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ORIGINAL ARTICLE

To move or not to move—factors influencing small-scale herder and livestock movements in the Dzungarian Gobi, Mongolia

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Abstract

In Mongolia, where nomadic pastoralism is still practiced by around one-third of the population, increasing livestock numbers, socio-economic constraints and climate change raise concerns over rangeland health. Little empirical evidence explains what triggers camp moves of pastoralists in the Dzungarian Gobi in Mongolia, which factors influence grazing mobility around camps, and how altitudinal migration benefits small livestock. We combined GPS tracking data of 19 small livestock herds monitored from September 2018 to April 2020 with remotely sensed climate and environmental data. We used general linear-mixed models to analyse variables influencing camp use duration and daily mobility patterns. To understand the importance of the altitudinal migration, we compared climatic conditions along the elevation gradient and looked at seasonal body weight changes of small livestock. We found that available plant biomass and season best explained camp use duration. Daily walking distance and maximum distance from camp increased with camp use duration. Pasture time increased with increasing biomass and rising temperatures. We conclude that herders in the Dzungarian Gobi have optimized pasture use by reacting to changes in biomass availability at landscape and local scale, and by embracing altitudinal migration. Flexibility in grazing mobility seems to have enabled local herder communities to practise sustainable pasture use. Maintaining this mobility will most likely be the best strategy to deal with environmental change under the current climate change scenarios.

Keywords Altitudinal migration · Enhanced Vegetation Index · GPS tracking · Grazing mobility · Mongolia · Pastoralism

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Introduction

Mobility is a well-adapted strategy of pastoralists and has been practiced globally for millennia to utilize fluctuating spatial and temporal forage and water availability (Coughenour 1991; Hogg 1992; Liao et al. 2017). However, socio-economic changes, globally increasing livestock numbers (Thornton 2010) and climate change (Christensen et al. 2004; Crook et al. 2020; Godde et al. 2020), have drastically reduced herder mobility, thereby threatening rangeland health and reducing the resilience of local pastoral communities to environmental changes (FAO 2023).

In Mongolia, 80% of the land is used for extensive grazing (Angerer et al. 2008), with about one-third of Mongolia's population still practicing a pastoral livelihood strategy (Mongolian Statistical Information Service 2022). However, herders no longer herd livestock for subsistence, but rather aim for a modern life in a market economy. As a consequence, livestock numbers in Mongolia have rapidly increased over the last 30 years (Lkhagvadorj et al. 2013) and have reached record numbers of over 70 million livestock heads (Mongolian Statistical Information Service 2022). In the Gobi regions, cashmere provides the main cash income for local herders and cashmere goats have become the dominating livestock (Berger et al. 2013). Grazing at high livestock intensities is seen as a main driver for rangeland degradation (Brown 2020), potentially leading to ecological and cultural tipping points (Fernández-Giménez 2017). Consequently, understanding herd movements and herder's decisions about when and where to move livestock herds are an important prerequisite for developing policy and management recommendations aiming to maintain rangeland resilience. In the Gobi region, changing climate in terms of increasing temperatures, altering rainfall patterns and an increase in extreme winter events (Han et al. 2021) has already influenced herder livelihood strategies (Mijiddorj et al. 2019, 2020). In particular, younger herders and herders with livestock herds too small to maintain their livelihoods move to urban areas (Mijiddorj et al. 2019).

Herders in the Dzungarian Gobi, in SW Mongolia, are still highly mobile, changing seasonal camps on average 9 times per year, moving 70 to 125 km between most distant camps (Michler et al. 2022). Camp selection seems mostly linked to biomass availability during spring, summer and autumn, while during winter, additional requirements like sheltered places with access to snow influence site selection (Michler et al. 2022). Despite a steep gradient in grazing intensity around herder camps, there is limited evidence for a corresponding gradient in plant species richness, biomass and cover on the Gobi plains (Michler et al. 2022). This suggests that herders leave their camps before the pasture is depleted. *We, therefore, expected that (1) herder's camp use duration primarily depends on biomass availability, and further tested if season and/or herd size also influenced the duration herders spent at single camps*, assuming that larger herds remove more vegetation and deplete resources more quickly than smaller herds. During winter, when snow is the primary source of water for livestock and people, *we expected that (2) moves into the winter camps are linked to the arrival of a lasting snow cover* (Behnke et al. 2011).

Rangeland studies in Mongolia focused widely on how livestock impacts the ecological state of pastures, but little on how pasture biomass effects livestock mobility (Fernández-Giménez et al. 2018). Herders who change camp sites frequently can make use of high biomass availability close to their camps (Liao 2018). More sedentary herders, on the other hand, have to lead their livestock further away in order not to deplete the pasture (Butt et al. 2009). *We hypothesized that (3) daily walking distance and daily maximum distance from camp are shorter when biomass availability is higher and herd size is smaller. Further, we expected (4) pasture time, daily walking distance, and maximum distance from camp to increase with increasing duration of camp use and larger herd size. We further expected that (5) pasture time, daily walking distance, and maximum distance from camp are primarily influenced by temperature on the Gobi plains and that the influence of temperature there is positive.* In summer, small livestock species of the temperate zones are sensitive to heat stress and will reduce their grazing activity when temperatures exceed the optimal temperature range for small livestock resulting in costs for thermoregulation (Joy et al. 2020; van Wettere et al. 2021). In winter, livestock faces the opposite challenge and will save energy during cold periods, by moving less. *We also tested whether (6) a higher goat to sheep ratio has an influence on herd mobility, as goats walk more than sheep* (Evangelou et al. 2014). To illustrate daily and annual mobility patterns, we additionally present data on small livestock speed as proxy for daily activity and total cumulative annual distance for overall annual mobility.

The situation in the Dzungarian Gobi is special relative to other parts of the Gobi, as local herders not only change camps within the Gobi plains, but additionally embark into an altitudinal migration to the Altai highlands in summer (Michler et al. 2022). In higher elevations, plant phenology is delayed and allows to access newly emerging, nutritious vegetation over a longer period (Albon and Langvatn 1992). In the Gobi, extreme climatic conditions with an up to 80 °C temperature difference between summer and winter (Brown 2020), and limited water availability, have far reaching consequences for seasonal pasture resources and livestock energy expenditure (Nardone et al. 2006; Horie et al. 2023), which ultimately impacts livestock fitness. We, therefore, used body weight as a proxy for small livestock fitness to understand the influence of altitudinal grazing and the overall suitability of this grazing regime for small livestock production. *We (7) expected to see body weights of small livestock in the Dzungarian Gobi at the higher end of the spectrum typical for Mongolia.*

Our study used high-resolution GPS data of 19 herds monitored over 20 months and combined it with remotely sensed climate and environmental data. Our data provide information on how grazing mobility can combat environmental change caused by pasture depletion and degradation.

Material and methods

Study area

Our study was conducted in the Great Gobi B Strictly Protected Area (SPA) in southwestern Mongolia from 2018 to 2020. Established in the year 1975, the protected area covered 9000 km^2 at the beginning of the study, but was extended to twice the size in 2019 (Sansarbayar 2019; Fig. 1). The Great Gobi B SPA is bordered by the Altai highlands in the North and by a chain of smaller mountains along the international border with China in the South, and belongs to the Dzungarian Gobi. The continental climate is characterized by temperature differences of up to 80 °C with long, cold winters with temperatures as low as – 40 °C and short, hot summers with temperatures as high as + 40 °C and an average precipitation of 100 mm per year (Kaczensky et al. 2004). In the desert steppe, plants like *Stipa* spp., *Artemisia* spp. and *Ajania* spp. dominate, whereas in the desert *Haloxylon ammodendron*, *Ephedra przewalskii*, *Reaumuria soongarica* and *Anabasis brevifolia* are most common (von Wehrden et al. 2006). Around 130 herder families and their livestock used the Great Gobi B SPA in its original size during the beginning of this study in 2018 (Michler et al. 2022). Herders use the pasture resources of the Great Gobi B SPA about 9 months during winter, spring and autumn and stay on the summer pastures on the alpine meadows of the Altai highlands outside the protected area for 3 months (Michler et al. 2022; Fig. 1).

Most common livestock in the region are, in decreasing order of abundance, goats (*Capra aegagrus hircus*), sheep

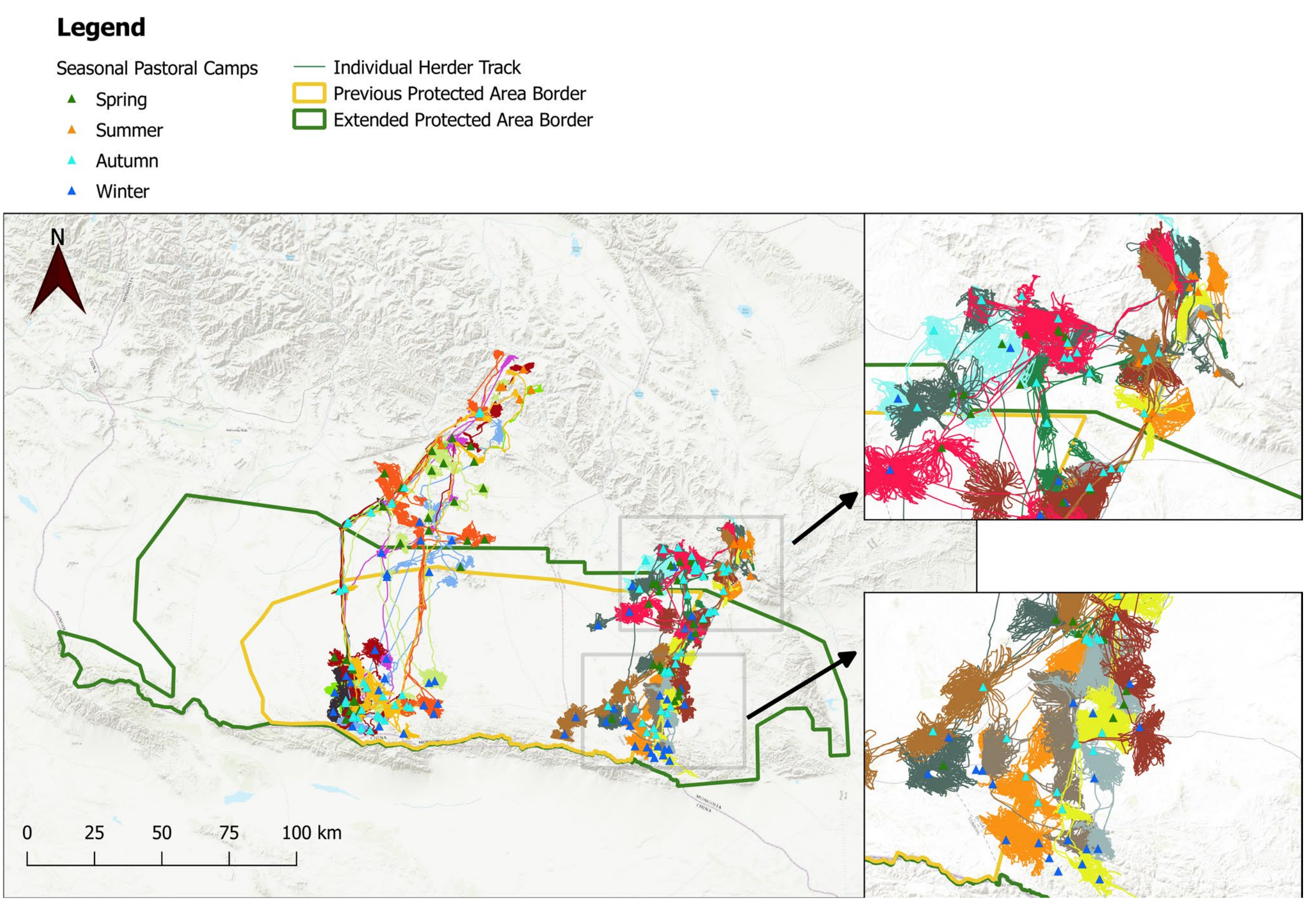

Fig. 1 Small livestock herd tracks over a period of 20 months in the Great Gobi B Strictly Protected Area, Mongolia. Each colour represents a different herd in each region. Zoomed-in areas represent main summer and winter grazing areas

(*Ovis aries*), cattle (*Bos taurus turano mongolicus*), horses (*Equus ferus caballus*), camels (*Camelus bactrianus*) and yaks (*Bos grunniens*; Kaczensky et al. 2008). Our study focused on small livestock (sheep and goats) that pastoralists tend in mixed herds on a daily basis. Herders kept mainly the native Mongolian goat and sheep breeds. Supplementary fodder was rarely provided and if so, only in very limited quantities during winter (personal observation).

During our study, we used climate data (monthly mean temperature and precipitation) around each camp location. We used Google Earth Engine to access the Copernicus Climate Change Service available at 27,830-m resolution (Hersbach et al. 2017). The climate regime at summer camps on the Altai highlands had higher rainfall, lower temperatures and in summer maximum monthly temperatures up to 24 °C. Camps on the Gobi plains had less precipitation, higher temperatures with maximum monthly temperatures up to 30 °C in summer. Snow coverage in the summer camps was shorter in the Gobi plains compared to the Altai highlands. In winter, minimum average temperatures were – 31 °C on the Gobi plains and – 38 °C in the Altai highlands. The total annual precipitation at camps in the Altai highlands was 1.4–1.5 times higher (217 mm in 2018; 203 mm in 2019) than at camps located on the Gobi plains (179 mm in 2018; 141 mm in 2019; Figure S1).

Seasonal and daily mobility data

As described in Michler et al. (2022), we equipped one healthy, adult male goat in each of 19 herds with a lightweight GPS collar (CatLog Gen2, Perthold Engineering LLC, Dallas, TX, USA) across two regions within the Great Gobi B SPA to document mobility patterns of mixed goat and sheep herds. We chose to collar goats for practical reasons as the GPS devices fitted the goats' body better than that of sheep. We deployed the collars over a 20 months period from the beginning of September 2018 to the end of April 2020. Due to costs and amount of time for field work, we only sampled one summer season. However, despite the lack of replication for the summer season, the herds originated from a large geographic area covering a wide range of environmental variation.

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). Camps were then categorized by their season and year of use (SeasonalCamp), as described in more detail in Michler et al. (2022). To understand daily grazing mobility patterns, we identified the camp use duration (CampUse) and calculated the daily walking distance (WalkDist) as the sum of all consecutive distances between GPS fixes per day, and the daily maximum distance from camp (MaxDist) in kilometer. We defined the daily pasture time (PastureTime) as time in hours per day spent by livestock on the pasture (defined as ≥ 100 m away from camp). Thus, PastureTime included not only grazing time, but also all other behaviours on the pasture such as drinking, walking, resting and ruminating. We determined movement activity of livestock herds with speed as proxy for livestock activity in km per hour between 7:00 and 22:00. Slower speed representing times of predominantly grazing and higher speed indicating walking activity. Total cumulative annual distance (TCAD) as proxy for annual total mobility was calculated by summing up the daily WalkDist over 1 year.

Biomass availability around seasonal herder camps

We used the EVI (enhanced vegetation index), as a proxy to estimate biomass availability within 5-km buffers around seasonal herder camps (maximum expected grazing distance from camp, Michler et al. 2022). We obtained the EVI from the image closest in aim to the start of camp use via 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 tested whether CampUse was dependent on biomass availability but excluded the winter season as snow cover does not allow for reliable EVI measurements.

Snow cover as trigger for winter camp moves

To identify whether the arrival of a permanent snow cover triggers herders to move to winter camps on the Gobi plains, we obtained snow cover information for the Great Gobi B SPA from MODIS/Terra Snow Cover 8-Day L3 Global 500m SIN Grid, Version 61 (MOD10A2) from beginning of October until end of March in 2018 and 2020. We used the "maximum snow extent" data over an 8-day period with a 500-m resolution (Hall and Riggs 2021). We defined snow arrival as first permanent snow cover when the maximum snow extent showed snow cover over a period of at least 16 days. Move dates of camps and the first permanent snow cover days were reported in Julian days.

Livestock weight

To understand small livestock weight dynamics, we repeatedly weighed 8 adult goats and sheep (2 males and 2 females of each species) and 4 young of the year (1 male and 1 female each; totalling 228 adults and young in 1 year) in each herd with a hanging scale. The measuring took place in the morning before the animals left the camp for grazing to assure the animals had an empty stomach. As the offspring stay with their mother overnight, adult females did not have full udders. The animals were weighed in spring (April

2019/2020), when the weight is usually lowest after winter, and in autumn (October 2019), when weight is highest after the summer grazing period and before weight loss due to colder weather (Punsalmaa et al. 2013). Goats and sheep were marked with ear tags so that the same animals could be weighed in spring 2019, autumn 2019 and spring 2020.

Statistical analysis

To analyse the influence of EVI, season by year (SeasonalCamp), herd size (HerdSize), herd ratio (HerdRatio; goats/sheep), temperature (Temp) and days sine herders started to use a camp (CampStart) on CampUse, PastureTime, WalkDist and MaxDist, we used generalized linear-mixed models in the package "glmmTMB" (Brooks et al. 2017) of the statistical software R version R-4.0.3 (R Core Team 2020). We derived the candidate models by trying out all possible combinations of all explanatory variables, using the Akaike Information Criterion (AIC; Cavanaugh and Neath 2019). We, further, checked the assumptions for these models like homogeneity of variance, normal distribution and independence (no temporal autocorrelation) of errors. Response distributions of the models were selected based on whether model residuals were normally distributed. Before analyses numeric predictors were standardized as our data showed entirely different ranges of variation.

We considered the following full models with respective response distributions:

- CampUse in response to EVI, SeasonalCamp, HerdSize and HerdRatio (negative binominal distribution)
- PastureTime in response to EVI, SeasonalCamp, HerdSize, HerdRatio, Temp and CampStart (gaussian distribution)
- WalkDist in response to SeasonalCamp, HerdSize, HerdRatio, Temp and CampStart (gaussian distribution)
- MaxDist in response to EVI, SeasonalCamp, HerdSize, HerdRatio, Temp and CampStart (gaussian distribution)

HerdSize and HerdRatio were given in sheep forage units (SFU) with a conversion of 0.9 for goats as goats eat 10% less than sheep (Bedunah and Schmidt 2000). For all models, we included HerderID as a varying intercept representing variation across the 19 herds. We identified the most parsimonious models based on the lowest AIC using the maximum likelihood method (Cavanaugh and Neath 2019).

Results

Seasonal patterns of pastoral camp moves and camp use duration

EVI, SeasonalCamp and their interaction best explained CampUse by herders (Table 1, Figs. 2 and S2). As expected, herders stayed longer at camps with higher biomass, with the effect being strongest in spring and summer. In contrast to our hypothesis, neither HerdSize nor HerdRatio led to more parsimonious models (Tables 1 and S1).

Contrary to our hypothesis that moves into the winter camps are linked to the arrival of a lasting snow cover, we did not find a consistent pattern between the timing herders moved to their first winter camp and the arrival of the first permanent snow cover (Figures S3 and S4). In 2018, 68% of herders moved up to 66 days before the first snow arrived while 32% of herders moved up to 40 days after the first snow has arrived. In 2019, 13% moved up to 16 days before the first snow arrived and 87% moved up to 27 days after snow arrival.

Daily livestock mobility patterns

In line with our hypothesis, WalkDist and the MaxDist were determined by SeasonalCamp and CampStart. Small livestock walked more and further away from the camp with increasing camp use duration, particularly in spring but less strongly in autumn (Table 2, Figs. 3 and 4). However, our results showed that neither EVI, temperature nor HerdSize

Table 1 Top five models that we used to estimate the camp use duration (CampUse) in the Great Gobi B Strictly Protected Area, Mongolia, based on GPS movement data collected in autumn 2018, spring 2019, summer 2019 and autumn 2019. The fixed explanatory variables in the model were enhanced vegetation index (EVI), season by year (SeasonalCamp), herd size (HerdSize) and herd ratio (HerdRatio; goats/sheep) in sheep forage units. Herder ID was included as a random effect in all models

Model	AIC_c	Delta AIC_c	AIC_c weight	Log likelihood
EVI + SeasonalCamp + EVI:SeasonalCamp*	32,169	0.00	1	– 16,075
EVI + SeasonalCamp	32,385	216	0	– 16,186
SeasonalCamp + HerdSize + SeasonalCamp:HerdSize	32,622	453	0	– 16,301
SeasonalCamp + HerdRatio + SeasonalCamp:HerdRatio	32,673	504	0	– 16,326
SeasonalCamp	32,675	506	0	– 16,332

*The division sign (:) represents an interaction between two explanatory variables

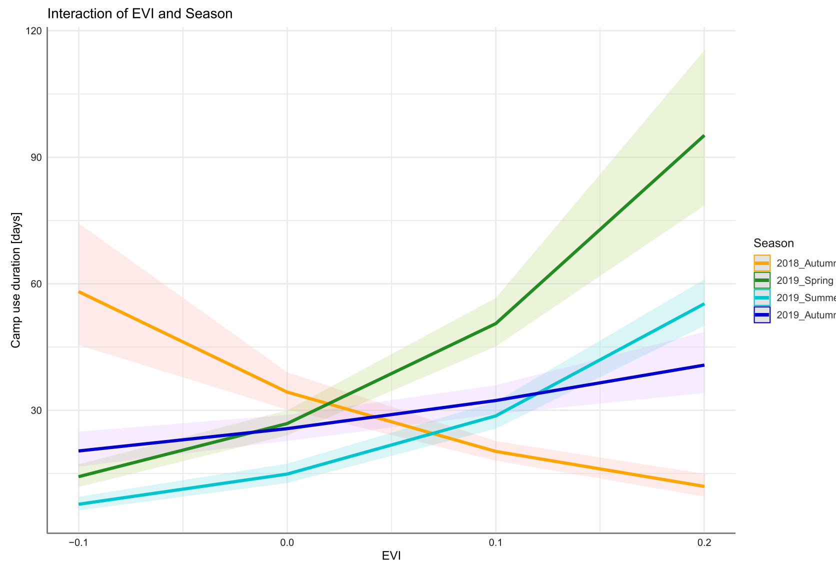

Fig. 2 Predicted interaction of herder camp use duration (days) dependent on enhanced vegetation index (EVI) and season by year (SeasonalCamp). Herder camps were located in and around the Great Gobi B Strictly Protected Area, Mongolia

Table 2 Daily Livestock Movement Patterns: time of the day for average grazing start (in hours) and end measured as first and last GPS point ≥ 100 m away from herder camp for different seasons. Daily pasture time (PastureTime) given in hours per day was calculated as time between grazing start and end. Daily walking distances (WalkDist) and daily maximum distance from camp (MaxDist) for 19 livestock herds monitored from September 2018 until April 2020 in the Great Gobi B Strictly Protected Area, Mongolia

Season	Grazing start time	Grazing end time	PastureTime [h/d]	WalkDist [km/d]	MaxDist [km]
Spring	10:22 ± 01:30	20:26 ± 01:14	10.1 ± 2.2	11.6 ± 3.7	4.3 ± 1.9
Summer	09:58 ± 01:22	21:17 ± 00:47	11.3 ± 1.7	10.2 ± 3.0	3.8 ± 1.7
Autumn	10:23 ± 01:16	19:26 ± 01:23	9.1 ± 2.1	9.0 ± 2.6	3.4 ± 1.3
Winter	11:21 ± 01:13	18:44 ± 01:22	7.4 ± 1.9	7.7 ± 2.5	3.1 ± 1.3

and HerdRatio improved model parsimony (Tables 3, S2 and S3).

As expected, the PastureTime of small livestock was longest in summer, shortest in winter and intermediate in spring and autumn (Table 2). PastureTime was mostly influenced by EVI and temperature (Tables 3 and S4, Fig. 5). PastureTime increased with increasing biomass and rising temperatures. Neither CampStart nor HerdSize and HerdRatio improved model fit.

Small livestock left camps by mid-morning and walked fast towards the most distant grazing point, which they reached around noon. Thereafter, livestock moved slower until the herders turned them back towards the camp in the late afternoon (Fig. 3). Small livestock herds walked an average total cumulative annual distance (TCAD) of 3520 km (range: 1798 to 4120 km).

Livestock body weights

As expected, body weights of adult sheep and goats were at the higher end of livestock weights in Mongolia (Table S5), averaging 50 kg and 63 kg for male and 32 kg and 41 kg for female goats in spring and autumn respectively and 58 kg and 70 kg for male and 42.0 kg and 55 kg for female sheep in spring and autumn respectively. Adult goats and sheep gained on average 18–23% (9–13 kg) of their body weight during summer and lost 11–20% (6–11 kg) during winter. Kids and lambs gained 68–70% (14–25 kg) during summer and lost none or hardly any weight during winter (Figure S5).

Discussion

Camp use duration—the importance of biomass

Our study supported our expectation that herder camp duration increases with increasing biomass availability; the effect was most evident in summer and spring. Surprisingly, the trend was opposite in autumn 2018, when additional rainfall in autumn led to a second green-up and herders moved in their winter camps although pasture around autumn camps was good. Previous work had already established that herders in the Dzungarian Gobi select areas of high biomass for their camp locations (Michler et al. 2022), and together,

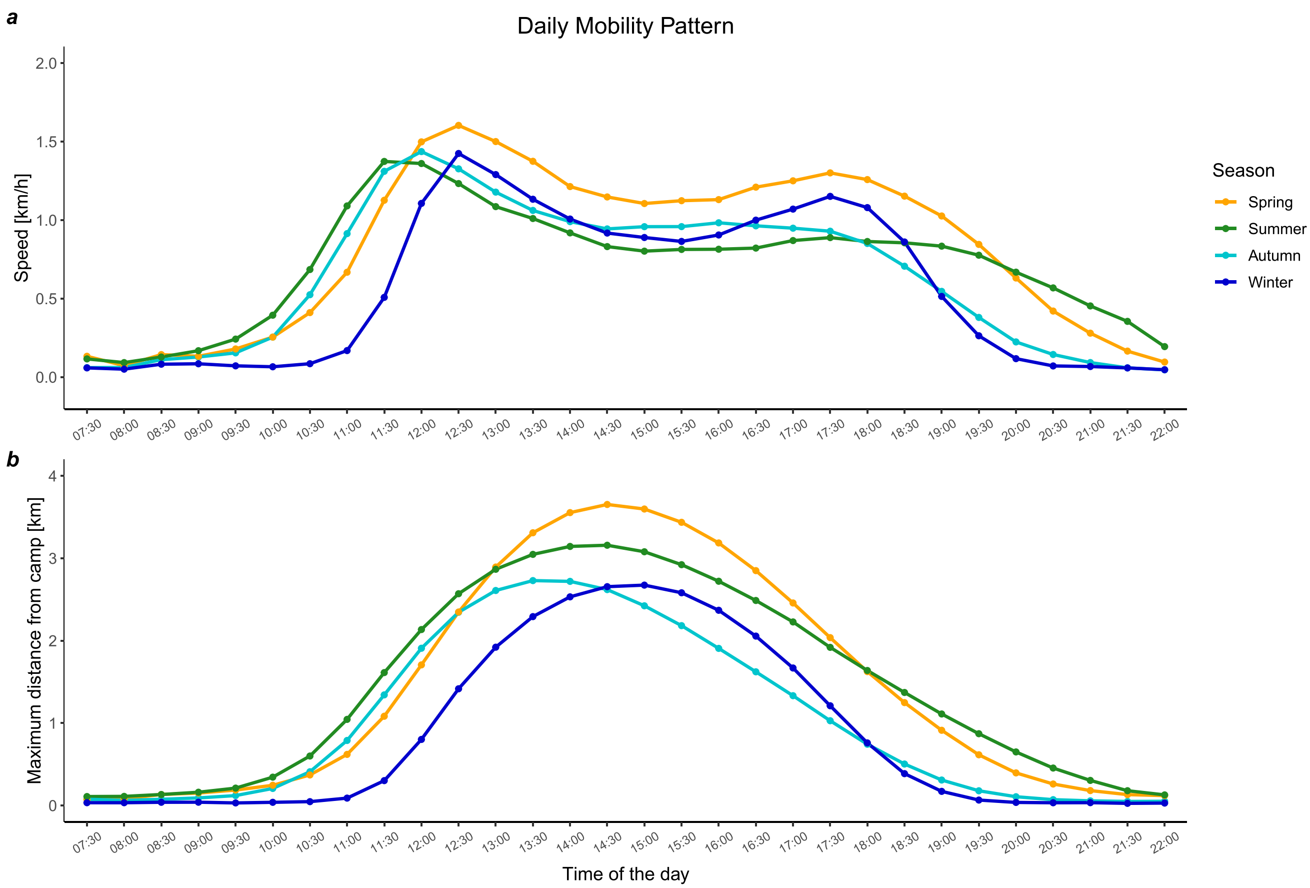

Fig. 3 Daily mobility patterns (speed in km/h (**a**) and maximum distance from camp (**b** MaxDist) in km) of 19 GPS tracked livestock herds in the Great Gobi B Strictly Protected Area, during the years 2018 to 2020 Mongolia

it confirms that herder mobility is strongly linked to biomass availability both at the landscape scale (where to set up camp) and at the local scale (how long to use the pasture around camp). A similar pattern has been shown in other places in Mongolia (Liao et al. 2014).

Contrary to our expectation, the arrival of the first permanent snow cover was a poor predictor for the timing of herders moves to the first winter camp. The arrival dates were also spread over a longer time than we had expected and varied between the years. This might be explained by the importance of biomass for camp use duration, which was also observed in autumn although to a lesser extent than in summer and spring. Informal conversations with local herders further revealed that they postpone moving to winter camps as long as possible if sufficient pasture is available elsewhere and weather conditions allow for it. Our findings contrast the findings of Behnke et al. (2011), who reports that the arrival of snow and colder temperatures trigger moves into the winter camps.

In the Dzungarian Gobi, good winter camp locations are limited, as they need to provide sufficient pasture, shelter and reliable access to snow for water during a period when mobility is lowest (Michler et al. 2022). When moving too late, herders risk getting trapped by high snow in a poorly sheltered camp, which can result in high livestock mortality (Kaczensky et al. 2011). When moving too early, they risk depleting their winter pasture(s), especially in years when pasture productivity is low, or the winter is unusually long. The large variation in the arrival dates seems to indicate that risk assessment happens at the herder level (i.e., based on individual choice), rather than at the level of the community or around a specific date. Since the political change to a democracy in the early 1990s, individual decisions by herders are common in Mongolia. However, to improve rangeland health, communal pasture management decisions are fostered by many governmental and non-governmental organisations (Upton 2008; Kasymov et al. 2023).

Livestock pasture mobility

Sheep and goat in the Dzungarian Gobi have a diurnal grazing pattern characterized by high walking activity in the morning, and grazing activity around noon and in the afternoon, until livestock is slowly walking back to the

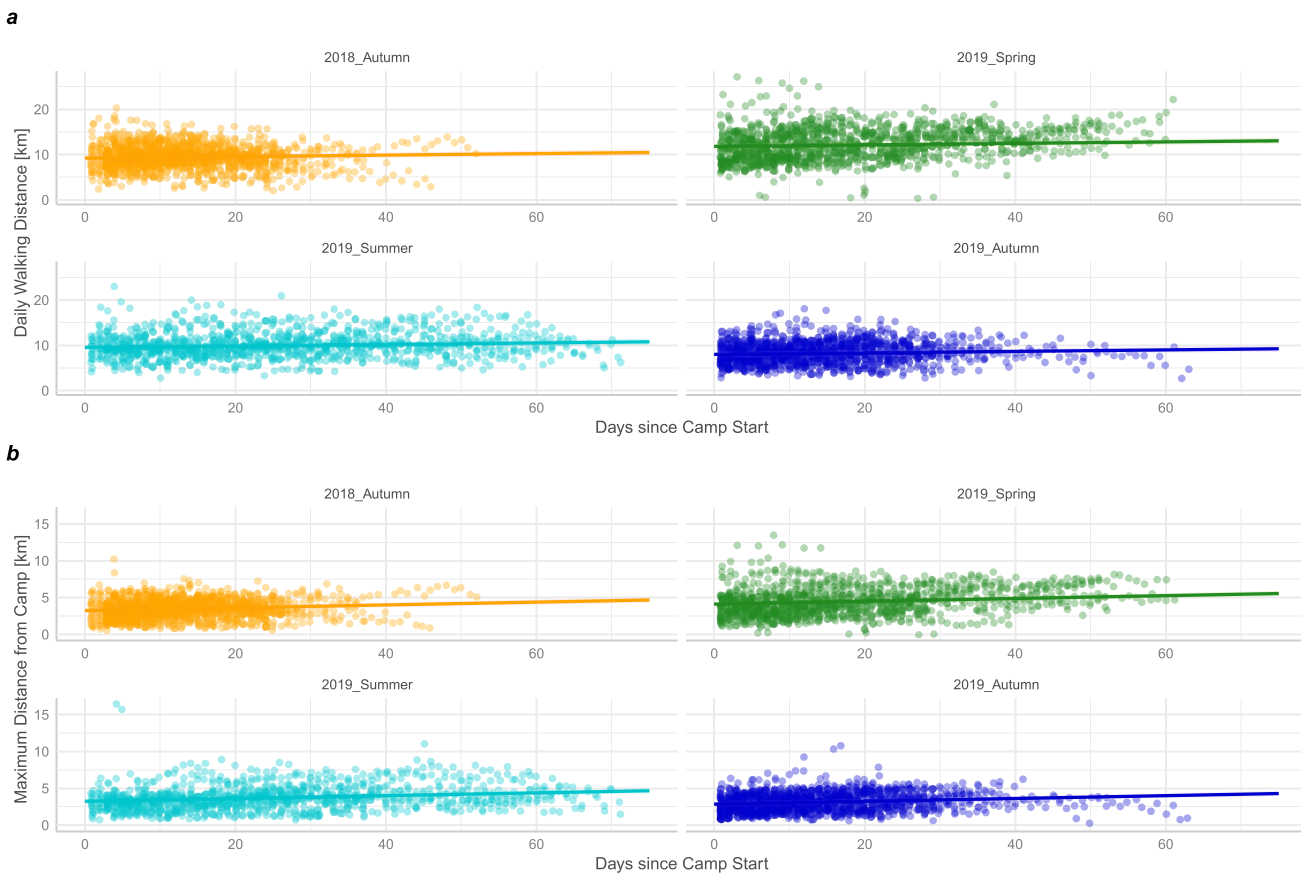

Fig. 4 Daily walking distance (**a**) and maximum distance from camp (**b**) in km ± prediction intervals (lines and shaded areas around) as a function of days since camp start in four different seasons

camp in the evening, typical for tended herds of small livestock in arid systems (Fierro and Bryant 1990; Birrell 1991; Kawamura et al. 2005; Lin et al. 2011; Joly et al. 2013; Jordan et al. 2016). As expected, daily walking distance and maximum distance increased with camp use duration and were influenced by season.

Biomass availability did not influence walking distance, but the increasing removal of biomass through prolonged grazing was most likely the driver behind the positive relationship between camp use duration and the daily walking and maximum walking distances. The increase in walking distance and maximum distance, either caused by the herd because there is less to feed on, or by the herder because the pasture closest to camp no longer provides what the herd needs, may be the cue which triggers the move to a new camp. In Western Mongolia herders report that movement to their summer camps depends on (1) environmental factors like rising temperatures, snow melt and lower biomass at spring camps; (2) behavioural observation of their lead animals and (3) social aspects like moving when the neighbour moves (Altmann et al. 2018).

As we expected, the time small livestock spent on the pasture increased with increasing biomass and temperature. In winter, spring and autumn, temperatures often fall below the critical lower temperature for sheep and goats (Holmes and Moore 1981; Fonseca et al. 2016; van Wettere et al. 2021), so that higher temperatures have a positive influence on pasture time. This positive effect of moderately high temperature on pasture time suggests that herders avoid heat stress for their animals by migrating to higher altitudes. Cool temperatures and long grazing times on high-quality pasture in summer allow small livestock to regain bodyweight and fatten up for the next winter, reaching body weights at the higher end of the scale typical for Mongolia. Although season had no obvious influence on pasture time in our study, biomass availability and temperature were strongly linked to season.

Grazing mobility, presented in our data by daily walking distances and maximum distance from camp, was slightly lower than for sheep and goat herds in other areas in Mongolia and Inner Mongolia (Kawamura et al. 2005; Tsevegemed et al. 2019). This suggests that either

Table 3 Top five models that we used to estimate daily pasture time (PastureTime), daily walking distances (WalkDist) and maximum distance from camp (MaxDist) by small livestock in the Great Gobi B Strictly Protected Area, Mongolia, based on GPS movement data collected in autumn 2018, spring 2019, summer 2019 and autumn 2019. The explanatory variables in the models were enhanced vegetation index (EVI), seasonal camp location in respective years (SeasonalCamp), herd size (HerdSize) and herd ratio (HerdRatio; goats/sheep) in sheep forage units, temperature (Temp) and days since camp use start (CampStart). Herder ID was included as a random effect in all models

Response variable	Model	AIC_c	Delta AIC_c	AIC_c weight	Log likelihood
PastureTime	EVI + Temp	17,058	0	1	− 8524
	Temp	17,192	133	0	− 8592
	Temp + CampStart	17,192	133	0	− 8592
	EVI + SeasonalCamp	17,348	290	0	− 8667
	EVI + SeasonalCamp + EVI:SeasonalCamp*	17,348	290	0	− 8667
WalkDist	SeasonalCamp + CampStart	20,007	0	1	− 9996
	EVI + SeasonalCamp	20,028	21	0	− 10,007
	EVI + SeasonalCamp + EVI:SeasonalCamp	20,028	21	0	− 10,007
	SeasonalCamp + HerdSize	20,029	22	0	− 10,008
	EVI + Seasonal-Camp + Temp + SeasonalCamp:Temp + HerdRatio	20,029	22	0	− 10,008
MaxDist	SeasonalCamp + CampStart	14,869	0	1	− 7428
	SeasonalCamp + HerdSize	14,985	116	0	− 7485
	SeasonalCamp	14,988	119	0	− 7488
	HerdSize + Temp	14,988	119	0	− 7488
	EVI + SeasonalCamp	14,989	120	0	− 7487

*The division sign (:) represents an interaction between two explanatory variables

the pasture in the Dzungarian Gobi is more productive or grazing pressure is lower as only limited access to herders in the protected area is given (Sansarbayar 2019). In a previous study, we showed how long travel distances and frequent camp moves impede pasture depletion (Michler et al. 2022). Total cumulative annual movement distance (TCAD) of small livestock herds averages 3520 km which is almost identical to the average 3464 km of the similar-sized Mongolian gazelle (*Procapra gutturosa*, famous for its large-scale nomadic movements; Joly et al. 2019; Dejid et al. 2022). The high overall mobility of tended small livestock herds in combination with the lack of evidence for obvious pasture degradation around herder camps in the Dzungarian Gobi (Michler et al. 2022) suggests that herders move camps before overgrazing the pasture around their camps. Within the Dzungarian Gobi environmental change through pasture degradation is not evident yet (Michler et al. 2022), however, socio-economic changes along with increasing livestock numbers are raising concerns over pasture health potentially leading to alterations of the environment (Michler et al. 2023, in revision).

Contrary to our expectation, herd size and herd ratio did not seem to affect herd mobility patterns, which was most likely due to our small sample size of 19 herds (Table S6). However, if herders do not adapt camp use duration and grazing mobility as a function of herd size, grazing pressure intensifies. Considering the ongoing increase in livestock numbers in Mongolia (Mongolian Statistical Information Service 2022), the impact of larger herd sizes on mobility pattern and rangeland health needs to be closely monitored.

Advantage of altitudinal migration

In Mongolia, mountain ranges are used as traditional summer pasture where available (Retzer et al. 2006), as it allows for optimal resource use due to different climate conditions and pasture dynamics along the elevational gradients (Hsiung et al. 2018). Differences in the temperature and precipitation regime around herder camps on the Gobi plains and the Altai highlands clearly show that by migrating to higher altitudes, herders are able to escape the worst of the summer heat. Due to the higher precipitation, they also gain access to pastures with higher biomass availability (Retzer et al. 2006; Michler et al. 2022).

Both, very high and very low temperatures entail high energy expenditure (Arnold et al. 2004; Trondrud et al. 2021). To survive the very cold winter months in Mongolia, livestock therefore has to gain sufficient fat reserves during the short vegetation period. Therefore, body weight is an important indicator of the animal's fitness and in livestock is linked to economic value. Adult Mongolian native sheep and goats in the Dzungarian Gobi were slightly heavier than the Mongolian average and at the higher end of some other breeds common in

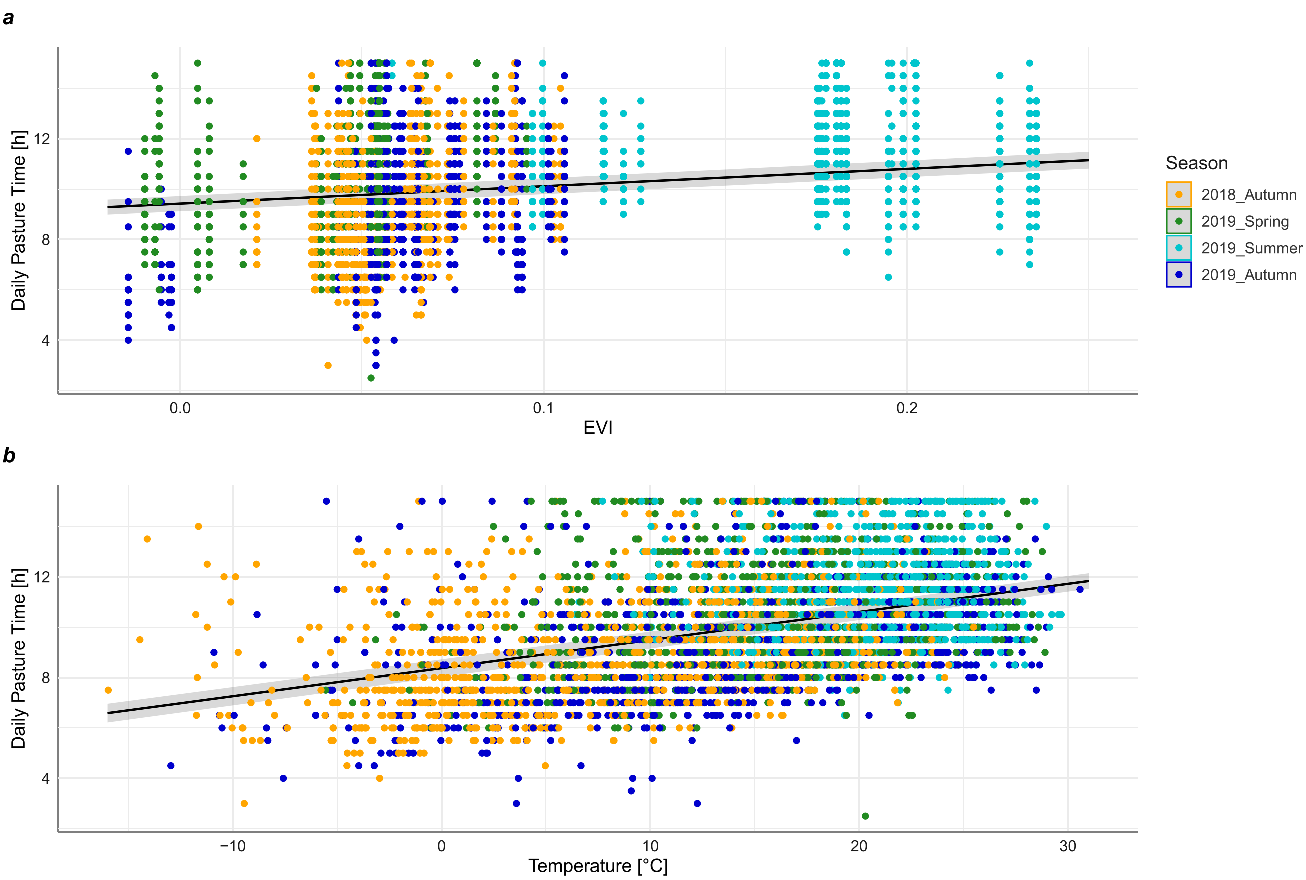

Fig. 5 Daily pasture time (PastureTime; black lines) in hours of small livestock ± prediction intervals (grey areas) in relation to biomass (EVI; **a**) and temperature (in °C; **b**) shown for season and year in the Great Gobi B Strictly Protected Area, Mongolia. Each colour represents different seasons

the region (Table S5; Jamsran et al. 2018). They lost less body weight (11–20%) during winter than sheep and goats in other parts of Mongolia (21–30%; Jargalsaihan et al. 2021; Tumurjav 2003). In areas with extreme temperature differences, thermal stress is a concern for livestock production. Heat-stressed livestock tend to seek shelter and reduce activity to minimize costs for thermoregulation. This reduces grazing time which in turn results in lower body weights, poorer reproduction and higher mortality (van Wettere et al. 2021; Goma and Phillips 2022).

The altitudinal migration of herders between the Gobi plains and the Altai highlands reduces exposure of livestock to very high summer temperatures on the Gobi plains and very low winter temperatures in the Altai highlands. Furthermore, altitudinal migration allows livestock a longer window of access to highly nutritious young vegetation by following vegetation green-up referred to as surfing the "green-wave" (Bischof et al. 2012; Fryxell and Avgar 2012). This illustrates how the altitudinal migration benefits small livestock fitness and shows that this grazing regime is benefitting livestock production.

Conclusion

We found that camp use duration and the decision to move camps are primarily driven by biomass availability and season. By embarking on altitudinal migration, herders avoid the extreme summer heat of the Gobi plains and the extreme winter cold of the Altai highlands. This allows small livestock to obtain above average body weights compared to other regions in Mongolia. These results in combination with the previously documented frequent camp moves and the lack of evidence for obvious pasture degradation in the Dzungarian Gobi suggest that herders in the Dzungarian Gobi still operate well below the irreversible threshold of ecological change. However, the continuously rising livestock numbers are of concern for rangeland health and wildlife conservation, especially because winter and many of the spring and autumn pastures of local herder families fall within the Great Gobi B Strictly Protected Area. Although local herders and wild herbivores have coexisted on shared pastures for millennia, the combination of ever-increasing livestock numbers and climate change can be expected to reduce resilience of both local herders and wildlife to environmental change. To counteract this threat, management should aim to maintain the high level of mobility of domestic and wild herbivores and regulate stocking densities.

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Data Availability Data will be made available upon reasonable request.

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