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Original Research

# Moving Toward the Greener Side: Environmental Aspects Guiding Pastoral Mobility and Impacting Vegetation in the Dzungarian Gobi, Mongolia ☆

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ABSTRACT

Livestock grazing often intensifies around herder camps, which can lead to degradation, particularly in arid areas, where vegetation is scarce. In Mongolia, nomadic herders have covered long distances between camps and changed camps regularly for centuries. However, changing socioeconomics, rising livestock numbers, and climatic change have led to growing concerns over rangeland health. To understand travel mobility and livestock grazing patterns, we combined Global Positioning System tracking data of goats, remotely sensing pasture productivity, and ground-based vegetation characteristics in the Great Gobi B Strictly Protected Area, Mongolia. We assessed herder preferences for camp selection, followed 19 livestock herds over 20 months, determined use and nutrient contents of the most dominant plant communities, and estimated plant species richness, vegetation cover, and biomass within different grazing radii around camps. Biomass availability was key for herder decisions to move camps, but in winter, other factors like shelter from wind were more important. Camps were mainly located in *Stipa* spp. communities, agreeing with herder preferences for this highly nutritious species, and its dominance around camps. Herders changed their camp locations on average 9 times yearly, with a maximum distance of 70–123 km between summer and winter camps, and an average visitation period of 25–49 d per camp, depending on season. Small livestock spent > 13−17 h daily within a radius of 100 m from camp, and livestock use intensity decreased steeply with distance from camp but was remarkably similar around spring, autumn, and winter camps on the Gobi plains. However, we found little evidence for a corresponding gradient in plant species richness, biomass, and cover on the Gobi plains. The high mobility of local herders and the overriding impact of precipitation on pasture dynamics contribute to a sustainable vegetation offtake by livestock in the nonequilibrium rangelands of the Dzungarian Gobi.



## Introduction

Pastoralism is the main income generation activity of local communities in many arid and semiarid regions that are unsuitable for agriculture (Hogg 1992). However, globally increasing livestock numbers (Thornton 2010), in combination with climate change (Christensen et al. 2004; Crook et al. 2020), have led to growing concern over degradation and loss of rangeland. Pastoralism is often practiced in areas with high biodiversity but overall low biomass productivity (Berzborn and Solich 2013). Mobility is a key strategy for herders worldwide to maintain adequate forage intake for livestock and distribute grazing pressure across the rangeland (Coughenour 1991; Liao et al. 2017). This flexibility is of major importance in arid and semiarid regions where forage availability and quality differs within and between years, mainly due to un-

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predictable precipitation (Noy-Meir 1973; Le Houérou et al. 1988). However, this mobility is threatened by trends toward fewer camp moves and reduced walking distances by livestock (Jordan et al. 2016; Tsvegemed et al. 2018).

Movement patterns of herders and their livestock are differentiated into broad- and fine-scale movements: 1) travel mobility describes the seasonal movements between camps, and 2) grazing mobility focuses on daily grazing patterns (Adriansen 2008; Liao 2018; Turner and Schlecht 2019). Different grazing mobility models have been discussed in the literature, suggesting an evenly distributed grazing pressure around herder camps (Homewood and Rodgers 1991) or grazing gradients radiating away from settlements (Spencer 1973) known as piosphere (Lange 1969) or central-place model (Coppolillo 2001). The area directly around the camps is often described as a "sacrificed" zone due to heavy and repeated use by livestock, followed by a "transition" zone with decreasing grazing intensity radiating away from the camp toward areas that are rarely used for livestock grazing (Liao et al. 2017). "Sacrificed" zones are characterized by heavy trampling, dung and urine depositions, and opportunistic grazing (Andrew 1988; Hess et al. 2020). Grazing gradients might be weakened by large-scale travel mobility patterns and short duration of stay at single camps. Only a few studies have investigated both large-scale and small-scale grazing patterns of livestock using Global Positioning System (GPS) tracking devices (Adriansen and Nielsen 2005; Butt et al. 2009; Jordan et al. 2016).

Higher livestock numbers, and therefore higher grazing intensity, have been affiliated with lower plant species diversity, vegetation cover, and biomass (Lambin et al. 2001), particularly of herbaceous plants (Treydte et al. 2017) but also in woody communities (Chaideftou et al. 2008). The daily maximum walking distance and time spent grazing at different distances from camp on one hand can be expected to vary with forage availability and on the other hand will determine grazing pressure (Coppolillo 2000; Schlecht et al. 2004). This grazing distance is often determined by daily maximum distance from camp, grazing loop, or home range (Liao 2018). However, few studies have investigated the recorded GPS locations as time spent by livestock per area (Coppolillo 2001), and those studies often omit the importance of local socioecological herding strategies (Butt 2010), such as local knowledge about livestock, climate, and vegetation interactions (Fernandez-Gimenez 2000).

Herders' traditional ecological knowledge (TEK) about grazing areas has been passed on for generations (Fernandez-Gimenez 2000; Oba and Kaitira 2006; Treydte et al. 2017), whereby herders characterize different pastures according to plant community, nutritional quality of plant species, and season in which the pastures are used (Fernandez-Gimenez 2000). Combining travel and grazing mobility with vegetation resource availability on the ground is crucial to avoid too general conclusions and abstractions (Turner and Schlecht 2019). Rangeland studies have mainly focused on forage availability in terms of biomass and vegetation cover (Ahlborn et al. 2020; Sasaki et al. 2008b; Sternberg 2012), whereas few studies have included nutritional values of pastures across seasons (Beher 2014).

In Mongolia, 80% of the 150 million−ha land is used for extensive livestock grazing (Angerer et al. 2008), and pastoralism is the main livelihood for around 240 000 herder households (Mongolian Statistical Information Service 2021). The rapid increase in livestock numbers over the past 30 yr (Lkhagvadorj et al. 2013) has resulted in a record number of over 70 million animals in Mongolia in 2019 (Mongolian Statistical Information Service 2021). This increase in livestock numbers, especially goats, is often quoted as cause for rangeland degradation (Liu et al. 2013; Hilker et al. 2014). However, the negative impacts of high livestock numbers on the degradation risk of rangelands are highly debated, especially where precipitation is scarce (Addison et al. 2012).

In the arid Gobi regions of southern Mongolia, temporal and spatial variability of precipitation leads to a nonequilibrium system where precipitation is the key driver for pasture productivity and subsequently ungulate numbers (Fernandez-Gimenez and Allen-Diaz 1999; von Wehrden et al. 2012). Variability in precipitation forces herders to move (Pfeiffer et al. 2020), and extreme weather results in mass die-offs, which "downregulate" livestock numbers, allowing vegetation to recover; nonequilibrium rangelands under a traditional grazing regime are therefore considered to be rather resilient to degradation by several authors (Wesche and Retzer 2005; Wesche et al. 2010; Cheng et al. 2011). Herders in the Gobi are known for their longer travel distances and more frequent camp shifts as compared with herders in other parts of Mongolia (Reading et al. 2006). This mobility and spatiotemporal flexibility allows them to react to variation in pasture availability within and between years (Niamir-Fuller 1999) but has rarely been tracked, especially in arid systems.

Until recently, herder and livestock mobility has been primarily studied through interview data in Mongolia (Lkhagvadorj et al. 2013; Ono and Ishikawa 2020). Therefore, little day-to-day data on seasonal movements or livestock use intensity around seasonal camps are available. Furthermore, few studies have examined different spatial scales in Mongolia (Teickner et al. 2020) or interlinked social (Fernandez-Gimenez and Febre 2006; Mocellin and Foggin 2008; Fernández-Giménez et al. 2018) and ecological (Fernandez-Gimenez 2000; Narantsetseg et al. 2018; Lang et al. 2020) disciplines. To close this knowledge gap to better understand drivers behind herder travel mobility and assess the impact of grazing mobility around herder camps, we chose an integrative data analysis framework, combining GPS data of livestock herds, remote sensing products characterizing pasture at the landscape scale, and vegetation assessments at the local scale, and complemented those data with traditional ecological knowledge. With this approach we aimed to answer the following questions:

1) What are the key determining factors for travel mobility and camp selection of herders across seasons? How do herders' travel mobility patterns and camp use duration vary between seasons?
2) Do herders choose specific plant communities for their camps? Is this selection consistent with forage quality and availability of respective plant communities?
3) What is the grazing intensity around herder camps, and how does it vary with distance from camp and season? Is the grazing intensity reflected in the vegetation around herder camps?

Our study pinpoints travel and grazing mobility patterns and combines those with in-depth vegetation analysis joined with herder perspectives to help pastureland management within a protected area.

## Material and Methods

### *Study area*

The research was conducted in the Great Gobi B Strictly Protected Area (SPA) in southwestern Mongolia from 2018 to 2020. The Great Gobi B SPA was established in 1975, stretching over ≈9 000 km$^2$ of semideserts and desert-steppes (Kaczensky et al. 2004) and was recently extended to ≈18 000 km$^2$ (Sansarbayar 2019) covering similar steppe plant communities. The Great Gobi B SPA is part of the Dzungarian Gobi, bordering China in the South along the Takhin Shar Naruu Mountains and framed by the Altai Mountains in the North (Kaczensky et al. 2008). The international border is fenced, but the remainder of the protected area is not (Kaczensky et al. 2008). The Great Gobi B SPA is registered as IUCN category Ib (UNEP-WCMC 2022) with a core, limited use,

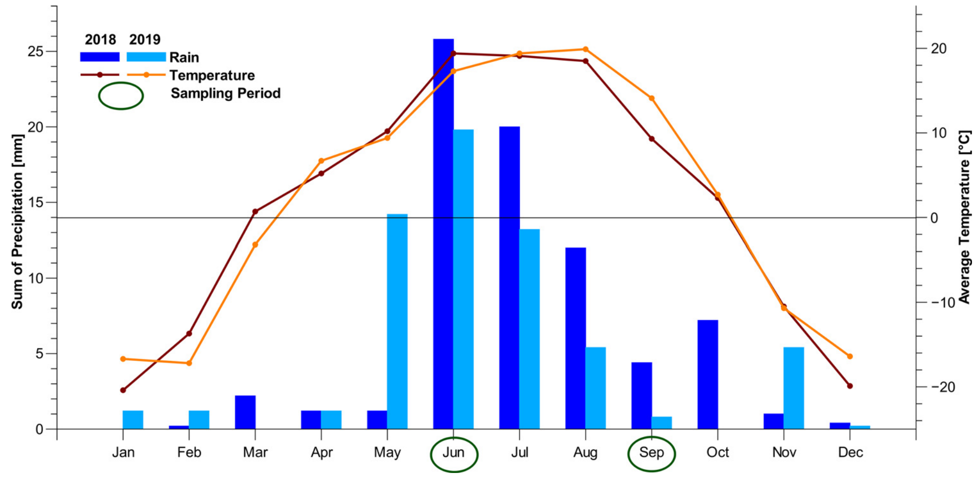


**Fig. 1.** Average monthly temperature collected with a HOBO weather station at Takhiin Tal research station in the yr 2018–2019. Green circles mark the months of vegetation sampling period at the beginning and end of the growing season, respectively.

and buffer zone. Elevations are between 1 000 and 2 840 masl, with plains toward the East and rolling hills in the West. The climate is continental, characterized by long, cold winters (with average monthly temperatures of 4°C to −20°C between October and April); short, hot summers (with temperatures of 14°C–19°C between May and September); the climate is dry (with average precipitation of 96 mm per year) and falls into the nonequilibrium zone (von Wehrden et al. 2012). Weather data (hourly temperature [°C] and rainfall [mm]) have been recorded since 2013 with a HOBO weather station at the protected area administration camp (45°32′19.20"N 93°39′4.02"E), Takhiin Tal. During our study period, summer rains peaked in June but varied over the main study duration in 2018 and 2019, in both timing and overall amount (Fig. 1).

The Great Gobi B SPA is part of the central Asian flora region with shallow and poorly developed soils and is dominated by semidesert and desert-steppe vegetation with characteristic plants adapted to aridity like *Haloxylon ammodendron, Ephedra przewalskii, Reaumuria soongarica,* and *Anabasis brevifolia*. In areas where desert-steppe is found, Poaceae like *Stipa* spp. and Asteraceae like *Artemisia* spp. and *Ajania* spp. dominate (von Wehrden et al. 2006). The Dzungarian Gobi has a relatively high plant biodiversity for a desert, hosting around 717 plant species (Gubanov 1996).

Around 130 herder families (personal communication, Ganbaatar Oyunsaikhan, director of the Great Gobi B SPA, 2018 and 2019) and their livestock use the Great Gobi B SPA in winter and on their way to and from the summer pastures on the alpine meadows of the Altai mountain range. Herders spend about 9 mo inside or adjacent to the Great Gobi B SPA (personal communication, Ganbaatar Oyunsaikhan, director of the Great Gobi B SPA, 2018 and 2019). These herder families have to register their winter camps at the district level and are mostly granted grazing rights for around 15 yr, after which the contract can be renewed (personal communication, Mr. Myatav, local governor, 2019). On the basis of old agreements, herders are allowed to use camp sites within the limited-use and buffer zones but are only allowed to move across the core zone quickly during their travel movements.

Most common livestock in the region are, in decreasing order of abundance, goats *(Capra aegagrus hircus),* sheep *(Ovis aries),* cows *(Bos taurus turano mongolicus),* horses *(Equus ferus caballus),* camels *(Camelus bactrianus),* and yaks *(Bos grunniens;* Kaczensky et al. 2008). Only sheep and goats ("small livestock") are tended in mixed herds on a daily basis while large livestock is only checked daily or weekly and may even go unaccompanied over extended periods (Kaczensky et al. 2008, personal observation). Our study focused on mixed livestock herds consisting of sheep and goats because they provide the most important source of income for local herders and are by far the most numerous livestock species (Mongolian Statistical Information Service 2021).

*Herder movement decisions*

To understand how herders choose their camps we conducted three focus group interviews with a total of 36 local herders (11 women and 25 men), in November 2019. The focus group meetings took place at three different herder families' camps, were led by a moderator and assistant interpreting the discussion, and each lasted between two and three hours (Krueger, 2014). Prior to the focus group discussions, we informed participants about the research aim and obtained consent through participants signatures. Participants were divided into subgroups to discuss questions about movement decisions and the decision-making process behind camp selection, when and why to move. Participants further discussed about rangeland plants most relevant and preferred by livestock. Subgroups agreed on the most favourable and nutritious plant species for each livestock species and season, and subsequently presented their results after mutual consent to the whole group. Notes were taken simultaneously in Mongolian and English. We analysed the focus group interview data based on the *keywords-in-context* method as described by Onwuegbuzie et al. (2009). Herders named those plant species indicating good grazing sites and we subsequently related this information with the plant species we recorded around the herder camps.

*Livestock movement patterns*

To document travel and grazing mobility (Fig. 2), we equipped one healthy, adult male goat each in 19 different livestock herds with a lightweight GPS collar (CatLog Gen2, Perthold Engineering LLC, Dallas, TX). Goats were chosen as representative animal species for all small livestock herds as the GPS devices fitted the goats' body better than that of sheep. Of the 19 tracked livestock herds, 11 used the pastures of the Eastern part of the Great Gobi B SPA and 8 of the Western part. However, we combined the analyses of all livestock herds, except when we reported the maximum distances between summer and winter camps. We programmed the GPS units to record a position at 30-min intervals between 7:00 and 22:00 h and pause the remainder of the night to save battery life, based on herder information that small livestock sleep in the

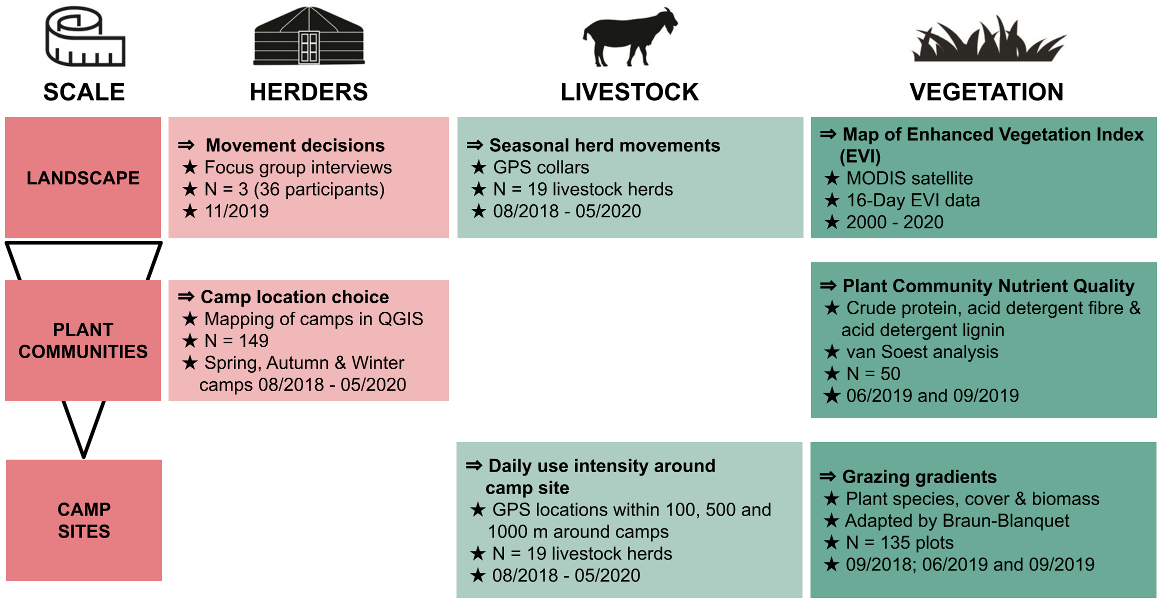


**Fig. 2.** Schematic graph of data collection and analysis from 2018 until 2020 in the Great Gobi B, Mongolia. The figure illustrates how we investigated travel and grazing mobility with various methods at different scales and related it to the vegetation.

camp during this time. Collars were deployed over a 20-mo period from the end of August 2018 to the beginning of May 2020 (Table A1, Fig. A.1, Fig. A.2) and collected on average 16 541 GPS locations per goat. The data set was corrected for outliers, stationary periods, and missing values caused by technical issues with the GPS devices or temporary removals of GPS devices by herders.

On the basis of the GPS tracking data, we visually identified camp locations in the middle of dense clusters of GPS points and movement paths returning to a specific location in QGIS (2.18.18); in many cases, camp location could be confirmed on the Google satellite image by the presence of a dark dung circle or man-made structures like stone corrals. We defined camps as "herder camps" when used for >7 days and "transition camps" when used ≤ 7 days, mainly used as short stop-over locations during camp moves (personal com., Ganbaatar Oyunsaikhan, director of the Great Gobi B SPA, 2018 and 2019). We classified the herder camps based on the date of use and location into "summer" (June to August), "intermediate" (March to May [spring] and September to November [autumn]), and "winter" camps (December and February). To understand grazing intensity by season and distance from camp (adapted from Coppolillo 2001), we calculated the time GPS tagged goats spent at different distance radii of 100, 500, 1 000, and 5 000 m from the camp (the time GPS units paused at night was added to the 100-m radius). Distance categories for grazing intensity corresponded with the location of our vegetation assessment plots. We subsequently determined grazing intensity, first by calculating the hours spent per ha in each distance radius to account for the difference in available grazing area and then multiplied the value by the average number of days herders stayed at different seasonal camps to compare livestock use intensity among seasonal camps. Livestock use intensity can be assumed to correlate with grazing intensity and entails trampling and nutrient intake via urination and defecation.

*Vegetation assessments*

*Enhanced vegetation index as proxy for biomass*

To estimate biomass availability at the landscape scale, we used the EVI (enhanced vegetation index) as a proxy, which is sensitive to spatial and temporal variations in biomass productivity,

**Table 1**
Average number of camps per season used over a 20-mo period and duration of stay calculated for 250 seasonal herder camps (including repeated camp use) and average number of 166 seasonal transition camps used by 19 herder families in and around the Great Gobi B SPA in Mongolia. Average numbers were adapted to different sample sizes according to missing values in each season. Duration of stay was only calculated for herder camps and not for transition camps. Data are based on 314 275 GPS locations during the monitoring period between the end of August 2018 and beginning of May 2020.

| | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| No. of camps | 2.3 ± 1.2 | 1.6 ± 0.5 | 3.1 ± 0.7 | 2.2 ± 0.7 |
| No. of transition camps | 2.1 ± 2.1 | 1.1 ± 1.1 | 1.7 ± 2.1 | 1.1 ± 1.3 |
| Duration of stay (d) | 28.7 ± 15.7 | 42.6 ± 21.6 | 24.6 ± 11.2 | 49.1 ± 29.5 |

especially in areas with high soil exposure (Huete et al. 2002; Kawamura et al. 2005; Garroutte et al. 2016). We processed a 20-yr time series (2000–2020) of the EVI in Google Earth Engine using the Terra Moderate Resolution Imaging Spectroradiometer layers (MODIS; MOD13Q1; Version 6), available at 16-d intervals (Didan 2015; Paltsyn et al. 2019). We calculated the annual mean EVI for the vegetation period (May to September) at 250-m resolution for the entire Great Gobi B SPA as a baseline value and within a radius of 1 000 m around 187 seasonal herder camps identified from tracking data of GPS collared goats (Fig. A.3). During spring and autumn, herders often used the same camps; therefore, we combined these camps as "intermediate" camps for this analysis. We additionally produced a map visualizing the average EVI over the entire 20-yr period to visualize the underlaying productivity gradients responsible for the seasonal movements.

*Plant community nutrient quality of herder camps*

We obtained the plant community type at each herder camp location from a digital vegetation map (von Wehrden et al. 2006). To assess forage quality in the five most dominant plant communities (von Wehrden et al. 2006), we collected mixed biomass samples in the beginning and end of the growing season (June 2019; September 2019). The five plant communities sampled were 1) grasslands dominated by *Stipa* spp. and shrublands dominated by 2) *Caragana* spp., 3) *Nanophyton erinaceum*, 4) *Reaumuria soongorica*, and 5) *Haloxylon ammodendron* (von Wehrden et al. 2006). We randomly selected five sites within each plant community on the ground and established two $10 \times 10$ $m^2$ plots within a distance of 100 m. Within each plot, we randomly sampled one 1-$m^2$ subplot by cutting all herbs and grasses to 1 cm above ground level. In total, we collected 10 samples per vegetation community, summing up to 50 plant community samples. We oven-dried the mixed samples at 60°C for 48 h, ground them, and analyzed them for crude protein (CP), acid detergent fiber (ADF), and acid detergent lignin (ADL) according to Van Soest et al. (1991) as indicators for forage quality in the laboratory of the Mongolian University of Applied Life Sciences, Ulaanbaatar, Mongolia.

*Grazing gradients around herder camps*

We assessed vegetation characteristics around 45 herder camps (15 winter, 15 spring, and 15 autumn camps) in the Eastern part of the protected area. We collected data on the same plots twice at the end (September 2018 and 2019) and once at the start of the growing season (June 2019). We walked transects in a North–South direction away from each camp and sampled vegetation within quadrats of $10 \times 10$ $m^2$ at 100-m, 500-m, and 1 000-m distance intervals ($N = 135$). We started the transects at the point where the vegetation-free "sacrifice zone" (Hess et al. 2020) around the herder camps stopped (i.e., beyond a radius of 25 m) to avoid any potential bias through intense trampling or camp/housing impacts. In each quadrat, we identified and counted all individual plant species using Tungalag and Boldgiv (2016) and Jigjidsuren and Johnson (2003) to identify plant species richness and estimated species cover visually in % (Kent and Coker 1992). Where species identification was difficult, we took photographs and collected herbarium samples for species determination by botanists from the National University of Mongolia (NUM). We harvested biomass samples within two randomly selected subplots (1 $m^2$) within each 10-$m^2$ plot with common pruning shears and sorted them into the plant groups "grasses," "annual forbs" and "perennial forbs," "subshrubs," and "shrubs" adapted from Jamsranjav et al. (2018). This resulted in a total of 388 biomass samples collected on 90 subplots. All samples were stored in labeled paper bags and dried in the shadow until arrival in the laboratory of the Mongolian University of Applied Life Sciences, Ulaanbaatar, Mongolia. There, samples were dried at 60°C for 48 h in a common drying oven and weighed for dry matter (DM) content to calculate biomass·$m^{-2}$ (Jamsranjav et al. 2018).

*Statistical analysis*

GPS data were analyzed with R software version R-4.0.3, using the "car" package (Fox and Weisberg 2019). We compared grazing intensity (hr·$ha^{-1}$ by average seasonal camp use in days) with a type III 2-way analysis of variance to identify differences between distance radii 100 m, 500 m, 1 000 m, and 5 000 m around different camp types (spring, summer, autumn, and winter) and interaction effects between distance radii and camp types.

Forage quality parameters were compared for differences among plant community type, season, and interaction effects in R software version R-4.0.3 using type III 2-way analysis of variance. The Levene test was applied for homogeneity of variances plus visual assessment of normal distribution of the residuals from scatter plots and histograms. Tukey post-hoc test was used for pairwise comparisons.

Vegetation data were analyzed with SAS/STAT software version 9.4. We compared plant species richness, vegetation cover, and biomass data with a linear general mixed model to identify differences across distance classes around camps and sampling month (September 2018 and 2019: end of growing season and June 2019: beginning of growing season). To account for spatial and temporal repeated measures, we applied the anisotropic power model (Piepho et al. 2004). To meet the assumptions of homogeneity of variance and normality, data were transformed if necessary. Percentage data (vegetation cover) was arcsine-transformed, and biomass data were log or square root transformed. The outcomes were plotted with Qtiplot (IonDev SRL software, version 5.12.8) showing means and standard deviation or errors of the untransformed data. For all statistical analyses, significance levels were set at $P \leq 0.05$.

## Results

*Herder travel mobility decisions and camp selections in different seasons*

We recorded a total of 187 unique camp locations, of which some were used repeatedly by herders during our 20 month tracking period totalling up to 250 camps, and additional 166 transition camps. Maximum travel distances between winter camps in the Gobi and summer camps in the Altai mountains differed between herders in the eastern and western part of Great Gobi B SPA due to the NW to SE orientation of the Altai range (Fig. 3). The mean (± standard deviation) annual distance between the northernmost summer camp and southernmost winter camp averaged 123 (± 20) km in the west and 70 (± 21) km in the east (see Fig. 3). Herders changed their camp locations on average 9 (± 2) times per year, most frequently making use of 2 different summer and winter camps each, 2 spring and 3 autumn camps. Herders stayed around 3-4 wk in spring and autumn camps, and around 6-7 wk in summer and winter camps (Table 1). Biomass estimates for the growing season were 2.5 × higher around summer camps in the Altai mountains (mean EVI: 1 400 ± 328), slightly higher at intermediate (spring and autumn) camps (mean EVI: 739 ± 119), and around the same at winter camps (mean EVI: 584 ± 92) compared with the average over the entire Great Gobi B (mean EVI: 581 ± 61; Fig. 4).

The decision criteria of herder families were reflected well by the remote sensing data as herders identified pasture productivity as the key variable for camp selection in summer, spring, and autumn. Further, our interviews revealed that for the intermediate camps in spring, herders preferred areas of early snow melt and green-up, found in the Gobi plains close to springs and oasis. These sites ideally were sheltered from the wind by natural topography or man-made corrals. In summer, herders preferred areas with lush, nutritious vegetation, access to rivers, cooler temperatures and few biting insects, usually found in the Altai mountains. Herders considered the cooler climate and grass-dominated mountain meadows close to the numerous mountain streams as important to allow livestock to gain weight. For the intermediate camps in autumn, herders preferred areas with nutritious vegetation close to water sources, often near or at spring camps, until the first snowfall. In winter, herders preferred sheltered areas with moderate snow depth, allowing livestock easy access to forage and satisfying water requirements via snow consumption.

*Camp selection in different plant communities based on forage quality*

Local herders identified *Stipa* grasslands and specifically *Stipa gobica, Stipa glareosa,* and *Allium mongolicum* as the most important forage plants throughout all seasons (Table 2), whereas the plant communities *Reaumuria soongorica* and *Caragana* spp. were mainly important for livestock during the winter months. This preference was reflected in the location of herder camps based on GPS data, where the majority of spring, autumn, and winter camps (62%) were located in *Stipa* spp. communities, followed by mountain meadow and *Haloxylon ammondendron* communities (see

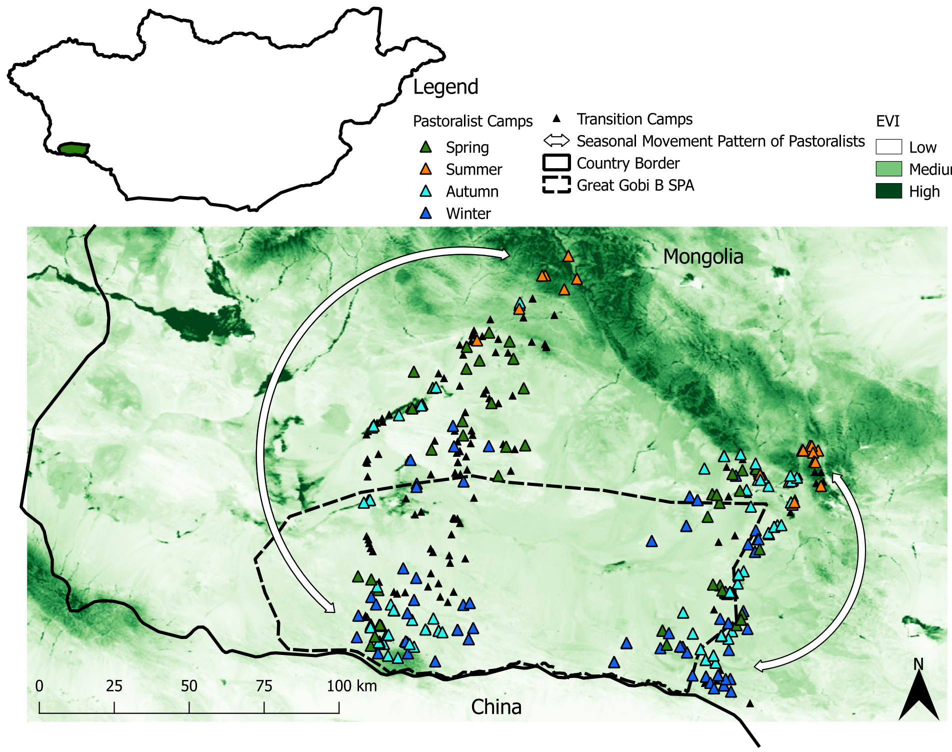


**Fig. 3.** Location of 187 seasonal herder camps and 160 transition camps occupied by 19 herder families from August 2018 until May 2020 in the Great Gobi B SPA, Mongolia. The background shows the 20-yr average of biomass availability using the Enhanced Vegetation Index as proxy. *White arrows* illustrate the herders' seasonal movements between summer camps on alpine pastures in the Altai mountain range and winter camps in the Gobi.

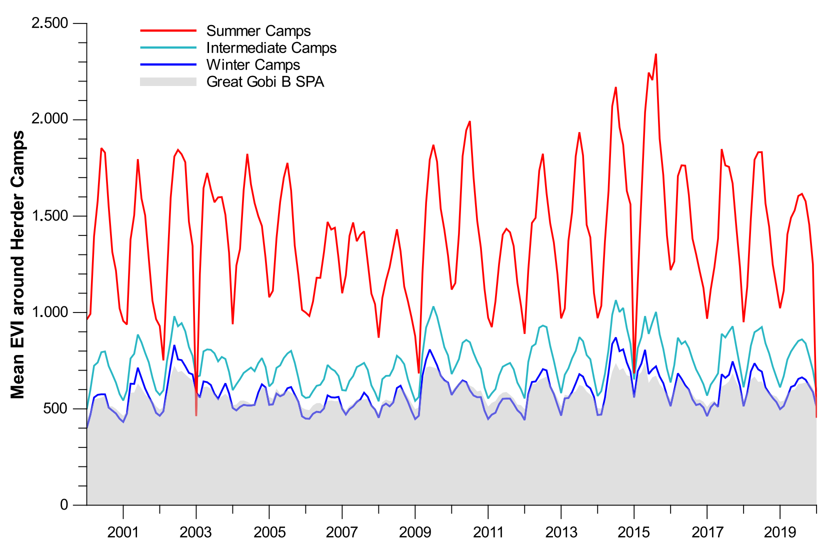


**Fig. 4.** Mean EVI from 2000 until 2020 in a 1 000-m radius around 187 seasonal herder camps in and around the Great Gobi B SPA in Mongolia. Only the growing season, from May to September, was considered. The average for the entire Great Gobi B SPA is shown as a shaded gray area for comparison.

Table 2). The herders' preference also agreed with forage quality of the different plant communities, whereby we assumed that high CP combined with low fiber contents (ADF and ADL) indicated good forage quality (Newman et al. 2009). *Stipa* spp. communities showed moderate CP values but the lowest ADF and ADL values compared with other plant communities, indicating highest palatability (Fig. 5). Plant communities differed significantly in their CP contents ($F_{4,38} = 4.74$; $P = 0.003$; see Fig. 5), and there was an interaction effect between plant communities and sampling month ($F_{4,38} = 3.45$; $P = 0.017$). CP contents were on average 23% higher in June 2019 compared with September 2019 for four out of five plant communities ($F_{1,38} = 20.89$; $P = 0.001$). ADF contents differed

**Table 2**
Herder camp locations across different plant communities in the Great Gobi B SPA in Mongolia. Vegetation at summer camps were not assessed as they were located outside the protected area (see Fig. 3). Plant communities are based on the vegetation map by (von Wehrden et al. 2006). Genera highlighted with asterisks were used to mark plant communities, which were sampled for forage analysis in June and September 2019 at five sites within each plant community ($N = 50$) (see Fig. 5). Calculations are based on 149 unique spring, autumn and winter camps.

| Plant communities | Spring Camps ($n = 38$) | Autumn Camps ($n = 59$) | Winter Camps ($n = 52$) |
|---|---|---|---|
| *Stipa* spp.** | 23 | 35 | 34 |
| *Haloxylon ammondendron*** | 3 | 8 | 3 |
| *Mountain meadows* | 5 | 7 | 10 |
| *Achnatherum* spp. | 3 | 5 | 1 |
| *Nitratia* spp. | 1 | 2 | 3 |
| *Nanophyton* spp.** | 1 | 0 | 0 |
| *Salt meadows* | 1 | 0 | 0 |
| *Juniper shrubs* | 0 | 2 | 1 |
| *Reaumuria soongarica*** | 1 | 0 | 0 |
| *Caragana* spp.** | 0 | 0 | 0 |

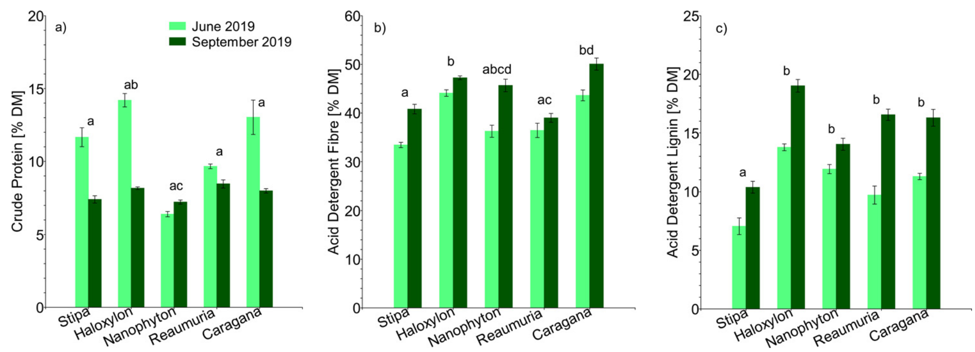


**Fig. 5.** Mean (± standard error) nutritional values expressed as percentage of dry matter of selected plant communities common in Great Gobi B SPA in Mongolia. **a**, Crude protein (CP), **b**, Acid detergent fiber (ADF), and **c**, Acid detergent lignin (ADL). Samples were collected in June and September 2019 ($N = 50$). Bars with the same letter are not significantly different at $\alpha = 0.05$ according to Tukey post-hoc test. Post-hoc test refers to differences between plant communities, not across seasons.

significantly among plant communities ($F_{4,38} = 7.06$; $P \leq 0.001$) and were 13% lower in June 2019 than September 2019 ($F_{1,38} = 14.75$; $P \leq 0.001$). The ADL averages differed significantly between plant communities ($F_{4,38} = 9.76$; $P \leq 0.001$), and highest seasonal differences ($F_{1,38} = 33.56$; $P \leq 0.001$) were observed in ADL, with 29% lower values in June 2019 compared with September 2019 (see Fig. 5).

*Livestock use intensity around herder camps and influence on vegetation*

With an average visitation period of 49 d, herders stayed almost twice as long at winter camps compared to spring and autumn. Summer camps were used almost as long as winter camps (Table 1). Small livestock spent > 50% of time per day within a radius of 100 m around the camps, primarily resting. Consequently, use intensity of the rangeland at the different distance radii differed significantly by distance ($F_{3,984} = 548.71$; $P < 0.001$) but also by season ($F_{3,984} = 33.42$; $P < 0.001$), as well as their interaction ($F_{9,984} = 33.37$; $P < 0.001$). Use intensity (over the average visitation period) steeply decreased from 118 to 264 h/ha at 0−100 m away from the camp to 43−94 min at 101−500 m, to 9−18 min at 501−1 000 m and to 1.1-2.3 min at 1 001−5 000 m. At winter camps, use intensity was twice as high around camp (0−100 m), so despite the much longer presence time, use intensity within the other distance zones was within the same values as for spring and autumn camps. At summer camps, use intensity was higher in the 101−500 and 501-1 000 distance radii, compared with spring, autumn, and winter camps, potentially reflecting the much higher pasture productivity in the close vicinity of the camps at the alpine meadows (Table 3).

Out of 47 different plant species found across all plots around herder camps, 9 species were mentioned by herders as important forage plants for livestock (Table 4). Five genera/species, namely *Stipa* spp., *Artemisia* spp., *Allium mongolicum, Kraschennikovia ceratoides,* and *Anabasis brevifolia,* occurred on ≥ 50% of all plots around herder camps. The first four of these species/genera were on the list of important forage plants by local herders (see Table 4). Plant species richness was with 45 plant species generally low, averaging 7 species per plot, and did not differ significantly across distance categories ($F_{2,123} = 0.80$; $P = 0.45$), and no interaction effects between season and distance were found ($F_{4,123} = 0.1.88$; $P = 0.12$; Fig. 6). However, plant species richness differed depending on sampling time ($F_{2,123} = 4.66$; $P = 0.01$), with slightly higher species richness in September 2018 and June 2019 compared with September 2019 ($P = 0.004$ and $P = 0.04$, respectively; see Fig. 6).

Plant cover averaged 14.0%, with 7.4% herbaceous (annual/perennial forbs and grasses), 4.1% subshrub, and 2.5% shrub layer. Only the shrub layer significantly increased with increasing distance away from the camp ($F_{2,84} = 8.86$; $P < 0.001$), whereas there were no significant differences in the herbaceous ($F_{2,123} = 1.89$, $P = 0.16$) and the subshrub layer ($F_{2,84} = 0.10$; $P = 0.90$). Only the grass layer varied between sampling period, being higher in September 2018 compared with June 2019 and September 2019 ($F_{2,84} = 3.23$; $P = 0.05$; see Fig. 6).

Foliar biomass averaged 23.3 $g \cdot m^{-2}$, with 8.7 $g \cdot m^{-2}$ for the herbaceous, 13.4 $g \cdot m^{-2}$ for the subshrub, and 1.2 $g \cdot m^{-2}$ for the shrub layer. Average (± SE) total foliar biomass was highest in September 2018 at 0−100 m around camp, but this pattern was not consistent across all three sampling periods and, hence, no significant differences were found among distance categories

**Table 3**
Livestock presence as a proxy for use intensity at different distance radii away from the center of 250 seasonal camps, in the Great Gobi B, Mongolia. Values were calculated taking into account the exclusive area of different distance radii. The average number of days herder families occupy camps during different seasons and are expressed as hr·ha$^{-1}$·over an average visitation period (see Table 1). N shown for each season corresponds to the total GPS points used for calculation.

| Radius (m) (area [ha]) | Distance from camp centre | | | |
|---|---|---|---|---|
| | 100 (3.1) | 500 (74.4) | 1 000 (235.6) | 5 000 (2 185.8) |
| Livestock use intensity (hr·ha$^{-1}$ over an average visitation period) during camp occupation | | | | |
| Spring ($N$ = 51 105) | 127.02 ± 67.52 | 0.78 ± 0.65 | 0.15 ± 0.09 | 0.03 ± 0.01 |
| Summer ($N$ = 32 160) | 172.40 ± 86.56 | 1.57 ± 0.84 | 0.31 ± 0.14 | 0.04 ± 0.02 |
| Autumn ($N$ = 73 916) | 117.89 ± 56.05 | 0.72 ± 0.49 | 0.15 ± 0.09 | 0.02 ± 0.01 |
| Winter ($N$ = 114 220) | 263.95 ± 155.67 | 0.72 ± 0.50 | 0.21 ± 0.14 | 0.03 ± 0.02 |

**Table 4**
Plant species frequency and cover within a radius of 1 000 m around the center of 45 herder camps in the Great Gobi B SPA and importance rank based on focal group interviews. Ranks represent summary scores of the plant's seasonal importance based on interviews with 36 herders: 0 = plant not mentioned as a livestock forage plant in any season, 4 = plant considered a livestock forage plant in all four seasons. Plant genera marked with two asterisks are plants associated with the main plant communities in the Great Gobi B SPA according to von Wehrden et al. (2006). Single asterisks mark plant species mentioned by herders as important, but which were not found on sampling plots. We only listed plant species that occurred at ≥ 10% of the sampling plots. Species names are based on the "Virtual Guide to the Flora of Mongolia | Plant Database as Practical Approach" (accessed March 2, 2022).

| Plant species/genus | Plant sampling | | Pastoralist interviews |
|---|---|---|---|
| | Frequency [%] | Cover [%] | Importance in N seasons |
| *Stipa* spp.** | 91 | 5.50 | 3 |
| *Artemisia* spp. | 61 | 1.32 | 4 |
| *Allium mongolicum* Turcz. ex Regel | 53 | 0.42 | 4 |
| *Anabasis brevifolia* C.A. Mey. | 52 | 1.11 | 0 |
| *Krascheninnikovia ceratoides* (L.) Gueldenst. | 50 | 0.51 | 1 |
| *Ephedra* spp. | 39 | 0.54 | 1 |
| *Ajania fruticulosa* (Ledeb.) Poljak. | 39 | 0.24 | 0 |
| *Reaumuria soongarica* (Pall.) Maxim.** | 36 | 0.55 | 1 |
| *Zygophyllum* spp. | 24 | 0.08 | 0 |
| *Bassia dasphylla* (Fisch. et Mey,) O. Kuntze | 23 | 0.08 | 0 |
| *Salsola* spp. | 22 | 0.31 | 0 |
| *Caragana* spp.** | 21 | 0.72 | 1 |
| *Achnatherum splendens* (Trin.) Nevski | 19 | 0.21 | 1 |
| *Lappula* spp. | 16 | 0.03 | 0 |
| *Artemisia xanthochroa* Krasch. | 16 | 0.52 | 0 |
| *Nanophyton erinaceum* (Pall.) Bunge** | 14 | 0.23 | 1 |
| *Scorzonera pseudodivaricata* Lipsch. | 11 | 0.02 | 0 |
| *Oxytropis aciphylla* Ledeb. | 10 | 0.02 | 0 |
| *Convolvulus ammanii* Desr. | 10 | 0.05 | 0 |
| *Halogeton* spp. | 10 | 0.02 | 0 |
| *Iris lactea* Pall.* | – | – | 1 |
| *Juniperus sabina* L.* | – | – | 3 |

($F_{2,84}$ = 0.26; $P$ = 0.77). Only the herbaceous layer biomass differed between sampling periods, being twice as high in September 2018 compared with June 2019 and September 2019 ($F_{2,42}$ = 2.56; $P$ = 0.01).

## Discussion

### *Herders' travel mobility patterns, camp selection and use duration varies across seasons*

Our results highlighted that biomass availability was key for herders when leaving the desert-steppe region of the Great Gobi B SPA for higher-elevation sites in summer, similar to travel mobility patterns by herders in the Altay region of China (Liao et al. 2014). Herders stated that in these mountain regions of our study site, nutritious vegetation, cooler climate, fewer biting insects, and access to rivers and streams are available. The latter had also been identified as important by Ono and Ishikawa (2020). Traditionally, herders in Mongolia travel between spatially fixed winter (Lkhagvadorj et al. 2013) and more flexible spring, summer, and autumn camps based on the availability of forage, water, and shelter from adverse environmental condition (Behnke et al. 2011). In our interviews, herders claimed that moving to spring camps was primarily motivated by early snow melt and sprouting of fresh vegetation, which we could also show through higher-than-average EVI values at these sites. Spring camp locations were mainly selected close to water, where green-up happens early, and in sheltered areas to protect newborn livestock from extreme temperatures, which was also found by Behnke et al. (2011). On the basis of interviews, pastoralists selected autumn camps in areas with higher biomass availability for livestock to gain weight through high-quality forage before the winter months, similar to Behnke et al. (2011) in the steppes of Mongolia. While spring and autumn camps were changed more often in our study, being open for all herders without any registration requirement according to Ono and Ishikawa (2020), winter camps of fixed locations were officially allocated to individual herder families and often marked by stone corrals (Lkhagvadorj et al. 2013). For the winter camp selection, biomass availability was not the primary concern; rather, other factors like shelter and availability of snow providing drinking water were key, according to our focus group interviews. We found that herders in the Great Gobi B SPA shifted their camps frequently, on average 9 times per year. Some of the recorded

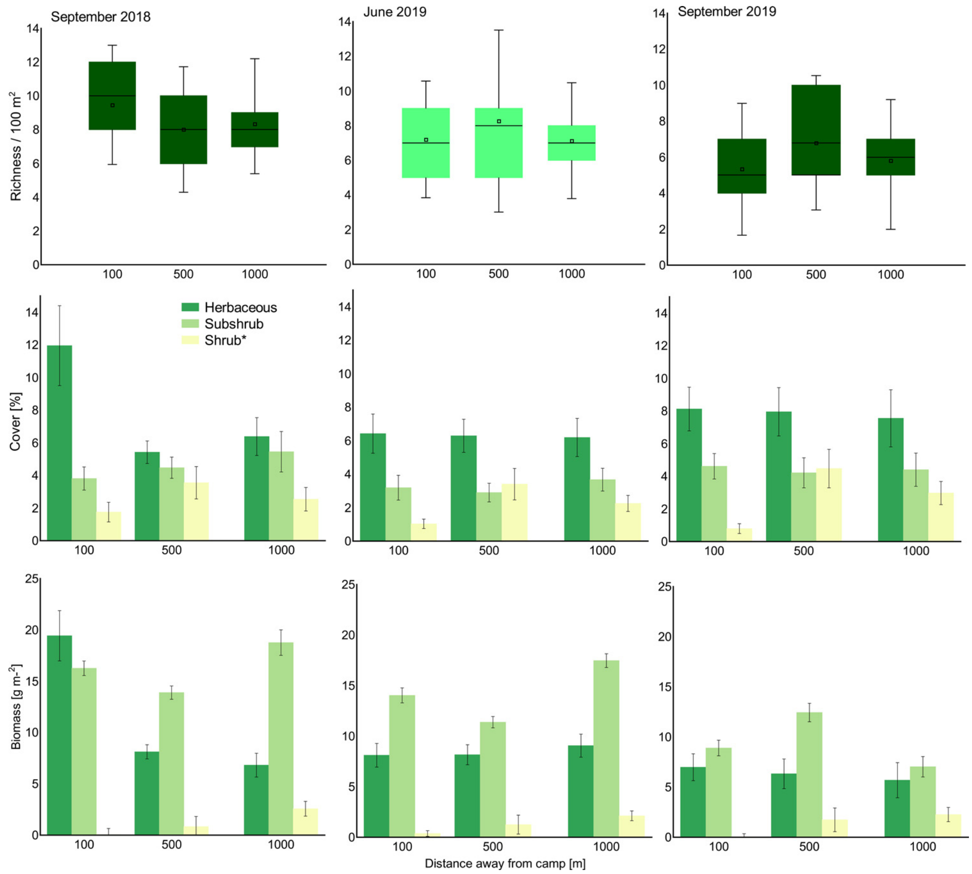


**Fig. 6.** Vegetation characteristics at different distance intervals from the herder camps**.** Vegetation data around intermediate and winter camps ($N = 45$) in three different seasons (September 2018, June 2019, and September 2019) along gradients away from the camp (distance classes: 100 m, 500 m, and 1 000 m). **a,** No. of species (richness) counted per 100 $m^2$ are shown as boxplots. Ranges from 25% to 75% quartile show the mean (square inside boxes) and median (line inside boxes). Whiskers indicate standard deviations. **b,** Mean (± standard error) plant cover per 100-$m^2$ plot of herbaceous (grasses, annual and perennial forbs) plants, subshrubs, and shrubs given in percentage. **c,** Mean (± standard error) biomass per 100-$m^2$ plot of herbaceous (grasses, annual and perennial forbs) plants, subshrubs, and shrubs given in gram per $m^2$ of dry matter. *Shrub biomass solely measured of the species *Ephedra przewalskii* and *Ephedra equisetina Bunge*.

camps were used 2 or 3 × by herders during the monitoring period, especially the intermediate camps in spring and autumn. In summer, the hot Gobi plains were not used by herders and vegetation could recover. Our observed mobility of herders can strongly reduce vulnerability to forage shortage (Liao et al. 2014). Overall, we found that herders stayed longest at their winter camps, directly followed by summer camps, and shortest camp use in spring and autumn, similar to results reported by Lkhagvadorj et al. (2013). In the Mongolian province of Bayankhongor, herders move only among three seasonal camps and stay on average 6 mo at the same winter camp. Some herder families do not move at all due to socioeconomic factors (Ahearn 2018).The highly fluctuating resource availability in an arid region like the Great Gobi B SPA, in contrast, likely forces herders to move much more frequently compared with other arid regions globally: herders in South Africa rotate 2–4 × per year, mainly between summer and winter camps, following a dry and rainy season pattern (Michler et al. 2019; Samuels et al. 2019). In northern Pakistan, herders traditionally change between winter and summer pastures, while they change summer camps 2–3 × (Joshi et al. 2013). Our results showed that herders in the Dzungarian Gobi followed a four-season travel mobility pattern, similar to pastoralists in Western Mongolia and the Chinese Altay region (Joly et al. 2013; Liao et al. 2014), and we highlight that this might strongly contribute to a sustainable grazing management, not resulting in shifts in species composition or degradation. To maintain this ecological sustainability, frequent camp shifts and extended travel mobility patterns should be encouraged, especially on pastures in and around protected areas.

### *Herders choose mainly* Stipa *spp. plant communities for their camp selection*

In our study, herders classified different suitable habitats in the landscape as was expected based on their TEK to meet the nutritional needs (Meuret and Provenza 2015). Our nutritional analyses confirmed the herders' TEK and showed that they selected the most nutritious grass communities composed of *Stipa* spp. as pastures for their mixed livestock herds, in line with findings by Fernandez-Gimenez (2000). We observed for these communities a lower CP and higher-fiber contents with advancing growing period, indicating decreasing digestibility, similar to findings in the Inner Mongolian steppe (Glindemann et al. 2009; Hao et al. 2013). Both vegetation quantity (Joly et al. 2013) and quality (Beher 2014) seem to be important in arid environments. Our results confirm that herders choose grazing areas high in both biomass and nutritional quality. Herders in western Mongolia also were shown to prefer *Stipa* spp. for their summer pastures (Joly et al. 2013), with higher protein contents compared with other common Mongolian forage grasses (Jigjidsuren and Johnson 2003). High nutritional quality of forage plants is often found on pastures with low forage availability, which is particularly important in arid regions (Shi et al. 2013), such as the Great Gobi B SPA. Hence, these ecosystems are highly fragile and livestock grazing must be maintained on a low and ecologically sustainable level, which does not result in degradation or a shift in plant species composition.

*Limited evidence for grazing gradients around livestock camps in the Dzungarian Gobi is likely linked to the high mobility of local herders*

Our results highlight highest livestock use intensities closer to camps, which is generally associated with high grazing intensity, trampling, and nutrient input through urine and dung (Andrew 1988; Sasaki et al. 2008a; Hess et al. 2020).While this long-term and high-intensive grazing pressure around camps often leads to rangeland degradation, especially in arid regions (Vetter 2005), we found limited evidence for signs of degradation around our camps. We found that livestock in the Great Gobi B SPA spent between 13 and 17 h of the day within 100 m around the camps, and livestock grazed generally up to a 5-km radius around the camps. Similar to our findings, cattle herds in Cameroon had a grazing radius of around 4 km (Moritz et al. 2010), whereas the maximum distance of sheep and goat herds away from camps in Namaqualand of South Africa was around 2 km (Samuels et al. 2007; Michler et al. 2019). In winter, grazing pressure in the distance radii > 100 m was about the same as in spring and autumn, although livestock herds stayed almost twice as long at the winter camps. During winter, livestock move and graze less because of shorter days and cold temperatures. Reduced grazing activity and walking distances during winter were also observed in yaks in the Qinghai-Tibetan plateau under extreme winter conditions (Liu et al. 2019), and forage intake by cattle in Montana was found to be reduced during winter (Adams et al. 1986). Research shows that herders who frequently change their camps with their livestock can make better use of pastures closer to their camps (Liao 2018), compared with more sedentarized herders who have to extend their daily grazing distances when forage resources get scarce (Butt et al. 2009). It must be stated that our study did not take the herd size and respective stocking rate into account; instead, livestock use intensity was calculated as hours spent per ha on an average visitation period, used as a measure to relate to vegetation. Liao et al. (2014) reports a negative correlation between forage availability around winter camps and movement distance, especially in arid areas on overall lower altitudes, and a plant species shift toward more unpalatable annual and perennial forbs was observed around herder camps in the provinces of Mandalgobi and South Gobi of Mongolia by Sasaki et al. (2008b). However, in our study, we did not find grazing gradients for plant species richness and biomass across camps, and only shrub cover showed a significant increase farther away from the camps. We acknowledge that our study only spanned 2 yr, within which recent long-term grazing effects on plant species richness and biomass are likely not visible, and we recommend regular pasture monitoring, which is crucial for long-term pasture health. In Namaqualand of South Africa, where grazing radii are smaller compared with the Great Gobi B SPA (Samuels et al. 2007), vegetation characteristics in the vicinity around camps are negatively influenced due to intensive livestock use intensity (Michler et al. 2019). Our results are similar to other Mongolian studies that reported higher annual and perennial forb cover close to camps, corresponding to higher dung densities and, therefore, higher nutrient inputs (Sasaki et al. 2008b, 2012; Jamsranjav et al. 2018). As livestock spent around half of the day closest to the camps in our study, the nutrient inputs through dung and urine were most likely high, which favors certain plant species such as *Halogeton* spp., a salt-tolerant halophyte (Wang et al. 2015), poisonous to livestock (Li et al. 2021), which we often found directly adjacent to the herder camps. We highlight that potential plant species diversity shifts along the gradients is an important factor (Sasaki et al. 2008b) and should be studied more in long-term studies in the Great Gobi B SPA.

Despite the large differences in livestock use intensity, which can be assumed to correlate with grazing intensity, trampling, and nutrient intake via urination and defecation, differences in plant species richness, biomass, and cover were minor across distance radii. However, particularly biomass and cover were more strongly related to monthly precipitation than distance categories. Moderate livestock grazing impacts have been seen in the Mongolian desert-steppe (Sasaki et al. 2008a; Wesche et al. 2010; Jamsranjav et al. 2018), but our findings suggest that precipitation might be the overriding factor influencing vegetation quality and quantity, similar to Fernandez-Gimenez and Allen-Diaz (1999) and Wesche et al. (2010). We base this assumption on the fact that the differences in biomass availability were greater between sampling periods than across distances away from camps. The nonequilibrium system of the Mongolian semideserts and deserts indicates that precipitation is influencing vegetation parameters much more than grazing intensity (Fernandez-Gimenez and Allen-Diaz 1999). However, our study only spanned 2 different yr with high annual precipitation differences and calls for more long-term vegetation monitoring in this region.

We also realized that overlaps between grazing sites of different herders occurred. Hence, the grazing intensity and pressure in the Great Gobi B SPA might be even higher than shown by our data. Still, in our study, no significant grazing gradients around herder camps were detected, indicating that travel and grazing mobility patterns by herders of the Great Gobi B SPA are well adapted to biomass availability.

In conclusion, our results showed that frequent changes and long travel distances, both between camps and around camps, are crucial for rangeland health. However, recent declines in pastoral mobility will negatively influence pastureland sustainability and result in land degradation (Liao et al. 2020). To maintain suitable pastures for livestock while conserving the flora and fauna in and around the Great Gobi B SPA, herders' mobility should be encouraged. Further, travel and grazing mobility patterns must be monitored regularly to maintain healthy rangelands, especially during forage shortage in dry periods.

## Implication

The Great Gobi B SPA is a strictly protected area conserving biodiversity of flora and fauna, where in the limited-use and buffer zones, nomadic herders seasonally use the natural resources. Globally, pastoral movement patterns are declining, but in this system, mobility is still practiced on a large scale with limited evidence for pasture degradation. However, considering the increasing livestock numbers and climate change in Mongolia, pasture management is crucial and regular monitoring and control mechanisms of livestock use intensities in combination with vegetation assessments are needed. Our study only spanned 2 yr, within which slowly changing patterns in plant species richness or biomass due to grazing influence are likely not visible. Nevertheless, our combination of GPS tracking data, detailed vegetation analyses, and herders' TEK highlights the importance of interdisciplinary work to understand pastureland management and vegetation responses, especially in a strictly protected area. Our study further shows that traditional pastoral systems can be practiced within protected areas, as long as mobility of herders is maintained and those patterns are monitored and regulated according to biomass availability, especially in times of forage shortage.

## Declaration of Competing Interest

None.


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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2022.03.006.

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