found in meadow steppes, while dry steppes showed lowest values of these indicators, and floodplains were intermediate (Fig. 3). Overall, vegetation indices showed that there were no significant differences in terms of species richness (Fig. 3a) and above-ground biomass (Fig. 3c) between dry steppes and floodplains, although vegetation cover differed substantially (Fig. 3b). This pattern implies that herders residing in dry steppes of the central and lower Tuul region certainly prefer floodplains as pasture. Riparian habitats neighboring with the mesic steppes (upper Tuul) had significantly better vegetation condition than dry steppes.

Using only data from herbaceous vegetation types, simple correlation analysis confirmed that species richness was negatively associated with cover of bare soil and dung used as a proxy for livestock impact (Fig. 4 a & b). We also selected the two well-known grazing-indicator species *Artemisia adamsii* and *Carex duriuscula*, which are both perennials of poor forage quality. Species richness was negatively correlated with cover of both species (Fig. 4 c & d).

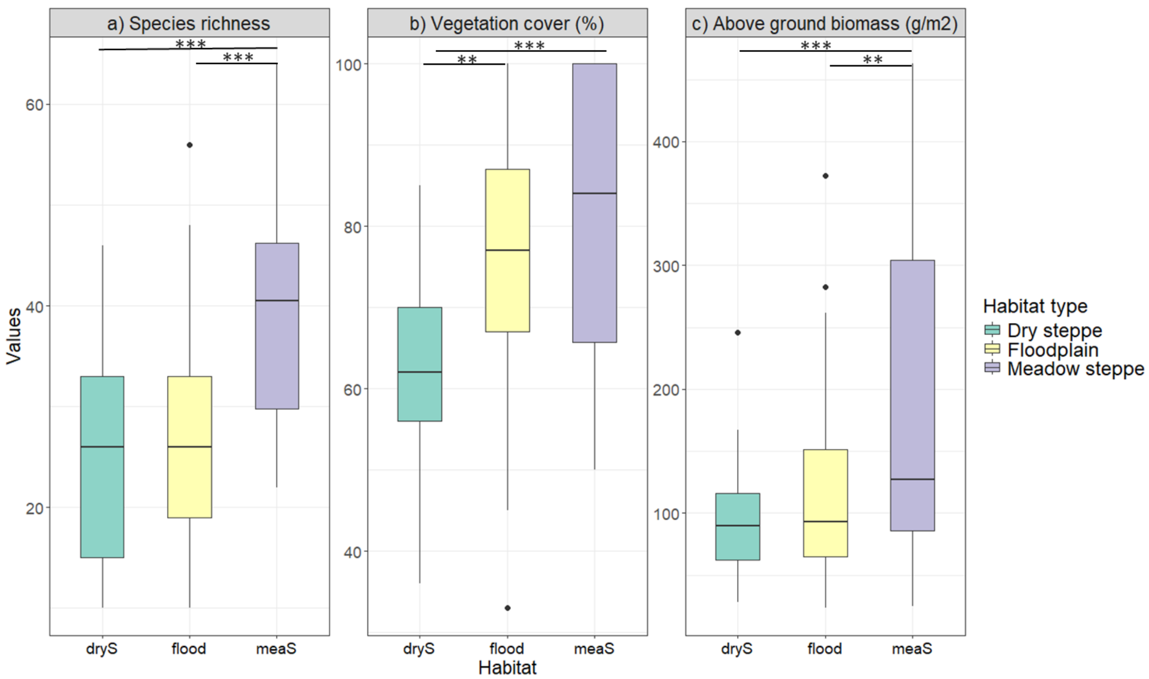

Figure 3. Summary of the vegetation indices: species richness, vegetation cover and above-ground herbaceous biomass across different habitat types in the Tuul river basin (n = 78)

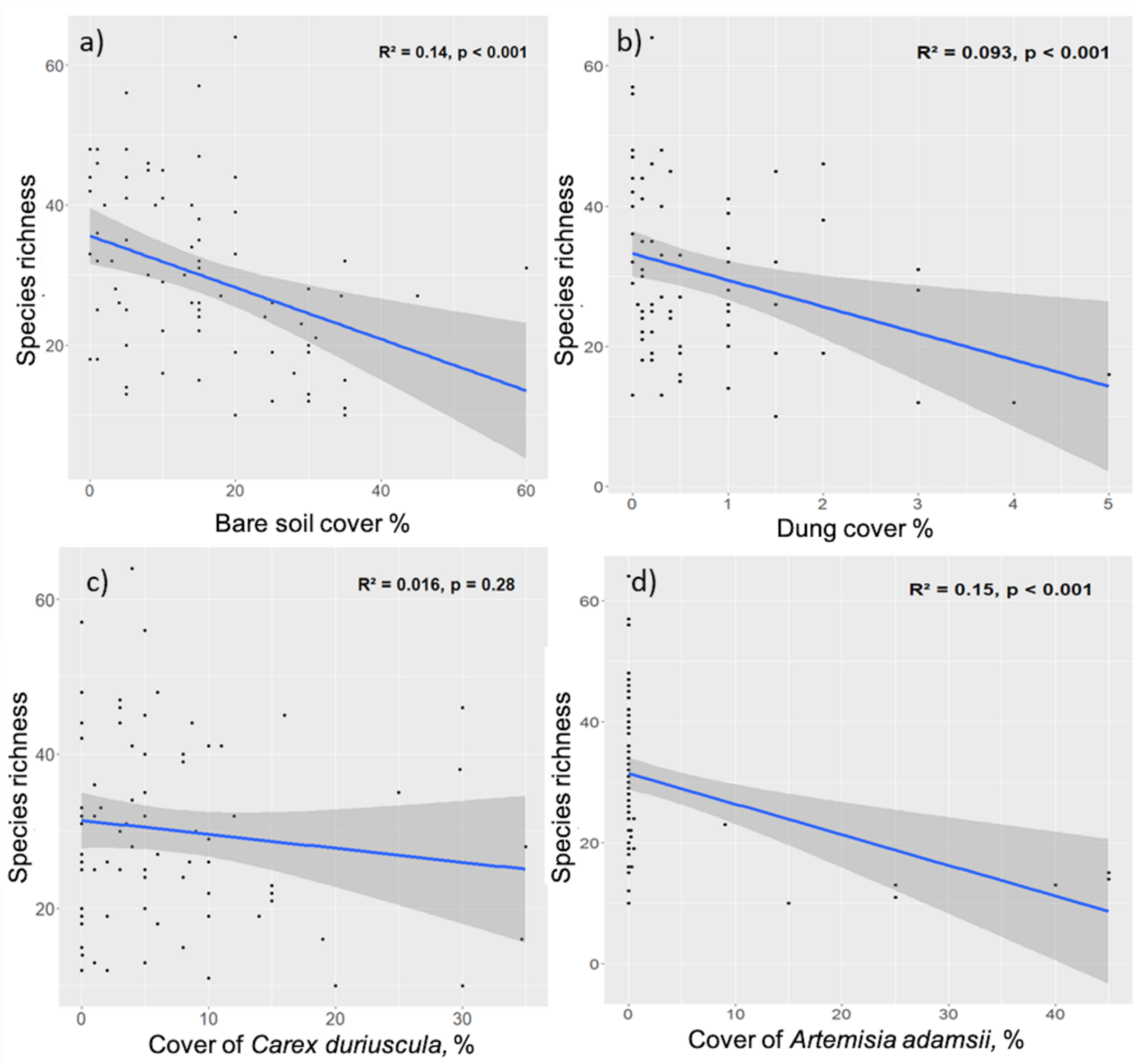

Figure 4. Correlation between species richness and a) bare soil cover, b) dung cover, c) cover of Carex duriuscula (grazing weed) and d) cover of Artemisia adamsii.

Goal 3: Assessment of forage availability and carrying capacity

Sampling of areas within IGG fences allowed us to assess effects of grazing on species composition and on carrying capacity in sheep units / ha, based on biomass data (Fig. 5). In line with expectations, under fencing forage availability of meadow steppes was almost thrice as high compared to dry steppes. The differences between the fence interior and the neighboring unfenced control site were smaller in absolute values but still considerable, especially in dry steppes. There, fencing resulted in a doubling of forage availability.

There were no discernible differences in species richness ($t = -0.5$, $df = 11.8$, p-value = 0.61) and vegetation cover ($t = 0.5$, $df = 11.9$. p-value = 0.58) between fenced and unfenced areas, and thus higher biomass under grazing exclusion (i.e., carrying capacity) was not associated with higher biodiversity. However, this should be interpreted with caution, as our sampling size was limited due to availability of only a few fenced plots.

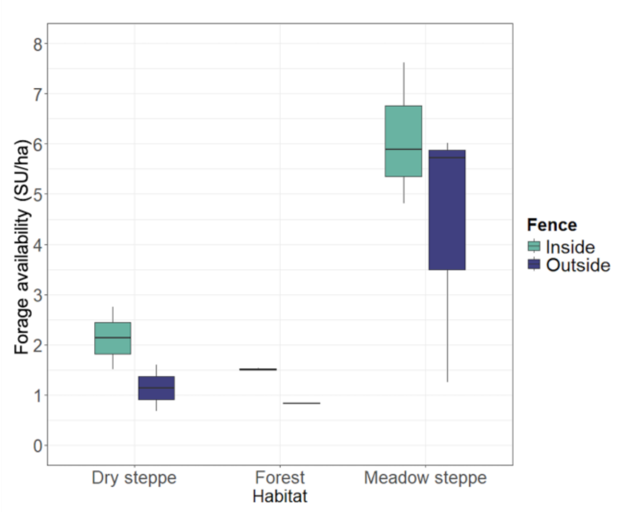

Figure 5. Estimated carrying capacity based on four fenced sites of the IGG (with seasonal repetitions) in the forest, dry and meadow steppes, calculated from harvested biomass (n = 14).

Goal 4: Analysis of soil nutrient, forage quality and their relationship

Soil nutrient analysis revealed variation in nutrient conditions across habitat types in the Tuul River Basin (Table 1). As expected, nutrient levels were generally lower in dry steppe areas compared to meadow steppes and floodplains, although these differences were not always statistically significant (Fig. 6). The soil pH ranged from 7.0 to 7.5, indicating slightly alkaline soil conditions with no significant salinity stress (EC = 0.7 dS/m). Soil nutrient indicators, namely nitrogen, organic carbon, and plant-available phosphorus reflected moderate to high levels of fertility (compared to own study in typical steppes of central and eastern Mongolia), indicating favorable conditions for plant growth and forage quality. Particularly, in herbaceous vegetation, the average nitrogen (N = 0.5%) and phosphor (P = 33 mg/kg; Table 1) content suggests relatively fertile soils, supported by a moderate level of organic matter as shown in the organic carbon content (C = 5.2%) (Thiagalingan, 2000; Agriculture Victoria Connect, 2024). However, high standard deviations (SD) in nutrient contents indicate variability across sites, which are probably due to differences in geological substrates, climate and land use types in the basin. Concentration of livestock, their droppings and urine serve as primary source for distributing phosphorus, nitrogen and carbon into the soil, whereas increased human population contributes to higher soil nutrient levels through wastewater, detergents, and improper waste disposal, causing phosphorus and nitrogen accumulation in the soil. Over time, overgrazing resulting in sparse vegetation cover and insufficient nutrient cycling, in the soil may pose a risk of reducing soil fertility. However, compared to the general soil nutrient deficiencies observed across Mongolia (Ronnenberg & Wesche, 2011), the soil characteristics in the Tuul River Basin are relatively healthy and fertile.

Table 2. Soil chemical characteristic of various herbaceous habitat types in the Tuul River Basin

Habitat	N	pH	SD	EC, dS/m	SD	N, %	SD	C, %	SD	C/N	SD	P, mg/kg	SD
Dry steppe	25	7.2	0.4	0.6	0.1	0.2	0.1	2.2	1.0	9.8	1.8	29.9	21.4
Meadow steppe	20	7.5	0.6	0.9	0.6	0.5	0.3	5.6	4.1	13.0	2.9	29.9	17.7
Floodplain	33	7.0	0.4	0.6	0.1	0.7	0.5	7.6	7.2	11.6	2.0	39.5	37.5
Mean		7.3	0.5	0.7	0.3	0.5	0.3	5.2	4.1	11.5	2.2	33.1	25.5

N – Sample number, SD – standard deviation, EC – soil electric conductivity, N – total nitrogen, C – organic carbon, C/N – carbon-to-nitrogen ratio and P – plant available nitrogen.

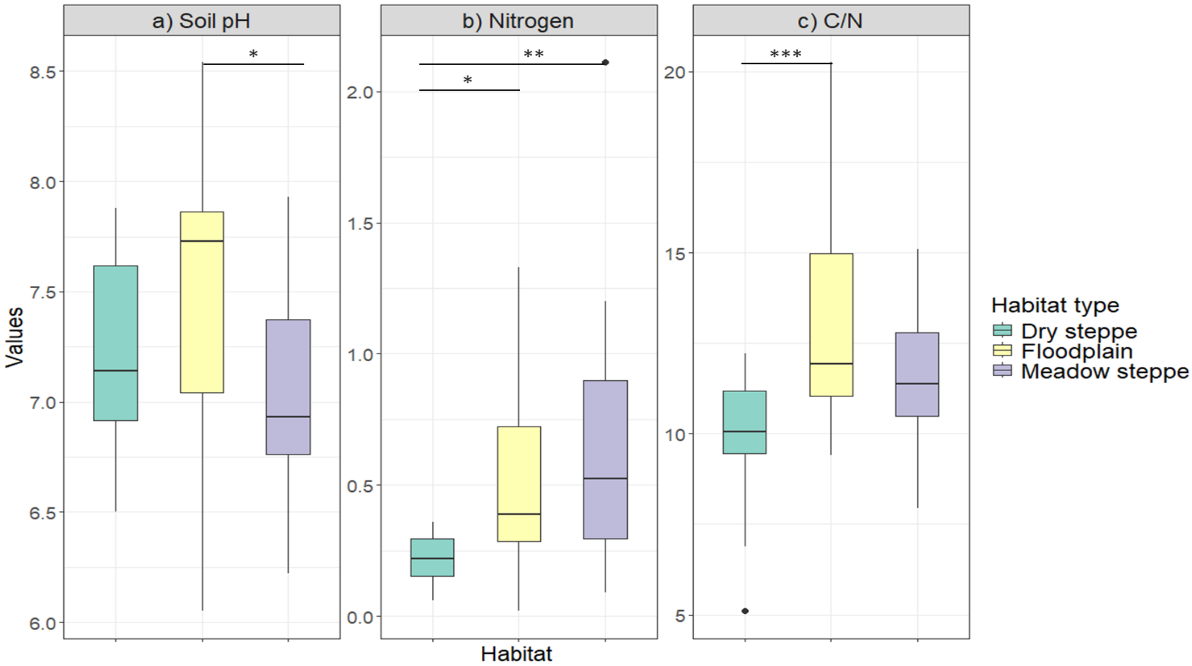

Figure 6. Summary of soil chemical properties: soil pH, total nitrogen (%) and carbon-to-nitrogen ration across different habitat types in the Tuul river basin (n = 78).

Healthy, fertile soils generally produce higher-quality forage, which is richer in proteins, is more digestible. Additionally, plants' stage of maturity (e.g., as plant matures from vegetative to reproductive stage, protein decreases and fiber increases) and species composition (e.g., legumes have higher quality than grasses) at harvest impact significantly on forage quality level (Rocateli & Zhang, 2017). Our analysis of forage quality from samples harvested during the peak growing season revealed that the pastures in the Tuul River Basin demonstrating a modest level of nutritional content. The average crude protein content of pasture vegetation was approximately 12%, and the crude fat content was about 3% (Table 2), indicating moderate-quality forage adequate for sustaining normal metabolic functions in livestock, in accordance with the findings of Hancock et al., (2014) that analyzed over 16,000 forage samples. However, elevated levels of acid detergent fiber (ADF > 40%) and neutral detergent fiber (NDF > 60%) indicated a high fiber content, resulting in lower digestibility for grazers (i.e., higher the fiber content, lower the absorption of nutrients in gastrointestinal tract of animals). Despite the moderate nutritional level, only about 50% of the total pasture area showed vegetation with digestible dry matter (DDM; the portion of the forage that is digested). This underlines that overall forage quality remained relatively low due to limited digestibility. Furthermore, we found no significant differences in the nutritional quality of herbaceous vegetation among different habitat types.

Table 3. Forage quality indicators of various habitat types in the Tuul River Basin

Habitat	N	Crude protein, %	SD	Crude fat, %	SD	NDF, %	SD	ADF, %	SD	DDM, %	SD
Dry steppe	25	11.7	1.0	3.0	0.6	69.6	5.9	46.7	4.8	52.5	3.8
Meadow steppe	20	11.9	1.9	3.0	0.6	71.4	5.5	48.2	5.3	51.3	4.1
Floodplain	33	12.7	1.8	2.7	0.5	68.0	5.6	47.1	5.9	52.2	4.6
Mean		12.1	1.6	2.9	0.6	69.7	5.7	47.3	5.3	52.0	4.1

N – Sample number, SD – standard deviation, NDF – neutral detergent fiber, ADF – acid detergent fiber and DDM – digestible dry matter content.

Soil nutrients have a positive impact on plant yield, species diversity, and cover and thus playing a crucial role in determining vegetation quality. Among these, soil nitrogen is one of the essential nutrients necessary for plant growth and development; therefore, we selected soil nitrogen as a representative indicator to study the relationship between soil nutrients and vegetation indices. Figure 7 shows that higher nitrogen content in the soil positively affects the overall vegetation cover, plant species richness and biomass. Interestingly, negative correlation between soil nitrogen (soilN) and biomass nitrogen (bioN) was observed, which is perhaps due to special environmental conditions influencing the efficiency of nitrogen uptake. In the water-limited conditions, like in dry steppes, plant's uptake of nitrogen can be restricted by limited soil moisture.

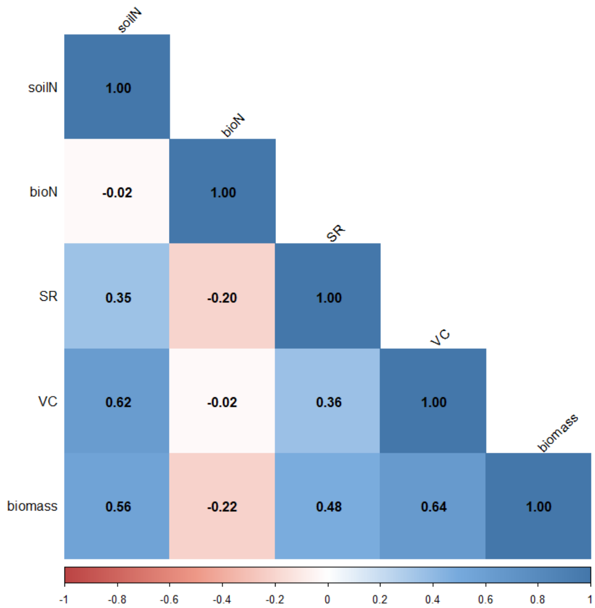

Figure 7. Correlation among nitrogen contents of soil (soilN) and forage (bioN) with vegetation indices: SR – species richness, VC – vegetation cover and biomass – biomass amount.

Goal 5: Comparison of vegetation and biomass development over the course of the summer season

We assessed short-term temporal stability of patterns by comparing repeated samples from June and August 2025 for ten sites (Fig. 8). Only biomass increased from June to August, while species richness and vegetation cover remained unchanged. The increase in biomass in August is most likely due to increased precipitation and thus moisture accumulation from June to August. In consequence, we considered all sites including those sampled only once for further analysis.

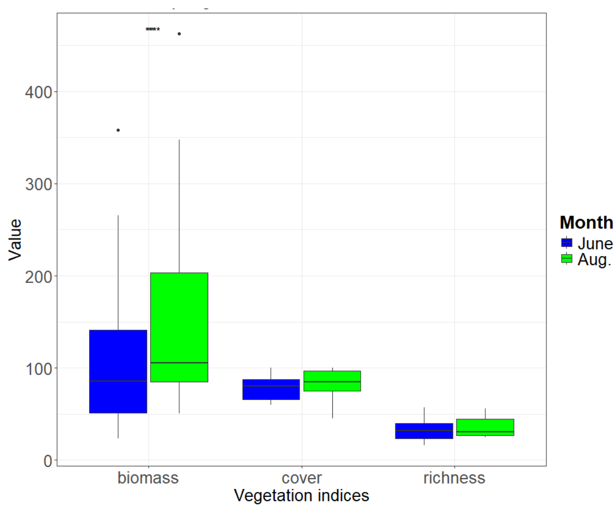

Figure 8. Changes of vegetation indices between different sampling times (June - August).

Goal 6: Rangeland changes over time: comparing data with similar studies

There were no long-term permanent plots available, and thus we compared our data against a set of vegetation samples collected by W. Hilbig across typical steppes of Mongolia in the 1980s. Focusing on the two main grazing indicators *Carex duriuscula* and *Artemisia adamsii* suggested strong changes (Fig. 9). Werner Hilbig had already noted that *C. duriuscula* benefits from heavy grazing, but mean cover values of that species were still much lower four decades ago. Changes over time were even more pronounced for *A. adamsii*, which was rare in the historical data set and was not even mentioned by W. Hilbig as grazing indicator.

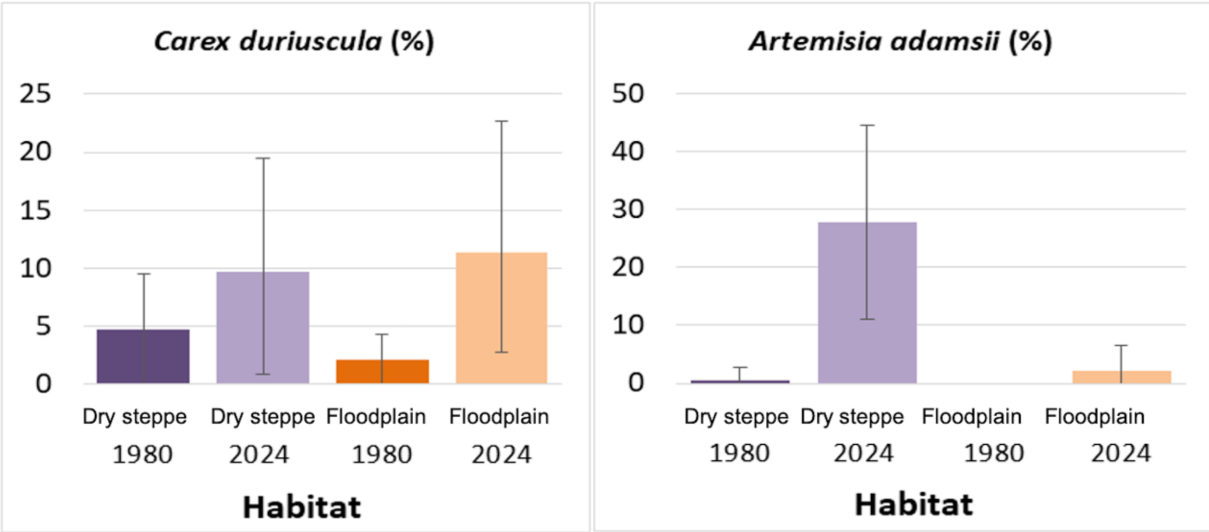

Figure 9. Comparison of mean cover of a) Carex duriuscula und b) Artemisia adamsii in historical vegetation samples from Mongolia's typical dry steppes collected in the 1980s (Hilbig, 1990, 1995; dark columns), and today (light columns). Data were split by main steppe types ("steppe" – dry steppes; "meadow" – meadow steppe).

When comparing data collected from the Tuul watershed with our recent studies, multivariate analyses revealed clear differences between the three datasets. Standard DCA-ordination (Fig. 10a) showed that vegetation samples from the MoreStep transect are largely different from the Tuul survey, supporting the notion that steppes in eastern Mongolia are different and more intact than those of the Tuul watershed. Data from the TRAITS survey were partly similar, but these were partly taken around UB and reflect the current conditions. The pattern becomes even more clear, if only data from steppe habitats for the three regions are analysed (Fig. 10b). Here, rather intact steppes from the MoreStep dataset are different from both the Tuul survey and the TRAITS survey. Samples of the latter two are all collected in the surrounding of Ulaanbaatar, showing the different steppe conditions there.

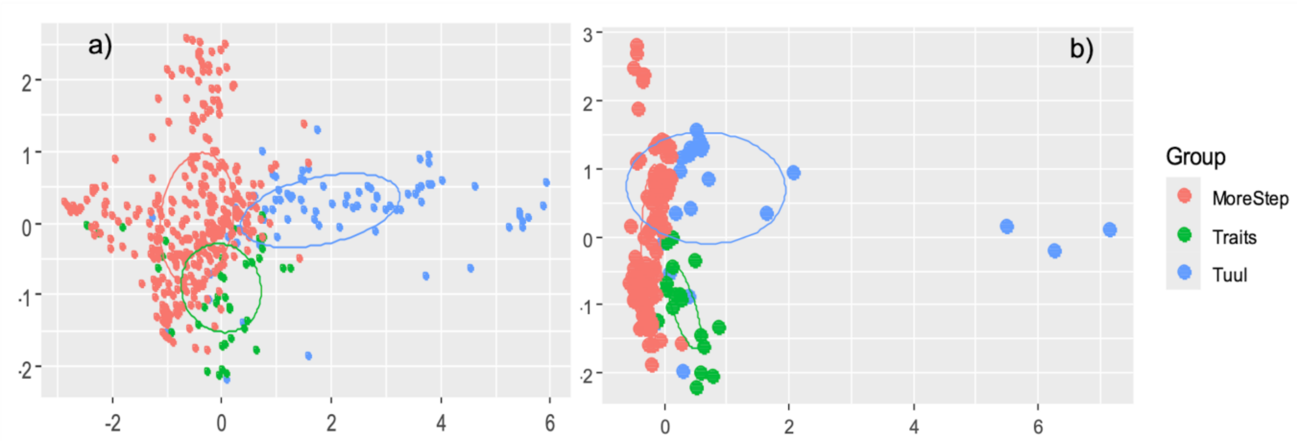

Figure 10. a) DCA ordination of the three datasets Tuul, Morestep and TRAITS (eigenvalue / length of gradient axis 1 0.71/8.8; axis 2 0.53/4.7). b) Same as a, but only for plots from typical steppes (eigenvalue / length of gradient axis 1 0.69/7.7; axis 2 0.61/5.0).

Differences between datasets were significant for the full dataset (p<0.002, permutation n = 999), and also for the subset on typical steppes only (p<0.002, permutation n = 999). Mean cover of grazing indicator species (see comparison with historical data above) points in the same direction. For a meaningful comparison, we assessed the typical steppe data only. Cover values of grazing indicators *Carex duriuscula* and *Artemisia adamsii* tended to be higher in both TRAITS and Tuul data compared to MoreStep data, while the grazing indicator *Chenopodium acuminatum* was overall less abundant and more or less equally present throughout (Table 3). In contrast, the high-quality forage grass *Stipa krylovii* showed lower mean cover values in the Tuul region than in both TRAITS and MoreStep sets.

Remote sensing data provide information for some decades, and although they do not capture species composition, they allow for inferences only on cover and productivity. We approximated changes in vegetation cover by plotting MODIS NDVI values over time (Fig. 10). There was considerable seasonal but also year-to-year variability, reflecting intra- and inter-annual variability in rainfall patterns, which is typical for dry continental regions. We did not observe any clear trend of vegetation cover change over time, although there was a tendency for median values to increase over 20-year period.

Table 4. Mean cover and standard deviation of the three key grazing and disturbance indicator species for the three datasets, and the same for the forage grass Stipa krylovii.

Species	Tuul	Traits	MoreStep
Carex duriuscula	6.9±5.0	7.9 ±10.3	5.3±7.7
Artemisia adamsii	6.0±13.3	12.0±13.3	3.1±5.7
Chenopodium acuminatum	0.2±0.6	0.3±0.5	0.4±1.6
Stipa krylovii	0.4±0.8	4.9±8.5	6.8±7.7

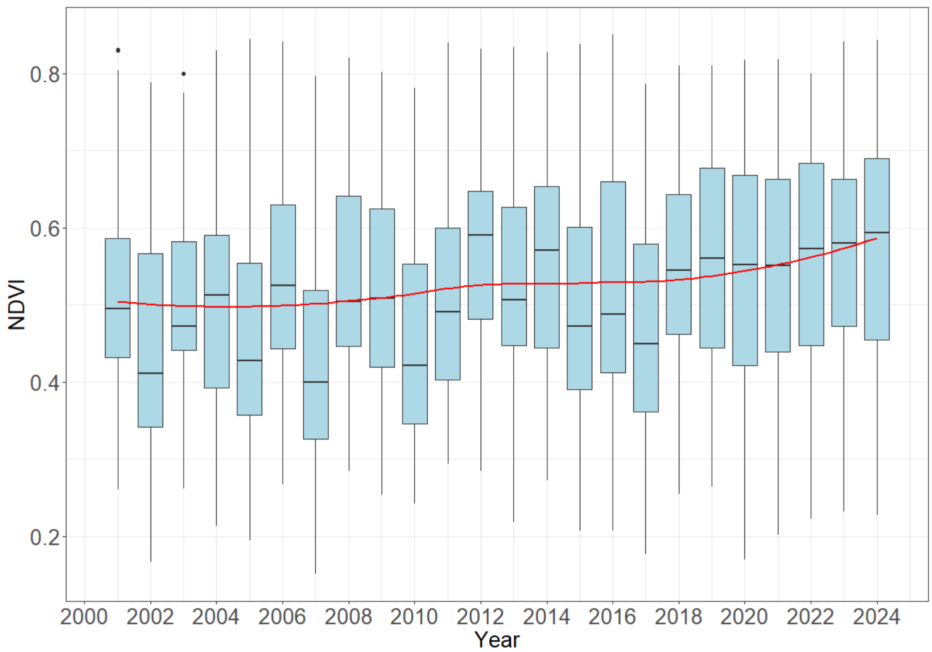

Figure 11. MODIS NDVI values between 2000 and 2024. The red line indicates a Loess local regression.

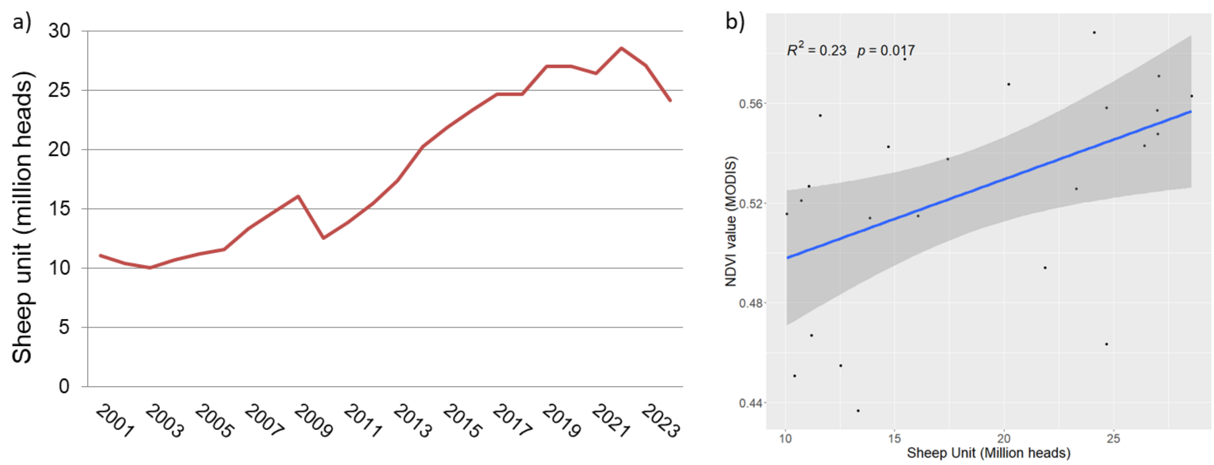

Figure 12. A) Change in livestock numbers (in sheep unit) in central region of Mongolia (NSO, 2025) and b) relationship between livestock number and NDVI between 2001 and 2024, the longest time period for which MODIS data was available.

The number of livestock (in sheep units) has increased almost three-fold in the last 20 years in central Mongolia (Fig. 12a), which undoubtedly has an impact on the vegetation in this region. According to a simple correlation test, mean NDVI (MODIS) and the average number of livestock were moderately correlated between 2001 and 2024 (Fig. 12b). This aligns with the tendency of increased NDVI over time, and does not necessarily mean that a large number of livestock is beneficial for vegetation cover. Potentially, cover of grazing-tolerant species with high greenness (e.g., tuft-growing plants with bundles of leaves) may have increased, which corresponds to Fig. 7 and the tremendous increase of *A. adamsii*. Conversely, animal numbers may have benefited from higher cover caused by external drivers, e.g. precipitation. Climate change effects in steppes are, however, debated and discussion is beyond the scope of this report.

Goal 7: Introducing students of the respective Mongolian University and staff of the Tuul River Basin Administration to techniques of vegetation sampling and pasture quality assessment

Field trips were conducted in multiple phases throughout the summer season, with varying group composition depending on resource availability and scheduling constraints. Some segments of the fieldwork were carried out in collaboration with students from the National University of Mongolia (Fig. 13a) and a GIZ advisor (Fig. 13b) across different habitats. Their assistance was instrumental in vegetation and biomass sampling. Additionally, students received training in species identification to assess pasture quality.

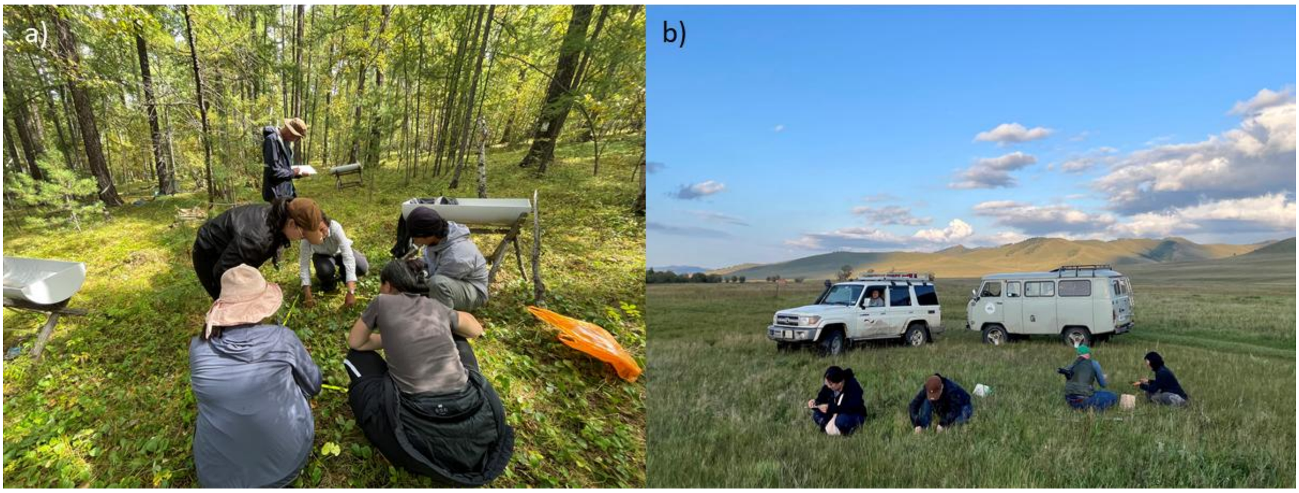

Figure 13. a) Capacity building through training students and b) GIZ advisor in vegetation sampling methods and species identification.

Source: Senckenberg Museum of Natural History Görlitz/ Oyundelger Khurelpurev

KEY RESULTS

- The vegetation in the lower reaches of the Tuul River also exhibited severe degradation, comparable to the areas near Ulaanbaatar. Vegetation indices commonly associated with degradation varied across habitat types, with dry steppe showing the lowest diversity and weakest vegetation production.
- The increasing abundance of degradation indicator plants caused by anthropogenic disturbance points to lasting degradation in plant species composition of pastures.
- Soil nutrient contents in the river basin was moderate to high, which may be partially influenced by the concentration of human settlements and livestock, even though the overall soil condition remains relatively healthy.
- Forage nutrient contents still are sufficient to support normal metabolic functions in livestock compared to summary statistic (Hancock et al., 2014), yet a relatively high fraction of non-digestible matter (i.e., elevated portion of fiber contents) in the vegetation results in an overall low nutritional value.
- Grazing exclusion did not result in higher biodiversity, i.e., plant species richness, indicating that permanent fencing is not the ideal approach for managing those pastures. On the other hand, an intermediate level of both human and natural disturbances maximizes the species diversity via fostering the coexistence of colonized species and dominant competitors (Yan et al., 2013; Yuan et al., 2016).
- The spatial and temporal variability in vegetation production and cover of Mongolia is largely positively influenced by the amount and variability of precipitation as demonstrated by numerous of studies (von Wehrden & Wesche, 2007; Vandandorj et al., 2015; Ahlborn et al., 2021), yet we detected no effects on species richness, possibly due to the short period of time covered by our field work (i.e., course of one summer season).
- Steppe degradation has significantly impacted the vegetation by altering the dominance of certain species. Some species, in particular, *Artemisia adamsii* and *Carex duriuscula* have spread rapidly, and degradation is leading to an expansion of their distribution.
- The remote sensing-based cover index (NDVI) may be misleading in implying that vegetation cover in the Tuul River is stable or even slightly increasing over time. An increase in green vegetation does not necessarily indicate that pastures are not deteriorating, as it could reflect the spread of less desirable, degradation-tolerant species.

4. CONCLUSIONS AND OUTLOOK

The meadow steppes of the upper reaches of the Tuul River basin exhibited relatively intact vegetation characterized by higher species richness and biomass production compared to the middle and lower reaches. Contrary to our expectations, vegetation indices such as biomass production, cover, and plant species richness showed minimal differences between floodplain and typical steppe habitats. Furthermore, the only significant difference was found in biomass production between non-grazed (fenced) and grazed (unfenced) conditions, which resulted in higher pasture carrying capacity under grazing exclusion. While there was no difference in species richness, this suggests that short-term fencing does not necessarily improve species composition. In fact, moderate grazing supports high species diversity and productivity in the more productive steppe, as predicted by the 'intermediate disturbance hypothesis', and subsequently demonstrated by studies conducted also in Mongolia (Sasaki et al., 2009; Ahlborn et al., 2020; Munkhzul et al., 2021).

Degradation in the middle reaches was affected by human settlements and intensive livestock grazing. Interestingly, similarly high levels of degradation were observed at the lower Tuul, near its convergence with the Orkhon River, which is relatively far from Ulaanbaatar. This was reflected in plant species composition, with a dominance of species tolerant to grazing and indicative of degradation. The cover of degradation indicator species has increased significantly when compared to species composition documented 40 years ago. This suggests that while overall vegetation cover has remained relatively stable over time, there have been substantial shifts in species composition with a marked increase in grazing-tolerant species. This can most likely be attributed to overgrazing in central regions, as seen by a virtual tripling of the animal numbers over the last 20 years, and increasing dominance of grazing weeds.

Soil nutrient content was in relatively good condition. Considering the general soil nutrient deficiencies observed across Mongolia, the soil characteristics in the Tuul River Basin are relatively healthy and fertile. However, forage quality was not necessarily high, because of high content of fibers that are less digestibility to animals. Grazing tolerant and degradation indicator plants are less nutritious and less digestible, and can negatively impact livestock productivity including milk and meat yields.

5. RECOMMENDATIONS

- **Monitor Grazing Intensity**:

  Regularly monitor the vegetation health and species diversity to assess grazing pressure, ideally with permanent plots.

- **Decreasing Livestock Number:**

  Establish thresholds for maximum grazing intensity based on forage availability and vegetation recovery rates to ensure that pastures remain intact.

- **Incorporate Rest Periods**:

  Permanent exclusion of grazing is not recommended. Rather allow pasture areas to rest periodically, especially during key growing seasons, to give vegetation time to regenerate and recover from impact of overly high grazing pressure.

- **Consider changes in plant species composition**:

  Changes in vegetation cover only are not reliable for evaluating true conditions of the pastures; therefore species-level monitoring of change is essential.

- **Regulate Grazing Through Policy**:

  Advocate for policies that limit livestock density based on ecological conditions, and promote the restoration of overgrazed areas. Setting grazing limits can help prevent further degradation.

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Appendix

Table 1. Characteristics of the surveyed vegetation plots along the TUUL river basin (2024)

Seq. #.	PlotID	Lat	Lon	Altitude	Sampling date	Location name	Province	Habitat	Repetition	Hydrologist ID
1	T1_DS	48.0409	107.7474	1517	7/1/2024	Bosgo bridge	Tuv	DryS	no	T1
2	T1_DSr	48.0409	107.7474	1506	8/29/2024	Bosgo bridge	Tuv	DryS	yes	T1
3	T1_FP	48.0430	107.7458	1516	7/1/2024	Bosgo bridge	Tuv	Floodplain	no	T1
4	T1_FPr	48.0430	107.7458	1510	8/29/2024	Bosgo bridge	Tuv	Floodplain	yes	T1
5	T2_DS	47.9864	107.6185	1482	7/2/2024	Yamaha camp	Tuv	DryS	no	T2
6	T2_DSr	47.9872	107.6185	1498	8/30/2024	Yamaha camp	Tuv	DryS	yes	T2
7	T2_FP	47.9853	107.6178	1479	7/2/2024	Yamaha camp	Tuv	Floodplain	no	T2
8	T2_FPr	47.9853	107.6178	1482	8/30/2024	Yamaha camp	Tuv	Floodplain	yes	T2
9	T3_FP	47.9933	107.4606	1525	8/27/2024	Lower Terelj	Tuv	Floodplain	no	T3
10	T3_FP_2	47.9933	107.4712	1516	8/30/2024	Lower Terelj, add. small river	Tuv	Floodplain	no	T3
11	T3_MoS	47.9947	107.4728	1530	8/30/2024	Lower Terelj	Tuv	MouS	no	T3
12	T4_FP	47.8736	107.6113	1446	6/26/2024	Harztai	Tuv	Floodplain	no	T4
13	T4_FPr	47.8736	107.6114	1445	8/29/2024	Harztai	Tuv	Floodplain	yes	T4
14	T4_MoS	47.8698	107.6105	1489	6/26/2024	Harztai	Tuv	MouS	no	T4
15	T4_MoSr	47.8700	107.6103	1478	8/29/2024	Harztai	Tuv	MouS	yes	T4
16	T5_DS	47.8148	107.3286	1390	8/26/2024	Terelj bridge	Tuv	DryS	no	T5
17	T5_FP	47.8242	107.3267	1380	8/26/2024	Terelj bridge	Tuv	Floodplain	no	T5
18	T6_DS	47.9155	107.1380	1323	6/28/2024	Gachuurt	Ulaanbaatar	DryS	no	T6
19	T6_DSr	47.9163	107.1369	1324	8/25/2024	Gachuurt	Ulaanbaatar	DryS	yes	T6

Seq. #.	PlotID	Lat	Lon	Altitude	Sampling date	Location name	Province	Habitat	Repetition	Hydrologist ID
20	T6_FP	47.9163	107.1369	1324	6/28/2024	Gachuurt	Ulaanbaatar	Floodplain	no	T6
21	T6_FPr	47.9149	107.1374	1321	8/25/2024	Gachuurt	Ulaanbaatar	Floodplain	yes	T6
22	T7_DS	47.8972	107.0296	1300	8/25/2024	Uliastai	Ulaanbaatar	DryS	no	T7
23	T7_FP	47.8998	107.0296	1306	8/25/2024	Uliastai	Ulaanbaatar	Floodplain	no	T7
24	T8_FP	48.1289	106.8868	1367	6/28/2024	Sanzai	Ulaanbaatar	Floodplain	no	T8
25	T8_FP_2	48.1592	106.8447	1537	6/28/2024	Sanzai	Ulaanbaatar	Floodplain	no	T8
26	T8_FP_2r	48.1591	106.8449	1277	8/31/2024	Sanzai	Ulaanbaatar	Floodplain	yes	T8
27	T8_FPr	48.1290	106.8870	1498	8/31/2024	Sanzai	Ulaanbaatar	Floodplain	no	T8
28	T8_MoS	48.1592	106.8457	1378	8/31/2024	Sanzai	Ulaanbaatar	MouS	no	T8
29	T9_Mea	47.8831	106.9655	1285	7/2/2024	Zaisan-UB Kharuul	Ulaanbaatar	Meadow	no	T9
30	T9_Mea_r	47.8831	106.9655	1285	9/1/2024	Zaisan-UB Kharuul	Ulaanbaatar	Meadow	yes	T9
31	T9_MoS	47.8820	106.9579	1302	7/2/2024	Zaisan-UB Kharuul	Ulaanbaatar	MouS	no	T9
32	T9_MoS_r	47.8820	106.9579	1302	9/1/2024	Zaisan-UB Kharuul	Ulaanbaatar	MouS	yes	T9
33	T10_MeS	47.8910	106.8238	1260	9/1/2024	Lower Selbe	Ulaanbaatar	MeaS	no	T10
34	T11_FP	47.8713	106.6933	1236	9/1/2024	WWTP	Ulaanbaatar	Floodplain	no	T11
35	T11_MoS	47.8740	106.6896	1246	9/1/2024	WWTP	Ulaanbaatar	MouS	no	T11
36	T12_DS	47.8506	106.6727	1225	6/30/2024	Biocombinate	Ulaanbaatar	DryS	no	T12
37	T12_DSr	47.8506	106.6727	1224	8/31/2024	Biocombinate	Ulaanbaatar	DryS	yes	T12
38	T12_FP	47.8496	106.6729	1233	6/30/2024	Biocombinate	Ulaanbaatar	Floodplain	no	T12
39	T12_FPr	47.8496	106.6728	1225	8/31/2024	Biocombinate	Ulaanbaatar	Floodplain	yes	T12
40	T13_FP	47.7147	106.3922	1205	6/29/2024	Altanbulag	Tuv	Floodplain	no	T13
41	T13_FPr	47.7146	106.3918	1173	8/31/2024	Altanbulag	Tuv	Floodplain	yes	T13

Seq. #.	PlotID	Lat	Lon	Altitude	Sampling date	Location name	Province	Habitat	Repetition	Hydrologist ID
42	T13_MoS	47.7131	106.3924	1192	6/29/2024	Altanbulag	Tuv	MouS	no	T13
43	T13_MoSr	47.7141	106.3910	1183	8/31/2024	Altanbulag	Tuv	MouS	yes	T13
44	T14_DS	47.2795	105.6266	1446	8/20/2024	Khaan Khudag	Tuv	DryS	no	T14
45	T14_FP	47.275	105.626	1446	8/20/2024	Khaan Khudag	Tuv	Floodplain	no	T14
46	T15_DS	47.524	104.992	1034	8/20/2024	Undurshireet	Tuv	DryS	no	T15
47	T15_FP	47.418	105.108	1037	8/20/2024	Undurshireet	Tuv	Floodplain	no	T15
48	T16_DS	47.886	105.180	987	6/29/2024	Lun	Tuv	DryS	no	T16
49	T16_DSr	47.886	105.180	990	8/19/2024	Lun	Tuv	DryS	yes	T16
50	T16_FP	47.887	105.181	993	6/29/2024	Lun	Tuv	Floodplain	no	T16
51	T16_FPr	47.887	105.179	984	8/19/2024	Lun	Tuv	Floodplain	yes	T16
52	T16_MoS	47.884	105.176	1026	8/19/2024	Lun	Tuv	MouS	no	T16
53	T17_DS	48.095	104.297	969	8/19/2024	Upper Zaamar	Bulgan	DryS	no	T17
54	T17_FP	48.097	104.300	954	8/19/2024	Upper Zaamar	Bulgan	Floodplain	no	T17
55	T18/2_DrS	48.240	104.319	965	8/18/2024	Shijir Alt	Bulgan	DryS	no	
56	T18/2_FP	48.234	104.330	942	8/18/2024	Shijir Alt	Bulgan	Floodplain	no	
57	T18_DS	48.219	104.277	949	8/19/2024	Khar Bukh, small river	Bulgan	DryS	no	T18
58	T18_FP	48.191	104.275	945	8/19/2024	Khar Bukh, small river	Bulgan	Floodplain	no	T18
59	T19_DS	48.538	104.561	899	8/18/2024	Lower Zaamar	Tuv	DryS	no	T19
60	T19_FP	48.540	104.549	892	8/18/2024	Lower Zaamar	Tuv	Floodplain	no	T19
61	T20_DS	48.795	104.796	825	8/17/2024	Orkhontuul	Selenge	DryS	no	T20
62	T20_FP	48.814	104.801	802	8/17/2024	Orkhontuul	Selenge	Floodplain	no	T20
63	T21_FP	47.928	107.160	1332	8/30/2024	Lower Gachuurt	Gachuurt	Floodplain	no	T21

Seq. #.	PlotID	Lat	Lon	Altitude	Sampling date	Location name	Province	Habitat	Repetition	Hydrologist ID
64	T21_MeS	47.927	107.158	1343	8/30/2024	Lower Gachuurt	Gachuurt	MeaS	no	T21
65	DU_FI_MeS	48.135	107.301	1627	8/25/2024	Terelj, Davaat Uvur	Ulaanbaatar	MeaS	no	
66	DU_FO_MeS	48.134	107.301	1641	8/26/2024	Terelj, Davaat Uvur	Ulaanbaatar	MeaS	no	
67	IGG1_FI_MeS	47.990	107.422	1427	6/27/2024	Terelj	Ulaanbaatar	MeaS	no	
68	IGG1_FI_MeSr	47.990	107.422	1654	8/27/2024	Terelj	Ulaanbaatar	MeaS	yes	
69	IGG1_FO_MeS	47.990	107.422	1645	6/27/2024	Terelj	Ulaanbaatar	MeaS	no	
70	IGG1_FO_MeSr	47.990	107.422	1649	8/27/2024	Terelj	Ulaanbaatar	MeaS	yes	
71	IGG2_FE	47.980	107.426	1581	6/27/2024	Terelj	Ulaanbaatar	Forest edge	no	
72	IGG2_FE_r	47.980	107.426	1597	8/27/2024	Terelj	Ulaanbaatar	Forest edge	yes	
73	IGG2_FI_Fo	47.977	107.425	1585	6/27/2024	Terelj	Ulaanbaatar	Forest	no	
74	IGG2_FI_Fo_r	47.976	107.425	1639	8/27/2024	Terelj	Ulaanbaatar	Forest	yes	
75	IGG2C_FP	47.982	107.426	1579	8/27/2024	Terelj	Ulaanbaatar	Floodplain	no	
76	Na_FI_DS	47.693	107.490	1537	6/26/2024	Nalaikh	Nalaikh	DryS	no	
77	Na_FI_DSr	47.694	107.489	1525	8/29/2024	Nalaikh	Nalaikh	DryS	yes	
78	Na_FO_DS	47.694	107.490	1525	6/26/2024	Nalaikh	Nalaikh	DryS	no	
79	Na_FO_DSr	47.694	107.490	1525	8/29/2024	Nalaikh	Nalaikh	DryS	yes	
80	P5_FE	48.110	107.253	1878	6/27/2024	Davaat davaa	Terelj	Forest edge	no	
81	Zaan_FP	48.136	107.306	1617	8/26/2024	Zaan river	Terelj	Floodplain	no	
82	KW7_FI	47.524	104.992	980	8/20/2024	Undurshireet	Tuv	DryS	no	
83	KW8_FO	47.523	104.909	990	8/20/2024	Undurshireet	Tuv	SS	no	