

The changing role of bio-physical and socio-economic drivers in determining livestock distributions: an historical perspective from Kazakhstan

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Abstract

Despite worldwide trends towards intensive livestock production, some extensive systems retain comparative advantages, particularly in arid regions. In such variable environments, the extent to which natural pastures can contribute to animal nutrition depends on how livestock are distributed with respect to forage resources in time and space. Animal movements are governed by the interactions of bio-physical, economic and institutional drivers and constraints, all of which are dynamic in time and space, making disentangling the relative importance of different drivers challenging. We examine a large migratory system in central Kazakhstan, using unique long-term data in the context of major socio-economic change, to explore the changing role of bio-physical variables in shaping livestock movement. We explore the determinants of livestock distributions across broad ecological zones in pre-Soviet, Soviet and current time-periods. Differences between zones were examined using Soviet literature, recent interviews with herders and satellite imagery. At the site level, we combined data on livestock locations and density for 2003 and 2012 with bio-physical data from remote sensing. Taken together, these data suggest that the importance of bio-physical variables in determining inter-zonal movements and their timing have decreased over time, whilst the significance of economic and institutional factors appears to have increased. Although resource density may still be a "pull factor" driving movement in some situations, there is evidence that "push factors" such as snow cover, presence of harmful insects and temperature combine with herd size to influence movements between zones, leading to a reduction in the matching between grazing distribution and forage resources. These changes reflect the move to livestock management by small household units owning highly variable numbers of animals. They are representative of global trends in pastoral systems, in which reduction in mobility is linked to declines in collective management institutions, increasing integration of pastoralists in the wider economy and land tenure change.

Keywords

Livestock; Pasture; Central Asia; Migration; Human-nature interaction

1. Introduction

1.1 Extensive pastoral systems: global trends

Recent decades have seen a global trend towards intensification of livestock production systems (de Haan et al., 2010, FAO, 2009). Yet in arid regions, extensive systems have a comparative advantage, as they require few inputs and can produce value from land which cannot be used for other purposes. Moderately stocked, well managed grazing systems are compatible with environmental goals such as carbon sequestration, and do not replace other ecosystems by logging, draining or ploughing (Toutain et al., 2010). Natural forage production on arid rangelands is highly variable in space and time; the potential economic and environmental advantages to be gained from pastoral land use are thus dependent on livestock movement (Coughenour, 2008a). Yet such systems have seen a cessation or shortening of livestock migrations in recent years (Reid et al., 2008). Pastures have become increasingly fragmented and even fenced; some areas are overused whilst others have been abandoned. This has implications for ecosystem function and resilience, livestock productivity and the sustainability of rural livelihoods from Africa to China (Boone and Hobbs, 2003, Li et al., 2007, Rohde et al., 2006).

Influenced by insights into the non-equilibrium nature of rangeland dynamics (Behnke et al., 1993, Ellis and Swift, 1988), these concerns have led to new thinking on appropriate ways to legislate for, and manage, livestock mobility, resulting in the promotion of common property systems and re-examination of open access systems (Turner, 2011). Yet this 'new paradigm' is by no means accepted by all - the perceived environmental and commercial advantages of highly secure individual property rights has underpinned the decision by many governments to promote pasture privatisation programmes. One focus of research informing these debates is the factors which influence animal distributions over the landscape (Behnke et al., 2011, Coughenour, 2008a, Dörre and Borchardt, 2012, Turner et al., 2005, Vanselow et al., 2012). Improved understanding of the natural, economic and political drivers of livestock movement (mediated through pastoralists' decision-making) can inform policies to support sustainable rangeland management.

1.2 Kazakhstan – pasture reserves of global significance

Our study country, Kazakhstan is a rapidly growing developing nation with large oil and gas reserves and a growing demand for livestock products (Government of Kazakhstan and the World Bank, 2004). It is located in one of the few regions of the world where animal feed production actually decreased in recent years, following the post-Soviet collapse in imports and subsidies (de Haan et al., 2010) and a feed deficit is seen as a major factor behind the country's low livestock production efficiency parameters (Government of Kazakhstan and the World Bank, 2004, Tazhibayev et al., 2014). Today the country is modernizing its livestock sector, and in particular beef production, through breed improvements, subsidies on feed prices, and investments in export-oriented feedlots (Ministry of Agriculture of the Republic of Kazakhstan, 2013, 2014). Yet, in these key strategy documents, it is also suggested that pastures may make a critical contribution to cost reduction in the livestock sector. Extensive production, which is dominated by family farms, holding both cattle and 18 million head of small stock, may also become a target for government support. At 1.8 million km², Kazakhstan is ranked fifth in terms of area of grazing land (FAOSTAT, 2015). It has been estimated that within arid pastures, comprising 80% of these grazing lands, natural vegetation comprises over 90% of livestock food intake, and agricultural activities other than livestock raising are marginal or impossible (Thornton et al., 2002). Yet rangeland resources are underutilised - it has been estimated that only about 30% of the total area are currently grazed (Government of Kazakhstan and the World Bank, 2004, Tazhibayev et al., 2014). There is evidence that loss of livestock mobility into remote areas has had negative effects on livestock nutrition (Kerven et al., 2004). Although government policy currently favours intensification, the presence of large areas of abandoned pasture and current debates within Kazakhstan around subsidies, pastoral property rights reform and approaches to supporting mobile pastoralism, make this a particularly interesting case in which to examine the drivers of livestock movement.

1.3 Understanding movement: scale considerations and theoretical frameworks

The majority of investigations which attempt to map and model livestock movement, follow daily grazing trajectories of individual animals moving between patches (Putfarken et al., 2008, Rinella et al., 2011, Senft et al., 1985). In semi-arid and arid systems, in which animals are both herded and restricted to water sources or other ‘central places’, the herd is the unit of interest (Coppolillo, 2001, Coppolillo, 2000, Turner et al., 2005). In these studies, mapping of livestock movements is limited to the daily grazing radius from the central point. Only a small number of studies on domestic livestock have investigated animal densities between multiple central points (Ogutu et al., 2010) at large scales (e.g. McCarthy, 2007, Moritz et al., 2014, Pin-Diop et al., 2007, Vanselow et al., 2012). This between-site level is most appropriate to the understanding and management of entire migratory systems, but most studies at this scale focus on a single component (season or ecological zone) of a larger system.

A framework within which site selection may be considered is the theory of ‘Ideal Free Distribution’ (IFD) which was originally developed to explain wild animal distributions (Fretwell, 1972, Fretwell and Lucas, 1970). This theory predicts that, where movements are not restricted, animals will distribute themselves according to the density of their feed resources, thus ‘matching’ or ‘tracking’ resource availability. Pastoralists having no considerations other than the maximization of forage availability for their livestock might be expected to behave in the same way. The theory thus constitutes a useful null hypothesis when investigating the extent to which livestock mobility is related to resource distribution. Few studies have used the IFD as a framework for exploring the drivers of livestock distributions, with Moritz et al. (2014) a rare exception. That study showed that predictions from the IFD were borne out within a single ecological zone and season. Using IFD as an analytical framework enables the evaluation of the importance of resource distribution in determining site use, in comparison to other factors. In the absence of a control or counterfactual, one way to disentangle the relative contribution of resource distribution over other potential drivers of livestock movement is to explore changes in livestock distributions as potential drivers vary over time, at different spatial and temporal scales (Bassett and Turner, 2007) and such a historical approach is also taken in this paper.

1.4 Study aims and system characteristics

Our major goal is to explore the changing role of bio-physical variables in shaping livestock movement across an entire migratory system. We take advantage of our long-term knowledge of this system to explore the relative influence of different components of resource density and other bio-physical variables on livestock distributions, under radically different economic and institutional circumstances, using IFD as an analytical framework. We firstly conduct a qualitative analysis of historical change in livestock distributions between broad ecological zones, followed by an analysis of more recent monthly site specific data for herds within these zones. This enables us better to understand the drivers of movement between ecological zones over the year, the importance of variability between specific chosen sites within zones and the consequences of historical changes in zonal migration in terms of forage resources foregone.

Central Kazakhstan is the site of an ancient migratory pastoralist system, in which livestock have traditionally moved up to 800 km between five ecological zones, migrating between summer pastures in the north and winter pastures in the south (Kazakh Academy of Sciences, 1980, Mansurova, 1984, Olcott, 1995). In Soviet times, this migration was formalised and constrained, and research into pasture composition and quality (e.g. Kirichenko, 1980, Kurochkina and Osmanova, 1973) was used to inform grazing plans. Following the break-up of the Soviet Union in the early 1990s, livestock numbers collapsed, flocks came under private ownership, and migrations virtually ceased (Behnke, 2003, Kerven et al., 2006, Robinson and Milner-Gulland, 2003b). Today, in a very different economic and institutional context, the set of factors affecting animal distributions, and their relative importance to decision making is very different from that of the past. This system exemplifies the dynamic challenges, benefits and constraints to movement in changing circumstances, and is uniquely well documented, both from Soviet era literature and from our own research

since 1998 (Kerven et al., 2004, 2006, Robinson and Milner-Gulland, 2003b). The study area includes multiple ecological zones used by the same livestock at different times of the year, and the factors determining bio-physical suitability of each zone vary by season. Site selection operates at two levels: between zones and within zones, where a "site" is a well or watering place where livestock are based in a given month or season.

When examining a system such as this, one obvious inference is that animals are distributed in order to track resources most efficiently. Here, this assumption is corroborated by the fact that a wild ungulate, the saiga antelope (*Saiga tatarica*) follows a similar migratory pattern to that observed in pre-Soviet times (Bekenov et al., 1998). However, this is clearly not the whole story, given that the livestock migration has not persisted through changing economic and institutional circumstances; there is also the question as to which natural resources exactly livestock are tracking (e.g. biomass, edibility, water) and how the importance of these different resource types varies by season and year, and at different spatial and temporal scales.

1.5 Specific research questions and hypotheses

Our analyses can be split conceptually into three main parts.

- (i) Firstly, we use Soviet literature to characterise biophysical features of the system, such as climate, vegetation, soils and hydrology (section 3.1). We then examine the drivers and distributions of livestock in pre-Soviet times and under the Soviet system of high-density planned stocking (section 3.2). Here, our information on livestock distributions and environmental variables is limited to the identity of the ecological zone in which animals were located in each month or season. If ideal free processes are operating, then we would expect to find that measures of vegetation quantity (or quality) are highest for each zone in the season during which that zone is used by livestock. It is also possible that, during the Soviet period, when livestock numbers reached historical highs, that resource depletion processes may have operated to drive movement. These questions are summarised as hypotheses 1-3 in Table 1 and addressed using descriptive data on the environmental and biological characteristics of ecological zones from the Soviet literature, remote sensing indices and material on movement decisions from Soviet sources.
- (ii) Secondly, we use spatially explicit datasets from 2003, when livestock numbers were near their nadir, and from 2012-2014, following some recovery under a new economic and institutional regime, to examine the modern drivers of livestock distributions in more detail. Here, we have *site specific* livestock location data for each month of 2003 and 2012, complemented by equivalent site-level environmental data from satellite imagery. We present these recent livestock distributions together with a description of the new economic and institutional conditions in which herders now find themselves in section 3.3, and ask whether broad inter-zonal use reflects forage resources in comparison to the previous periods already treated (section 3.4). We then go on to examine forage resources at the *site* level: pastoralists are still expanding into empty areas - thus the system is not yet approaching a dynamic equilibrium between grazing distribution and vegetation production because many sites are 'free'. Herders may be able to select key sites possessing an attractiveness not apparent from generalised zonal characteristics. For this period in time, the dataset enables us to use quantitative approaches to examine differences in forage resources at sites across zones, and to look for relationships between resource and livestock density (hypotheses 4-6).
- (iii) Lastly, we come back to decision making at the inter-zonal level, still focussing on the post-Soviet period, but examining the role of factors unrelated to forage density. Knowledge of the system gathered from a wide range of sources suggests that these are likely to include 'pull factors' such as water availability and 'push factors' such as snow cover, insects and temperature (Kerven et al., 2016a). We discuss the extent to which these may influence the decision to use different ecological zones (section 3.6) and examine the impact of herd size on zonal use (section 3.7).

Table 1. Hypotheses to be examined

| № | Hypothesis | Dependent variable or pattern to be explained | Explanatory variables and related data |
|---|--|--|--|
| Metrics of livestock distribution and resource density across zones: general | | | |
| 1 | Inter-zonal livestock distributions reflect seasonal differences in resource density between those zones. | Between-zone livestock distributions by season | Seasonal NDVI; vegetation biomass & quality indicators |
| 2 | Resource depletion in one zone may drive movements to another | | Resource depletion at water sources |
| 3 | Livestock movements to north in spring reflect vegetation green-up and are related to vegetation quality rather than quantity in that season. | Livestock migration dates between zones | Rate of NDVI increase over the growing season; data on vegetation productivity and quality dynamics. |
| Metrics of livestock distribution and resource density across zones: site specific | | | |
| 4 | There is a positive relationship between livestock density and resource density at sites used in 2003 and 2012 | Annualised stocking rates | Average annual NDVI at used sites. |
| 5 | In 2003 and 2012, taking the group of used sites only, occupation of sites in a given month can be predicted by monthly measures of relative resource density (if resource matching operates on a monthly basis occupied sites would have higher resource density than unoccupied sites for each month of the year). | Monthly stocking presence/absence | Average monthly NDVI at used sites |
| 6 | In spring, sites where livestock are present have highest rates of biomass accumulation | Livestock presence/absence at used sites during migratory period | Rate of NDVI increase |
| Metrics of livestock distribution and other bio-physical variables across zones | | | |
| 7 | Other environmental factors may also explain between-zone livestock distributions. | Between-zone livestock distributions by season | Water availability, temperature, snow cover, presence of harmful insects in each zone and season. |

2. Materials and Methods

2.1. The study system

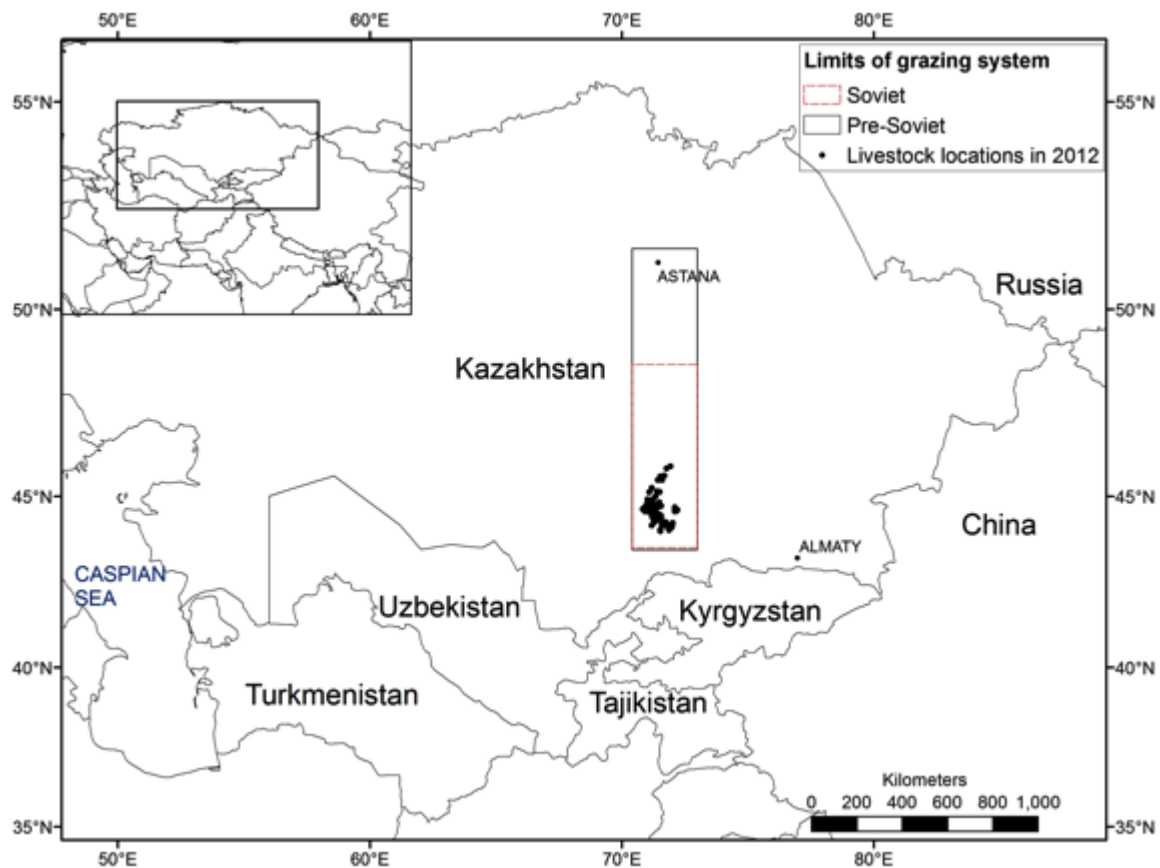
In the Soviet period, animals migrated over 350km between three ecological zones; from wintering grounds in the sandy Moynkum desert, across the clay deserts of Betpak-dala, to the desert-steppe region of Sary Arka in the north for the summer (Fig. 1). This was a truncated form of an older migration (also shown in Fig. 1) which previously extended over 800km, to the steppe zone in the north (Ohayon, 2005). Human populations were based, as today, in settlements along the Chu river valley, which constitutes the fourth ecological zone used in the Soviet era. Since the mid-1990s migrations have been further truncated (Kerven et al., 2004, 2006); the northernmost location used in 2012 was only about half-way across the Betpak-dala desert. Many livestock now spend all year in the Moynkum and/or river Chu zones.

The portion of the study site used in the Soviet era covered an area about the size of Ireland and corresponded to three former state farms (*sovkhoz*): Chu, Moynkum and Baital, located in Moynkum

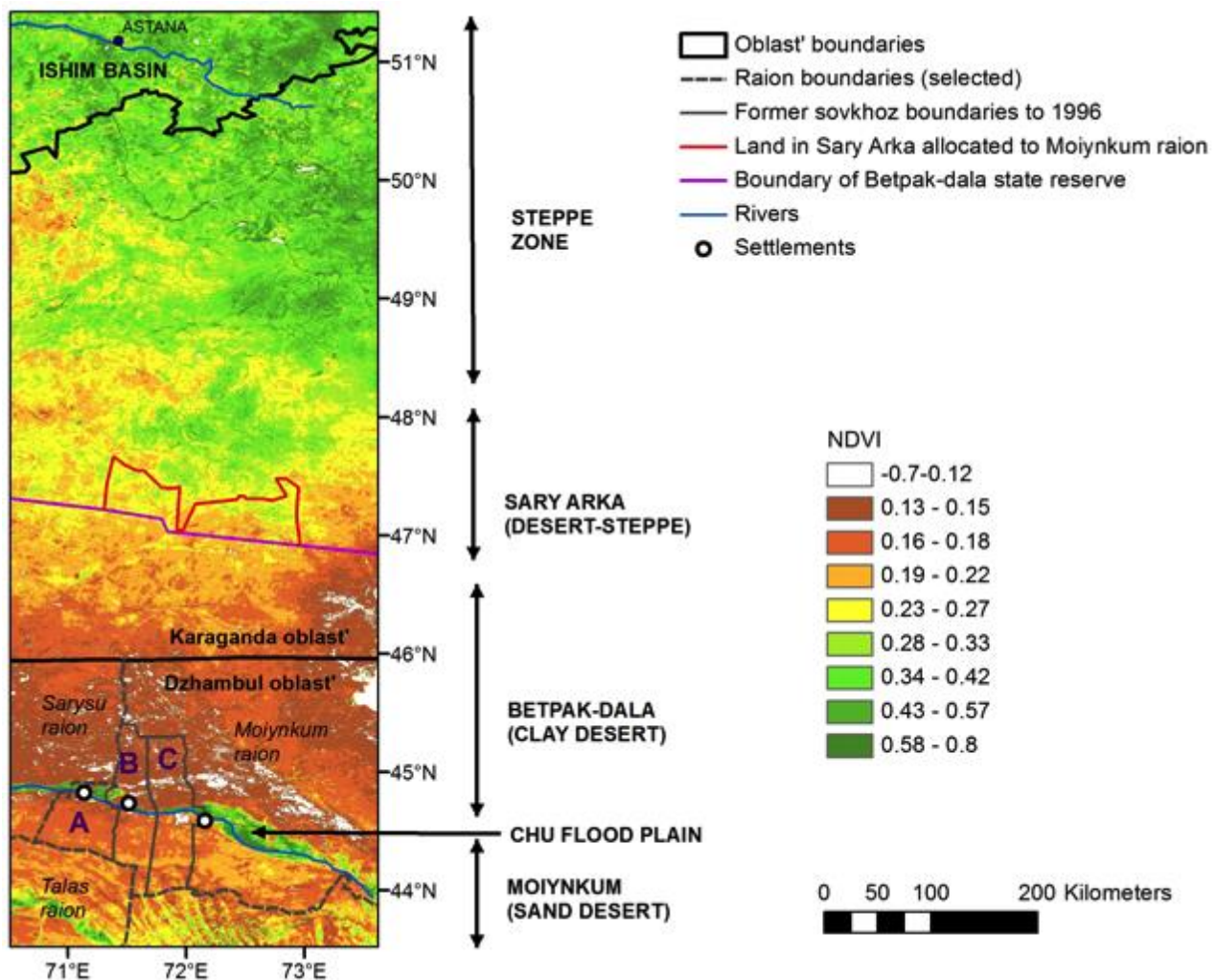
district of Dzhambul oblast' (Fig. 1b). The three farms specialised in sheep-raising and were allocated large areas of pasture to the north to which they moved on a seasonal basis.

Figure 1. (a) Location of the study area, showing the boundaries of the grazing system in the three periods of our study. (b) Ecological zones covering the entire historical grazing system, and administrative boundaries up to 1999 for the area of the study site used in the Soviet era. The Normalised Difference Vegetation Index (NDVI), a satellite-derived measure of green biomass, is shown for July 2012. The Chu River flood plain can be seen as a green band of high biomass running from east to west. Administrative divisions concern provinces (oblast') and districts (raion). Sary Arka is located in present day Karaganda oblast' and the portion previously allocated to livestock from Dzhambul oblast' for summer grazing is also shown. Letters indicate identities of former sovkhos (state farms): A= Chu, B= Moynkum; C= Baital), and their principal settlements (Ulan bel', Malye Kamkale and Sary Ozek respectively) are also shown. State reserve land in Betpak-dala; pastures close to settlements and those south of the Chu river are subject to different access requirements (see text). Ecological zones are marked in capitals at the side of the map.

(a)



(b)



2.2. Data collection and processing

Scope and context: Interview data were used for location mapping, to identify candidate explanatory variables for site selection, and to gather pastoralists' perceptions of the relative importance of factors influencing site selection. During five fieldwork periods between 2012 and 2014, 167 open-ended interviews were conducted with 97 individuals (many interviewed more than once). Interviewees included livestock owners, as well as their close family members hired shepherds, former livestock owners, village mayors, veterinary officers, former employees of the state livestock farm, and employees of the state forestry department (Kerven et al., 2016b).

Livestock distribution: For the Soviet period, the literature describes zonal livestock distributions and timing of seasonal movements, although some site-specific distribution data are also available from *sovkhos* plans. For the post-Soviet period, two censuses of livestock number, species and location for 12 months of the year (starting in October) were carried out in 2002/3 and 2011/12 using surveys, interviews with shepherds and site verification by GPS. Datasets were created containing records of stocking rates on a *monthly* basis and *annualised* stocking rates, at all used locations. Livestock numbers were converted to standard livestock units (LU; 1 LU is one sheep equivalent; 1 cow = 5 LU; 1 horse = 5 LU; 1 camel = 5 LU) and multiplied by the number of days at the location during the relevant time period (months or years) to give a single comparable figure for each location expressed in Livestock Unit Months or Years (LUM or LUY). These metrics are equivalent to one head of sheep grazing at a location for one year (LUY), or one month (LUM).

Resource density: Multi-year field measurements of total biomass over the growing season were available in each of the four major ecological zones from the Russian literature. Additional zonal metrics of resource density and site-specific measurements, were generated from the remote-sensing derived Normalised Difference Vegetation Index (NDVI), employed as an indicator of green biomass worldwide (Pettorelli et al., 2011). We used a gapless 250m 16 day NDVI dataset generated from the MODIS MOD13Q1 product (Vuolo et al., 2012) for the years 2001-2012, from which we extracted annual and monthly averages both over the entire period and for the years 2003 and 2012 alone. Average NDVI values were extracted around each location (usually where the livestock are watered or spent the night) at a radius of 6km, the typical extent of grazing impact around desert wells in Kazakhstan (Karnieli et al., 2008).

Some forage resources may not appear ‘green’ (for example in winter) and will thus be undetectable by NDVI; other vegetation may produce high NDVI values, but is inedible due to poor digestibility, toxicity or morphology. For this reason it is important to understand the species composition and edibility of the vegetation in the study area. We used detailed vegetation maps from the Soviet period which include information on edible biomass by season. These maps did not cover the entire currently grazed area, and defined a very large number of vegetation types, many of which were similar in terms of forage resources. These types were reduced to 12 major classes using botanical data in the Soviet map legends combined with field vegetation assessments conducted in 2013 and a classified Landsat image from 2001 covering much of the grazed area (supplementary materials 1). These same data sources were then used to identify training sites for the 12 classes which were used to classify a MODIS image covering *all* currently grazed areas and having a resolution of 500m, appropriate to the scale and level of detail required for our study. Soviet era maps of the northern (currently unused) portion of the study area were then used to extend the classification to the north, including two additional vegetation classes representing the desert-steppe areas (see supplementary materials 1 for details of classification processes).

The result was a simplified map (Figure S1), used primarily for the identification and visual assessment of the coverage of major vegetation associations in each ecological zone. Edible biomass values were derived for each association using values from the original Soviet map legends, which represent long term averages for each season. These figures were weighted by the area of each of the types assigned to the final generalised class, resulting in a set of estimates for average edible forage availability in space and time, for the vegetation types shown in Figure S1.

Pastoralists may choose locations at which vegetation has the highest energy or protein content, even if the edible biomass in these areas is low compared with that of surrounding zones (Fryxell et al., 2004, Senft et al., 1985, Turner et al., 2005). Seasonal data on digestible energy and protein could not be derived for associations, but data for the dominant species in each association were available from the Russian literature and were used to explore *zonal* differences in forage quality. In addition, rate of change in NDVI was used as a proxy for forage quality - rapid accumulation of fresh matter, which typically has high protein and energy concentrations, has been found to influence site selection in similar environments (Griffith et al., 2002, Mueller et al., 2008). Here, change between each 16 day NDVI composite (averaged over the 12 year dataset) and the composite one month previously was calculated, resulting in 23 ‘average rate of change’ images used for both zonal comparisons and site-level analysis.

Resource depletion: The impact of livestock themselves on the environment may also be a driver of movement. There is a large literature on pasture degradation in the Soviet era; whilst livestock numbers are lower today, they may concentrate in small areas for long periods of time, causing localised degradation, as shown in our study areas (Alimaev et al., 2008). For the recent period, two methods were used to explore depletion at the site level. Firstly differences between NDVI at 0-2km and 3-5km from wells, or *NDVI gradient*, were measured using the annual average NDVI data for 2003 and 2012. Relationships between such gradients and grazing pressure have been demonstrated elsewhere in the region (Behnke et al., 2016). Secondly, the slope of change in NDVI between 2001 and 2012 was measured for each used site; sites with

large negative slopes were considered to be subject to higher resource depletion than those exhibiting positive change or negative change of smaller magnitude.

Other drivers of site selection: Additional bio-physical variables were identified as important determinants of site selection during interviews (Table 1). Most of these are explored at the zonal level alone using literature and interview data. Land surface temperature products from the MODIS instrument were acquired and processed to multi-annual average temperature images at a resolution of 5 degrees.

Statistical analysis: Average annualised stocking rates at sites between zones in 2012 were compared using the Wilcoxon rank sum test, as stock numbers are not normally distributed. Average differences in NDVI at sites between zones were compared using t-tests. Analyses of relationships between site-level NDVI and stocking rates were carried out using a quasi-Poisson GLM, in which variance increases with the square of the mean. Zone was also included as a factor and F-tests were used in order to determine whether this model improved prediction of stocking rates relative to models with NDVI alone, zone alone and the null model. These analyses were carried out in R (R Core Team, 2014). Image processing and analysis were carried out using the Raster package for R (Hijmans and van Etten, 2013) and ARCGIS (ESRI, 2011).

3. Results

3.1. Biophysical characteristics of the system

In this section we look at how the biophysical characteristics of the system interacted with socio-economic change to explain the use patterns during the pre-Soviet and Soviet periods described in Section 2.1 and shown on Figure 1.

Throughout the study area, inter-annual variation is relatively low and seasonal variation, although high, is relatively predictable (Robinson and Milner-Gulland, 2003a). Precipitation limits vegetation growth, and differences in NDVI (Fig. 1b) are at least partially explained by precipitation differences between zones (Table 2). Average annual precipitation increases northwards from the Chu river and to the south across the Moiyunkum desert. In both the sands and Betpak-dala, the bulk of precipitation falls in the winter and spring, but to the north, an increasing proportion falls during the growing season.

Fourteen major vegetation types exist in the study area, with different types characterising the four zones (Fig. S1& supplementary material 2). A major factor explaining the differences in vegetation between zones is soil and the resultant topography. The psammophytic shrubs dominant in the sandy Moiyunkum are crucial for livestock in the winter, as they are accessible even during heavy snow, whilst dunes provide shelter from freezing winds. Poorly developed saline soils in the clay deserts of Betpak-dala support a limited range of smaller plant species and the flat landscape offers little cover. Differences in temperature, and in depth and frequency of snow cover also explain why animals are traditionally located in the Moiyunkum desert in the winter (Table 2). *Dzhut* (Kaz.) conditions occur when melting snow re-freezes to form an icy layer covering the grass, or during unusually heavy snow falls (Zhambakin, 1995). Animals cannot obtain food under snow when the depth is much over 30cm, or 20cm when the snow is dense (Sludskii, 1963). Such conditions are rare in the Moiyunkum desert. Together, these factors preclude the use of much of Betpak-dala and Sary Arka in the winter.

Table 2. Natural features of the main ecological zones in the study area. Data in the table are from Nagornyi (1957), Robinson (2000), Kubanskaya (1956), Kozhevnikova (1961) and Kurochkina & Osmanova (1973). Dzhut is a meteorological phenomenon whereby pasture is covered in a layer of ice, rendering it inedible for livestock. For location of zones see Figure 1b.

| Zone | Area (million ha) | Duration of dzhut | Snow depth (cm) | Snow- covered days | Average annual precipitation (mm/year) | Average temp. Jan °C | Recommended stocking period (Soviet) |
|-------------------------|-------------------------|----------------------|-----------------------|---------------------------|---|-------------------------------|--|
| Chu (river) | 0.3 | | | | 155 | | |
| Moiynkum (south) | 4 | Rare | 5-7 | <58 | 191 | -8 | 1 Dec-30 Mar |
| Betpak-dala (centre) | 11 | 10 days | 12 | 90-100 (S) 110-120 (N) | 152 | -12 | 1 Apr-end May & 1 Oct- end Nov |
| Sary Arka (north) | 7 | 6 days | 30 | 140-150 | 204 | -15.5 | 1 June-15 Sep |

Water supply development was crucial to the planning of state-directed migration patterns. In pre-Soviet times, pastoralists were dependent on shallow hand-dug wells and temporary water sources in order to cross Betpak-dala. The timing of migration was thus strongly linked to the retreating snow (Borodin, 1948). In the 1950s the distance between areas with easily accessible groundwater ranged from 18km in the east to over 100 km in the west. As sheep cannot move faster than 15-20km per day (Saliukov et al., 1959), considerable developments in bore hole construction and storage of temporary water were required to equip livestock migration routes across Betpak-dala (Nagornyi and Konstantinov, 1957). Sary Arka is rich in surface water and has shallow ground water. By 1957, 1,400 wells and springs were present in this zone, whilst in Betpak-dala only around 360 usable wells or springs existed, creating a ‘bottleneck’ to expansion of livestock numbers in this grazing system (Elemanov, 1957). There are a number of small ponds in the Moiynkum but otherwise herders are dependent on ground water which is deep and salty in some places; by the 1970s drilling and well building programmes meant that the Moiynkum was well watered, although the highly productive south eastern parts were last to be developed (Elemanov, 1957).

3.2. Livestock movements and zonal forage resources in the pre-Soviet and Soviet periods

Here we investigate whether historical inter-zonal livestock distributions might have reflected seasonal differences in forage resource density between those zones, defined in terms of biomass, edibility and vegetation accumulation rates. At first sight, the Chu river valley appears by far the most productive zone in terms of total biomass, whilst Betpak-dala has an advantage over the most northerly zone, Sary-Arka, and the most southerly zone, Moiynkum, in spring, but not in other seasons (Fig. 2a).

However, much of the vegetation in the Chu valley is cut for hay in June and is thus unavailable for grazing. *Phragmites communis*, in common with other local reed species, is poorly edible for much of the year, particularly by small stock, and energy and protein contents are very low (supplementary material 3). For large scale sheep raising, the use of areas outside the highly productive Chu valley is therefore essential.

Aside from water supply, the Soviet literature provides us with a number of biological reasons why state livestock were sent to the grass-wormwood pastures of Sary Arka for the summer rather than the far closer clay deserts of Betpak-dala. Standing protein (Fig. 2b), edible biomass (Fig. 2c), and protein and energy contents of major species (supplementary material 3) all reach July maxima which are higher than equivalent figures for Betpak-dala at the same period.

In order to reach Sary Arka, livestock had to cross Betpak-dala (also known as the “northern hungry desert”) in spring and autumn. This zone was not simply a poorly productive desert to be crossed, but also constituted an important forage resource for brief periods. The timing of peak productivity in Betpak-dala is different

from that of other areas; spring biomass is high and the subsequent die-off is abrupt partly because the dominant species, *Salsola arbuscula*, loses much of its foliage in summer (Fig. 2a). *Salsola arbuscula*-dominated pasture has poor edible biomass all year round in the southern part of the zone, and the dominant species exhibits distinctly middling energy and protein contents (supplementary material 3). The other major species in Betpak-dala are wormwoods (*Artemisia* spp.), which have high protein and energy values in spring and summer, but are not preferred forage species in summer, due to a build-up of ether oils (Kirichenko, 1980), leading some to declare Betpak-dala unusable for summer grazing (Borodin, 1948). In contrast, *Artemisia* species make valuable autumn and winter fodder. Additional high quality autumn pastures are provided by dense stands of *Atriplex cana* and other saltworts located in low lying areas. Lastly, areas along river beds and around wells where the water table is high provide a niche for dense vegetation comprised of *Haloxylon* shrubs with wormwoods, saltworts, tamarisk, reeds and grasses. Here, biomass may reach levels similar to those of the best vegetation in the Moiyunkum and exceed those of some vegetation types along the Chu. These areas constitute a key resource. According to Nagornyi (1957) they are the only parts of Betpak-dala which can be used in summer, but areas cover less than 5ha in most cases.

Figure 2. Vegetation dynamics and edible biomass across the four ecological zones, from the Soviet literature and MODIS. Vegetation types are described in supplementary material 2.

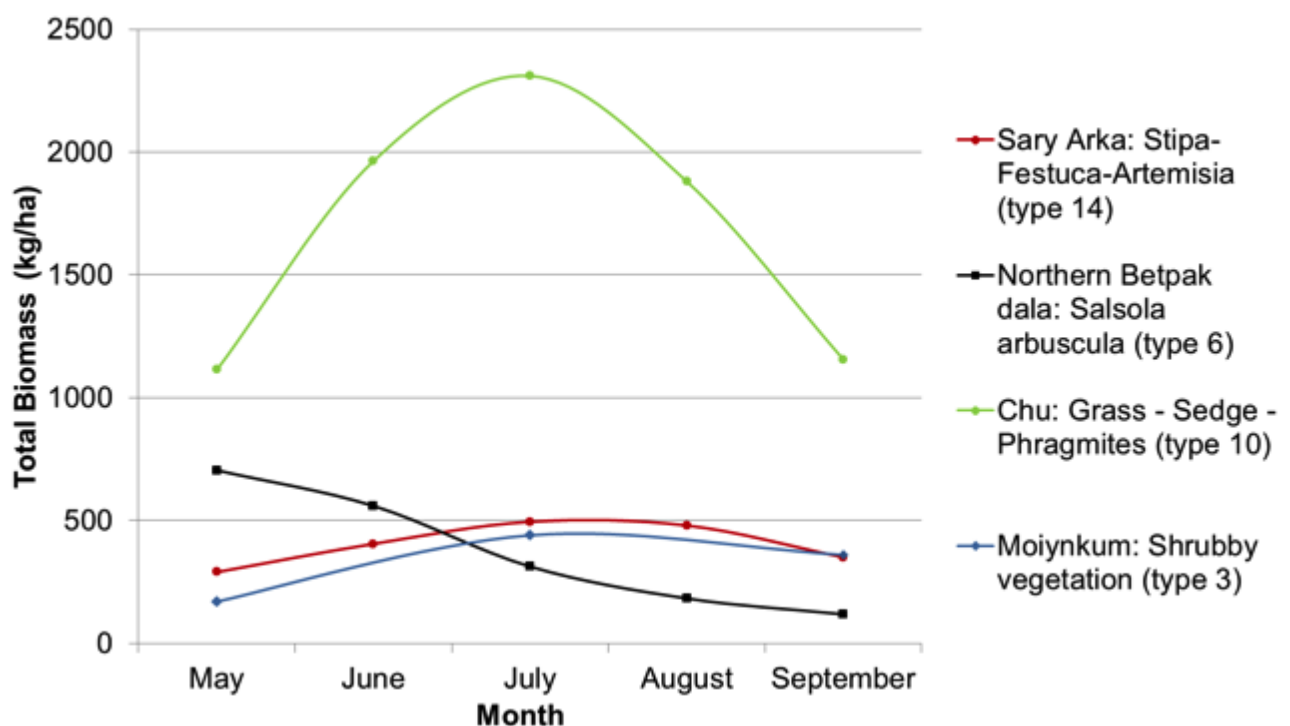
(a) Total biomass for the major vegetation associations in Sary Arka, Northern Betpak-dala & the Moiyunkum desert in the growing season. Sources for Sary Arka (Kozhevnikova, 1961) Betpak-dala (Kirichenko, 1964, Kirichenko, 1966); Moiyunkum (Bizhanova and Kurochkina, 1989); Chu valley (Nagornyi, 1957).

(b) Standing protein for major associations in Betpak-dala & Sary Arka (sources as above)

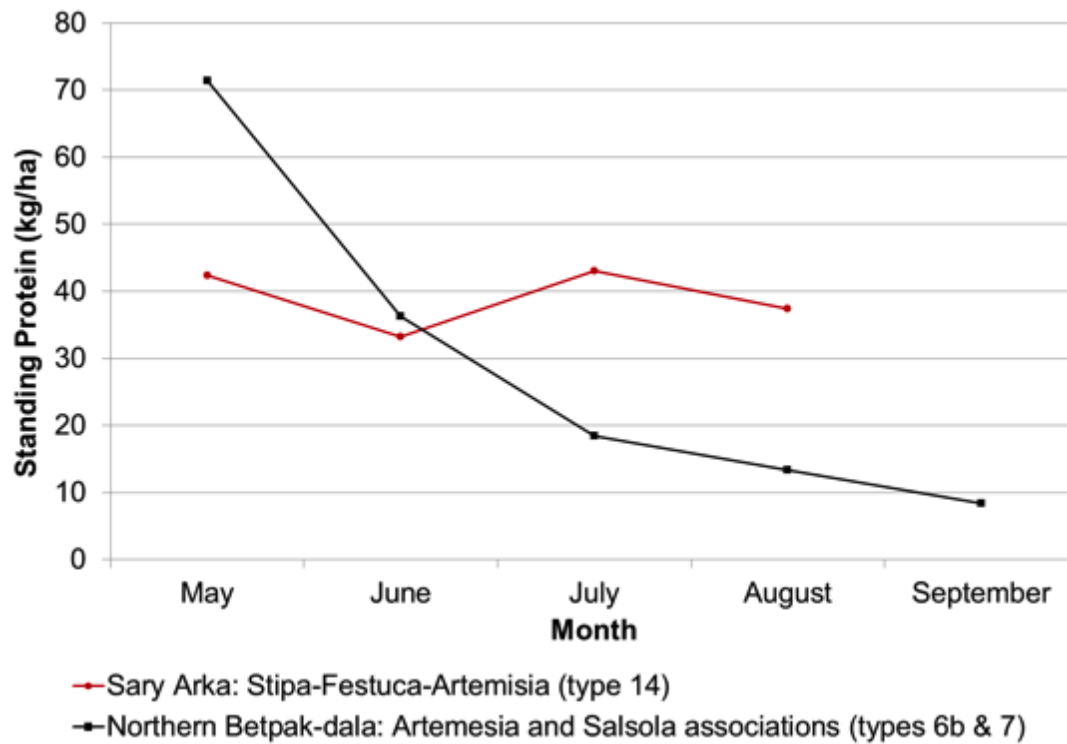
(c) Edible biomass for major vegetation types in the study area (source: Giprozem maps of sovkhos Chu, Moiyunkum and Baital, and Dzhezkazgan oblast). The zonal distribution of vegetation types given here is not exact; vegetation type 9, found in Betpak-dala, is also found in strips along the river Chu.

(d) MODIS-derived NDVI values during five 16-day periods for a north-south transect across the four ecological zones. The transect represents NDVI from a 1-pixel (250m) wide south-north transect across the study area at a longitude of 71.6 (between Ulan bel' and Sary Arka.

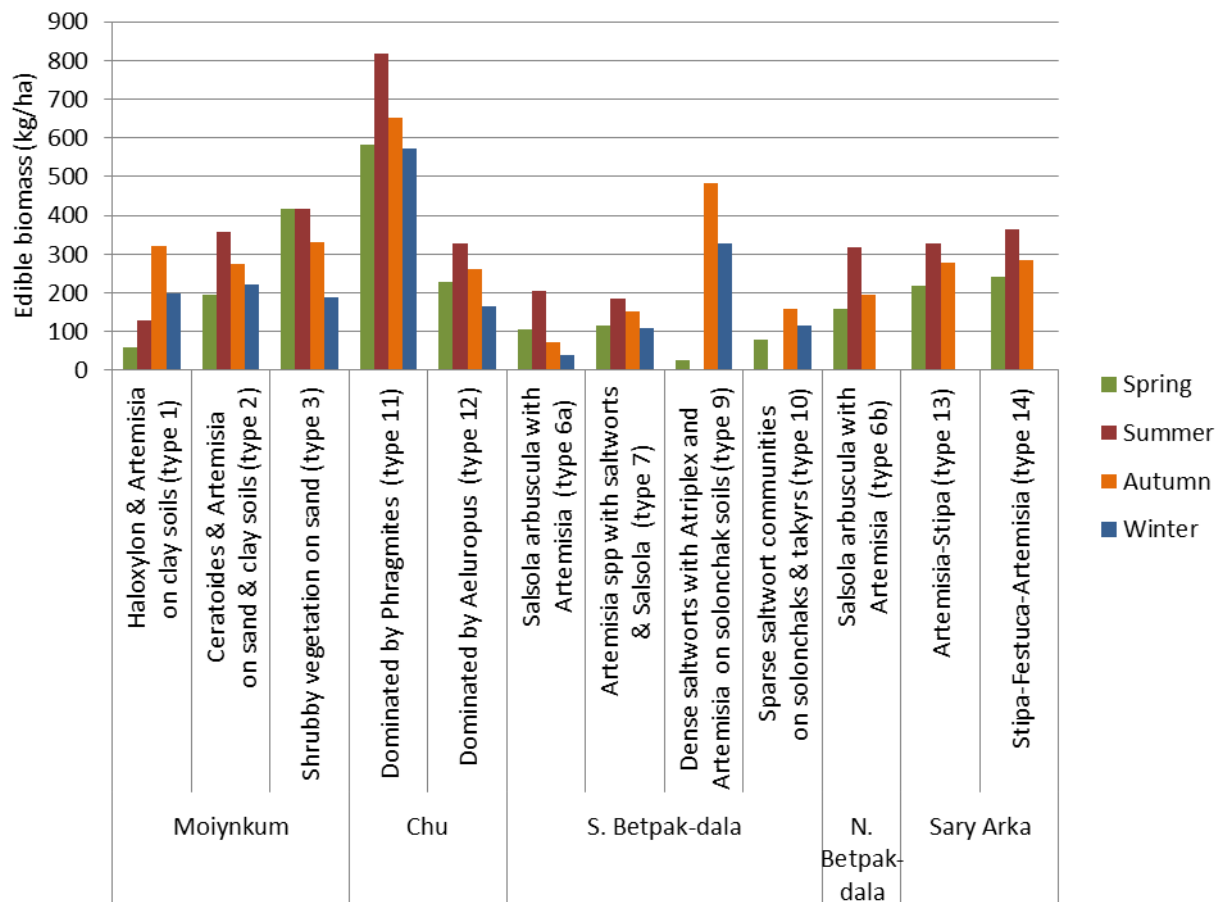
(a)



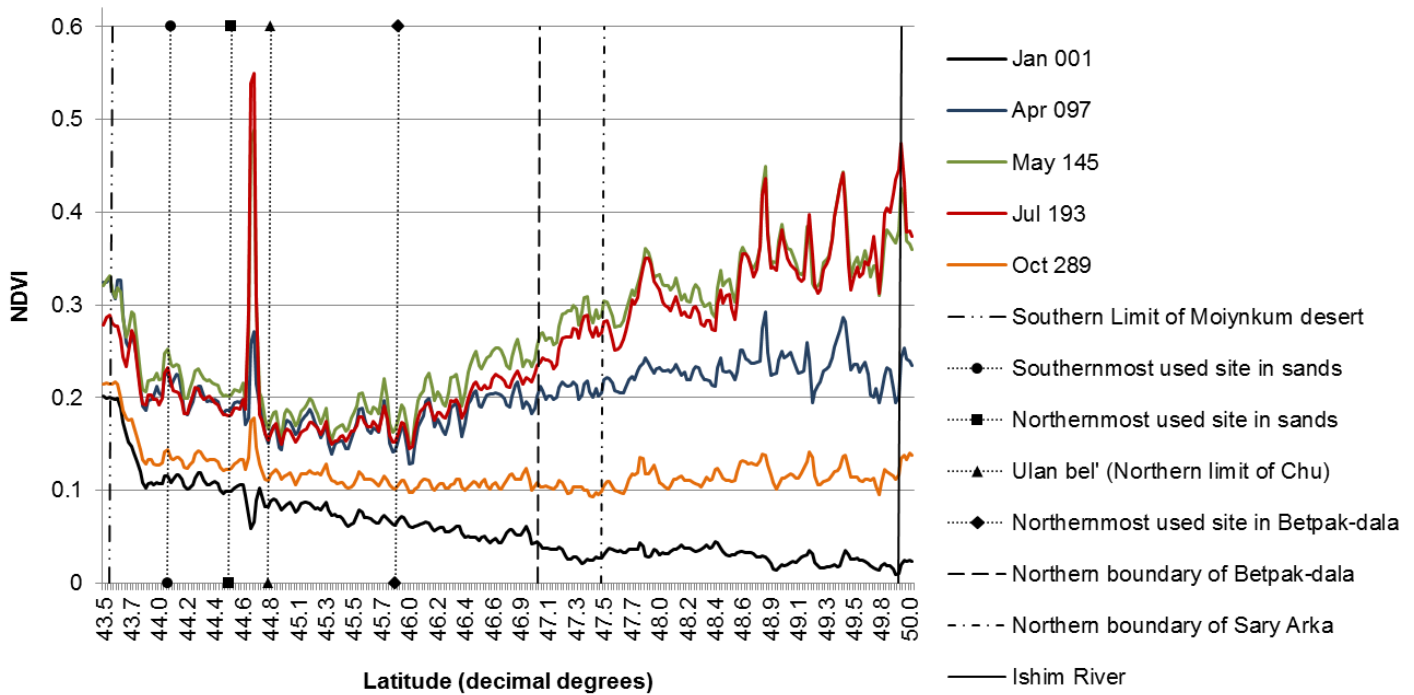
(b)



(c)



(d)



There appears, therefore, to be a window between April and June when Betpak-dala may indeed constitute an important pasture resource. In May digestible protein in ephemeral species such as *Rheum*, *Carex* and *Ferula* spp. and *Agropyron* spp. may reach up to 17-24% of dry biomass and the pasture contains high levels of easily assimilable carbohydrate, calcium and phosphorus (Fig. 2b). The installation of new water supplies allowed livestock to take advantage of this fact and the effects on livestock performance were documented by Tashbulatov (1957). This author noted weight gains amongst those sheep taking two months to cross Betpak-dala. This is corroborated by Saliukov et al. (1959) who documented significant weight gains amongst sheep crossing Betpak-dala in April, virtually zero gain amongst those making the move in May/June, and weight loss and increased mortality amongst those grazing up to July. An early crossing of Betpak-dala would enable stock to benefit from steep accumulation fresh growth - corresponding to a high rate of NDVI increase. In southern Betpak-dala, these rates appear high in April, but start to drop off in May (supplementary material 5).

Both a lack of winter snow cover and vegetation characteristics explain the Moiyunkum's importance as winter grazing. Here, shrubby vegetation in the sands has high edible biomass over the whole year. Overall, pastures in the sandy parts of the Moiyunkum (types 2 & 3 shown in Fig. S1, supplementary material 2) appear to be superior to those in Betpak-dala at all times of the year (Fig. 2c).

Remotely sensed data substantiate some of the patterns found in the Soviet literature but contradict others (Fig. 2d). As with field biomass, NDVI is generally higher in the Moiyunkum desert than in Betpak-dala at all periods of the year. From the Chu to central Betpak-dala, growing season NDVI increases little, but from this point northward it rises strongly, particularly in May. In Sary Arka, growing season NDVI is higher still, but the peak is in May, rather than in July as was suggested in Fig. 2a. July peaks occur only much further north – where they coincide with peak rainfall. The index also increases across the Moiyunkum desert from north to south, where July NDVI values are similar to those in southern Sary Arka; areas north of Sary Arka used in pre-Soviet times exhibit higher NDVI than all used areas further south, except the Chu valley.

Clearly, some of the forage indicators in Sary Arka do not appear much better than those in the Moiyunkum desert. However, although the 'pull' of the northern grazing grounds may have been weak, the 'push' of

resource depletion in the south may have been high. Concentrations of animals in Moiynkum may have been at their highest in Soviet times, and a number of sources agree that erosion processes reached threatening dimensions (Babaev, 1985, Dzhanpeisov et al., 1990, Zhambakin, 1995). Bizhanova and Kurochkina (1989) found that around 60% of pasture in this zone was degraded and shrubs replaced by inedible annuals. Robinson et al. (2002) found that by the end of the winter, biomass removal in Moiynkum was much higher than in neighbouring areas and may have approached the limit of sustainable use. These factors suggest a role for depletion in movement out of the Moiynkum.

3.3 The Post-Soviet transformation and current livestock distributions

Institutional change: By 1995 state support had vanished and livestock numbers collapsed (Table 3). Small stock numbers were at their lowest between 1999 and 2003; they have since increased but still represent only 15% of 1980s numbers. It is partly this fall in numbers which explains the collapse of the Soviet era migration system. Livestock are now held by private individuals. Tough economic conditions persist for many livestock owners who must pay for their own winter feed, transport and marketing costs themselves. Some pastures are now subject to exclusive forms of tenure; in the Moiynkum these concern annual leases from the forestry department, whilst some lands along the Chu may be leased for 49 years from the district administration. On the other hand ‘village land’ around settlements is held in common by residents and also includes some key pastures along the Chu. Remote pastures in Betpak-dala belong to the ‘state reserve’ and remain *de facto* open access, although 49 year use contracts may be applied for. Pasture users may theoretically apply for land use anywhere, yet in 2012 only four owners have leased land outside the boundaries of their former home *sovkhos* and only two (large operations) use pasture outside Moiynkum district. Thus, the importance of administrative boundaries is weakening only slowly.

Table 3. Sheep and goats in study farms (official statistics). Collective structures ceased to exist between 1997 and 1999, after which all livestock were privately owned. Ulan bel and Malye Kamkale sovkhos were merged into one rural locality after 1999, leading to aggregation of official statistics in later years.

| Ex-Sovkhoz (major settlement) | 1980s | 1997 ¹ | 1999 ² | 2003 | 2012 |
|----------------------------------|-----------------|-------------------|-------------------|--------------|---------------|
| Chu (Ulan bel') | 50,000+ | 18,221 | 8,035 | 6,432 | 13,700 |
| Moiynkum (Male Kamkale) | 50,000 + | 6,984 | 2,230 | | |
| Baital (Sary Ozek) | 48,000+ | 2,151 | 1,169 | 2,800 | 8,772 |
| Total | ~150,000 | 27,356 | 11,434 | 9,232 | 22,472 |

¹ Collective small stock only, official figures (Robinson, 2000)

² All small stock, official figures (from data collected by authors)

Livestock distributions: Livestock are constrained to sites with water (functioning wells or natural water sources). The Betpak-dala zone has a low density of wells, and therefore potentially available sites, whilst the Moiynkum sands have a high density (Fig. 3). The plain immediately south of the Chu is characterised by salty groundwater and consequently has very few wells, which explains why it remains little used.

There were around 130 base wells (with infrastructure) in the Moiynkum desert within the boundaries of our three study *sovkhos*. These were located at an average distance from one another of 3.5 km (well below the radius at which animals graze) so the area was essentially ‘full up’ with potential sites. Today, most are unused, but the number of occupied sites covered in the two annual censuses (i.e. with herd size information) rose from 23 in 2002/03 to 27 in 2011/12; the presence of livestock originating from our study settlements

was recorded at 40 sites between autumn 2011 and spring 2014. Use of the Moiynkum zone now ranges from one to four seasons rather than spring/autumn or winter alone, as in the Soviet period. In the Chu zone, livestock are present at settlements all year around, and use a number of other sites along the river in all seasons outside winter. Sites in Betpak-dala are occupied only in summer, but even in that season this zone is used by relatively few animals (Table 4 & supplementary material 4).

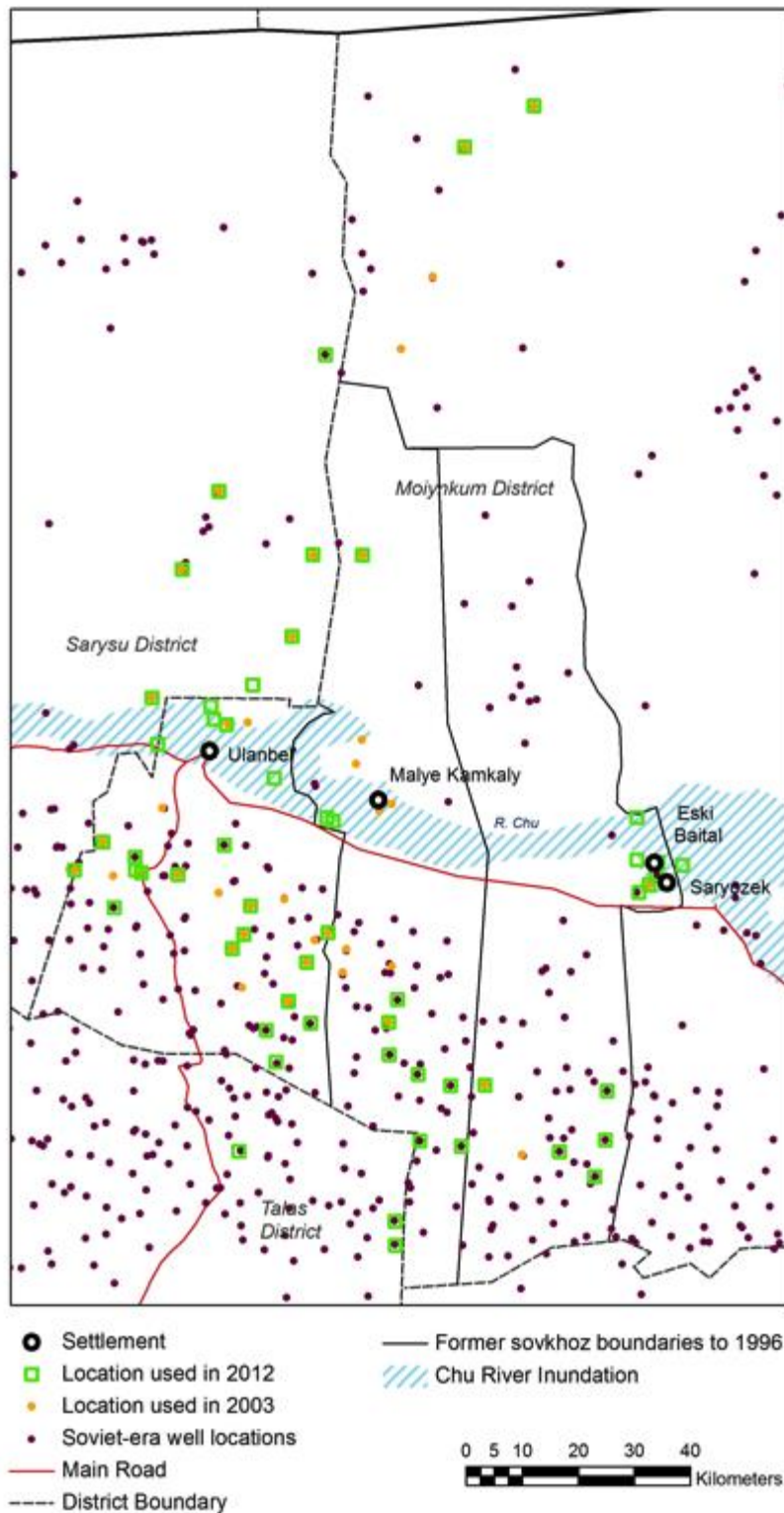
Overall, Soviet patterns of zonal use by season have broken down - some herders are moving between three ecological zones, others move between the river and sands alone, whilst some stay in the sands or close to the river all year round. The highest proportion of annualised grazing pressure of livestock based at Ulan bel' is found in the Moiynkum desert; whilst the majority of the grazing pressure associated with livestock based at Sary Ozek is located along the Chu river (Fig. 3 & Table 4). Not visible from the map is the fact that Betpak-dala is inaccessible to inhabitants of Sary Ozek because the only bridge across the Chu river is broken. In addition they have access to large areas of floodplain vegetation (see Figure 2 and Kerven et al., 2004), thus most livestock based at Sary Ozek stay there all year. Malye Kamkale is virtually abandoned due to poor access to riverine pasture for grazing and hay making (Coughenour, 2008b). Thus, the bulk of animals in the Moiynkum desert and all stock in Betpak-dala belong to owners registered in Ulan bel'.

Table 4. Percentage of total stocking pressure by ecological zone, shown for each former sovkhos. The main change is an increase in use of village areas and decrease in use of Betpak dala in Ulan bel'/Male Kamkale, and a shift from village areas to the Chu riverine area in Baital, along with an overall increase in stock numbers in both areas.

| | Ulan bel'/Male Kamkale | | Baital (Sary Ozek) | |
|----------------------|------------------------|---------------|--------------------|---------------|
| | 2003 | 2012 | 2003 | 2012 |
| Betpak dala | 12% | 8% | 0% | 0% |
| Moiynkum | 68% | 62% | 35% | 32% |
| Chu | 18% | 13% | 34% | 44% |
| Chu (Village) | 2% | 16% | 31% | 24% |
| Total | 100% | 100% | 100% | 100% |
| Total numbers | 13,997 | 18,019 | 4,866 | 11,821 |

As livestock numbers have grown between 2003 and 2012, expansion into the sands from the village of Ulan Bel' has occurred towards the south-east whilst areas in the south-west remain unused. Stocking pressure in the village zone of Ulan Bel' has risen substantially (Table 4). The stocking rate around Ulan bel' village was 314 Livestock Unit Years (LUY) in 2003; today it is 2,960 LUY. At Sary Ozek, although it has decreased as a proportion of total grazing pressure, the absolute stocking rate around the settlement doubled from 1,400 LUY to 2,827 LUY between 2003 and 2012.

Figure 3. Livestock distribution in relation to well locations in 2003 and 2012. This figure shows all used locations in the 2011-2012 census plus some additional locations recorded after the end of October 2012. These latter include a number of sites in Talas district and southern parts of the sands used principally by one large herder who arrived at the end of 2012. These sites are not included in the analysis but illustrate the southward-tendency of site occupation. The figure also shows a satellite settlement of Sary Ozek, Eski Baital. Locations having wells in the Soviet era and not used in 2003 or 2012 were digitised from a 1980s set of 1:50,000 topographic maps.



3.4 Inter-zonal use - how do post-Soviet livestock distributions compare with those of the past?

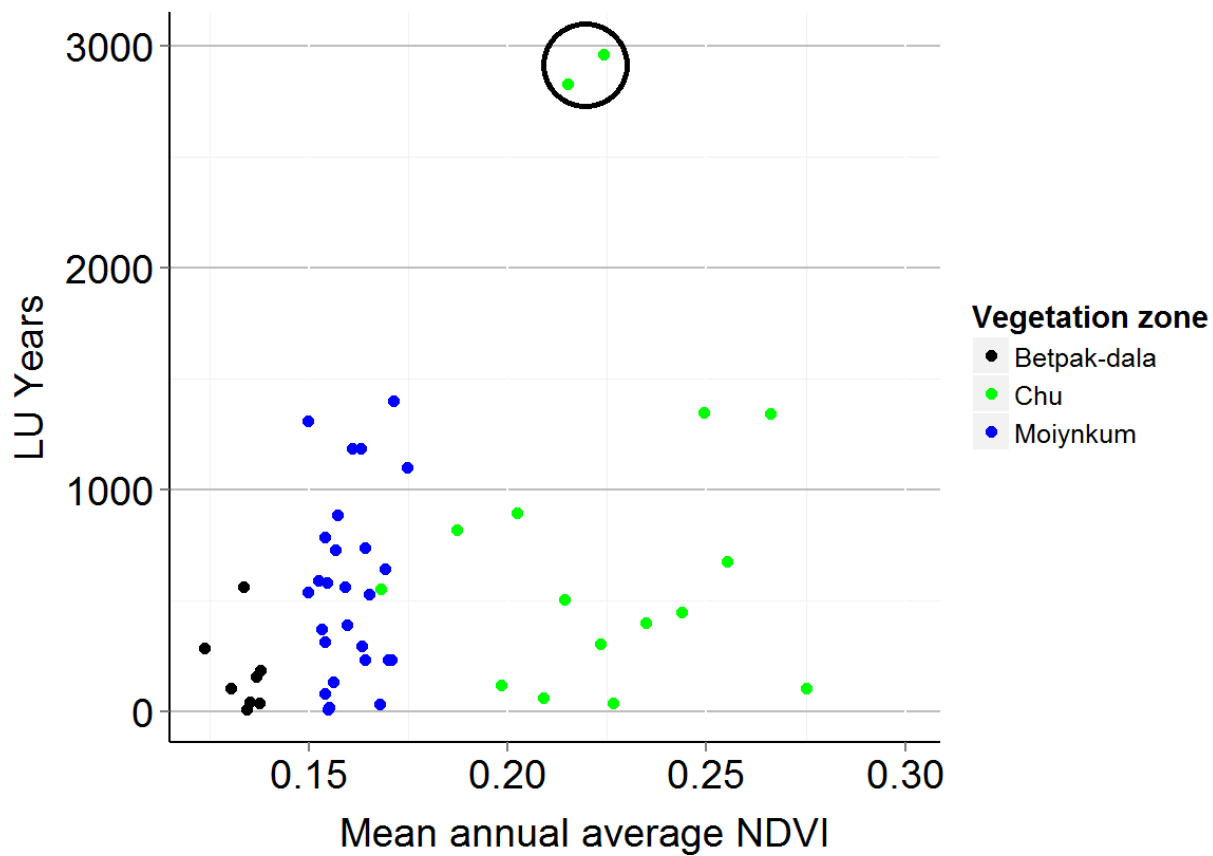
A comparison of current inter-zonal livestock distributions and our understanding of the system presented in sections 3.1 and 3.2 allow us to comment on whether hypotheses 1-3 from Table 1, might hold for the recent period. Firstly, it is clear that inter-zonal movement patterns are highly heterogeneous – they are not the same for every herd (Table 4). The decision of some livestock (albeit a small proportion) to spend the *entire summer* in Betpak-dala would appear to place them there at a period of low forage quality and quantity relative to that of other areas at the same time. Moreover, stock appear to be leaving too late to benefit from the period of maximum accumulation of fresh vegetation (see supplementary material section 5). Many livestock stay in the Chu valley all year around, despite the lack of high quality forage resources in that region in the winter. Given low livestock numbers, the decision to use the Chu valley in spring and Moynkum for the rest of the year, a strategy followed by some, may represent a limited form of resource matching in our simpler truncated system. It is also possible, in a non-equilibrium situation characterised by the presence of unoccupied sites, that resource matching is operating at the level of individual *sites* as much as between zones, and it is to this possibility that we now turn.

3.5. Resource density and stocking metrics at the site-level

In 2012, average annualised stocking rates were three times higher at sites in Moynkum than in Betpak-dala (Fig. 4; Wilcoxon rank sum test with continuity correction: $W = 42$, $p < 0.05$). At Chu sites, NDVI is higher than in the other zones but stocking rates are not correspondingly high except at the sites of villages of Ulan bel' and Sary Ozek, evident as the outliers in Fig. 4. These analyses were conducted using resource density measurements within 6km radius of each site centroid. At a radius of 1km the differences in NDVI between sites in Moynkum and those in Betpak-dala are significantly reduced: at 6km radius average NDVI is 0.134 in Betpak-dala and 0.160 in Moynkum (on log values of NDVI; $t = -12.37$, $df = 17.80$, $p < 0.0001$); at 1km radius the difference is smaller (0.138 & 0.155) but still significant ($t = -4.06$, $df = 9.94$, $p < 0.05$). Thus, the closer we get to a well, the lower the advantage of staying in the Moynkum desert may be. This supports observations from Nagorniye (1957) and Soviet pasture inventory data, which indicate high vegetation values very close to wells in Betpak-dala, but suggest that these resources cover too small an area to represent significant forage resources.

Overall, LUY values are largely related to differences in zone, rather than to differences in NDVI within zones (Fig. 4). The results of deletion tests between quasi-Poisson generalised linear models (in which the circled outliers shown in Fig. 4 were removed) suggest that the model including both NDVI and zone predicts LUY no better than the model with zone alone ($F=0.42$; $Pr(>F)=0.52$). Coefficients for Chu and Moynkum zones show significantly higher stocking rates than those of Betpak-dala, but the Chu zone exhibits a smaller increase in LUY than would be expected given its high NDVI values (slopes: Chu 1.4 $p(t) < 0.005$; Moynkum 1.8 $p(t) < 0.001$) compared to the intercept (Betpak-dala). Along the river, water availability is not confined to points, thus circles of a 6km radius around a central location are unlikely to capture true grazing patterns. Thus, grazing pressure at our sites in the Chu zone may be higher than represented here. Overall, there is some evidence that annualised livestock densities vary by broad ecological zone, but there is no evidence for resource matching at the *site* level (the model with predictor NDVI alone is no better than a null model ($F=2.14$; $pr(>F)=0.15$)).

Figure 4. Mean annual NDVI (2001-2012) at 6km radius from wells and annualised stocking rates (in Livestock Unit Years) in 2012. The circled outliers are the villages of Ulan bel' and Sary Ozek.



Comparisons of annualised animal and resource densities are perhaps unrealistic, as users target resources at particular periods of the year. If resource matching were operating on a monthly basis, we would expect to see higher stocking rates at those sites having higher resource densities compared with other used sites in the same month. However, a comparison of monthly standardised NDVI data revealed no relationships either between or within zones (see supplementary material 6). There is also no evidence that differences in vegetation accumulation rate in spring at the site level can explain livestock stocking rates (supplementary material 7).

Given the number of vacant sites in the Moiynkum sands, our analyses at the site and inter-zone level suggest that vegetation characteristics alone cannot explain why some livestock nowadays leave these apparently rich areas for Betpak-dala during the summer. One possible cause is depletion: for the recent period, analysis suggests greater resource depletion at used sites in the Moiynkum desert than in Betpak-dala. In 2012 mean NDVI gradients out from water sources were positive (indicating depletion) at used sites in the Moiynkum desert (0.0053) and closer to zero (and even slightly negative) in Betpak-dala (-0.0009), suggesting an inverse gradient with *higher* greenness levels closer to wells. But these differences are not statistically significant, and may reflect the fact that shrubby vegetation close to wells in Betpak-dala contributes to the positive gradient. On the other hand, there is a significant difference in the slope of NDVI trends over time in the period 2001-2012 between used sites in Betpak-dala and the Moiynkum. Sites were used for various lengths of time over the twelve year period, but the mean difference suggests more intensive impact on vegetation in the Moiynkum, as shown by the greater and negative slope in these areas (mean change in NDVI per year: Moiynkum: -0.0018, $n=43$; Betpak-dala: 0.001, $n=11$; $t = -5.8$, $df = 45.0$, $p < 0.0001$).

Some interviewed livestock owners mentioned the need to conserve forage resources in the Moiynkum as a contributing factor to their decision to move away from that zone in the summer. Within the set of Moiynkum sites used in 2012, the 11 sites used in summer as well as other seasons had on average >50% higher annualised grazing pressure (LUY) compared with the 16 sites used in other seasons only. This may explain the significant differences in mean NDVI gradients at the two groups of wells ($t = -2.835$, $df = 12.60$, $p < 0.05$). Yet many sites in the Moiynkum are apparently unused, so the question arises of why livestock do not simply make more frequent moves between these (as indeed some do). A number of zone-level characteristics other than resource density could cast additional light on the reasons behind current livestock movements between zones.

3.6. Other environmental factors affecting current inter-zonal livestock distributions

Interview results are examined in detail elsewhere (Kerven et al., 2016a) but suggest a number of alternative, conflicting or complementary influences on inter-zonal movement. Although our datasets do not allow us to quantify the relative importance of these, they all play a part in explaining some of the observed patterns. The literature reviewed here and data in Table 2 suggest that lack of snow cover explains to a large degree the importance of the Moiynkum deserts as a pasture in the winter. However, some owners move their livestock out from this area and from the Chu valley in the summer towards areas of apparently lower forage resource density. One factor mentioned by pastroalists to explain the migration to Betpak-dala is the heat of the sands in Moiynkum, which affects animal weight gain. Summer land surface temperatures in Betpak-dala are indeed around 5°C lower than in the Moiynkum desert, where they may reach well over 45°C (see supplementary material section 8); Sary Arka is even cooler.

A second characteristic which affects the attractiveness of the Chu and Moiynkum zones in summer was flies and ticks (Kerven et al., 2016a). Pastures along the Chu were considered by Soviet writers to be virtually unusable in summer due to mosquitos, botflies and horseflies (Borodin, 1948, Nagornyi, 1957). Stock owners today confirm that flies are a problem, yet many animals are currently located along the Chu in the summer months (supplementary material 2). Interviews also suggested that the presence of ticks in the Moiynkum desert is a factor behind the decision of some herders based there to leave the desert between the months of April and October; some moving to Betpak-dala stated that this push factor outweighed the poor quality of vegetation in the clay desert. However, as we have seen, a number of owners remain in the Moiynkum all year around.

Another factor influencing movement is water supply (Kerven et al., 2016b). Soviet water supply improvements were crucial to the development of Betpak-dala as a spring-autumn pasture, and allowed considerable increase of stocking rates in the Moiynkum. Following 1991, many deep bore holes requiring powerful pumps were abandoned; some shaft wells have fallen into disrepair, filled up or collapsed. Water quality and ease of extraction vary from site to site and are therefore likely to be key determinants of site selection *within* zones. Water quality and availability also influences livestock movements *between* zones. In Betpak-dala, herders are currently using a chain of shallow wells, most of which are less than 25km apart but which are limited in number. Interviews suggested that the distances between wells during migration do present a problem for movers, but once destinations are reached, the currently used wells are shallower (requiring lower financial outlay for pumping) and less salty than those in the northern Moiynkum. This is a particularly important factor in summer, when animals are less tolerant to high concentrations of salt. Water quality in the southern sands is good, but such areas are difficult and expensive to reach in summer, when the sand is loose. It is not clear whether all working shallow wells in southern Betpak-dala are now occupied such that their number and accessibility is now limiting use of that zone.

3.5. Non-biophysical factors as a determinant of movement

It is clear from the above discussion that not all herders are reacting in the same way to the environmental characteristics of zones or specific sites within them. Anthropological field work from the 1990s to the end of this study period in 2014 has consistently concluded that the distribution of livestock between and within

zones is highly influenced by the socio-economic status of the newly-privatised livestock owners – the best proxy for which is the number of livestock units owned (Kerven et al., 2003, 2004, 2006, 2008). Wealthier herders achieve the economies of scale required to cover labour and transport costs associated with mobility. For example, remaining in the Chu during winter requires the purchase of winter feed, costs which are higher for those with more livestock (Kerven et al., 2006, Milner-Gulland et al., 2006). Data for the settlements of Ulan bel’ and Malye Kamkale indicate that, broadly speaking, those with larger herds use all three ecological zones whilst those in the Chu all year round belong to owners having small numbers of animals (Table 5).

Table 5: Herd size and zonal pasture use in Ulan bel’ and Malye Kamkale.

| Ecological zone used | Number of owners | | Average herd size (LU) | |
|-----------------------------|------------------|------|------------------------|------|
| | 2003 | 2012 | 2003 | 2012 |
| Chu alone | 10 | 25 | 66 | 78 |
| Moiynkum alone | 33 | 6 | 152 | 791 |
| Chu & Moiynkum | 2 | 12 | 364 | 412 |
| Chu, Betpak-dala & Moiynkum | 4 | 9 | 1097 | 757 |

In 2012 at Ulan bel’, the average number of livestock owned by those whose stock remained around settlements all year was 78 LU (25 owners) . According to Masanov et al. (2001) traditional herds in the pre-Soviet migratory period were typically around 500-600 head (more rarely up to 800). Herds which currently use all three zones are similarly large (750-1000), whilst less mobile herds are less than 800 LUY (Table 5). Herd size is therefore likely to be an important determinant of inter-zonal migration.

4. Discussion

A summary of the evidence for each of our hypotheses is given in Table 6. Although we are not able to demonstrate causality, it does appear that historically, zonal livestock distributions broadly reflected seasonal differences in resource density, and that a combination of vegetation characteristics, water supply and snow cover may have driven livestock movements in both the Soviet and pre-Soviet periods.

Today, at the broad inter-zonal level, bio-physical variables are certainly not irrelevant, but interestingly for our IFD hypotheses, vegetation is not necessarily the most important of these. Stocking rates at sites in Betpak-dala are lower than those in the highly productive Moiynkum sands, as one would expect from resource density. But the existence of many vacant sites in the sands suggest that summer use of sites in Betpak-dala is probably more related to insect infestations, high temperatures and poor water quality further south than to limited resource availability in the Moiynkum. However, these drivers seem only to have become significant to decision making in the context of other, economic factors. Biophysical factors driving summer use of Betpak-dala have become important because other options, such as use of Sary Arka, are no longer economically viable. Flock sizes are now both much lower on average, and far more variable, today than in the Soviet period, and have become a crucial determinant of movement. The high variability of weight gain between stock with different movement strategies in the study area noted by Kerven et al. (2004) also suggests a deviation from resource matching behaviour by smaller, more sedentary flocks, which are mostly restricted to the Chu valley. Today then, the constraints and drivers of movement are far more complex than they have been in the past and in our non-equilibrium system, herder characteristics may be more important than site characteristics in determining movement.

Table 6. A summary of evidence for each hypothesis examined

| № | Hypothesis | Evidence |
|---|--|--|
| Metrics of livestock distribution and resource density across zones: general | | |
| 1 | Inter-zonal livestock distributions reflect seasonal differences in resource density between those zones. | <i>Pre-Soviet:</i> livestock tracked vegetation quality or quantity to a large extent; but water was a constraint in spring. <i>Soviet:</i> loss of northern pastures decreased access to most productive summer areas; but improved water availability improved access to spring green-up in Betpak-dala. <i>Today:</i> the high proportion of annual Ulan bel' grazing pressure located in the Moiynkum and spring grazing in the Chu valley are linked to high resource density; but summer movements to Betpak-dala and winter concentrations of stock in the Chu are not. |
| 2 | Resource depletion in one zone may drive movements to another | <i>Pre-Soviet:</i> unknown <i>Soviet:</i> evidence from literature of high depletion levels in the Moiynkum sands compared with neighbouring zones. <i>Today:</i> depletion is higher in the sands than in Betpak-dala; but likely to be important only combined with other factors. |
| 3 | Livestock movements north in spring reflect vegetation green-up and are related to vegetation quality rather than quantity in that season. | <i>Pre-Soviet:</i> resource quality probably less important than water availability during migration; <i>Soviet:</i> timing of migration close to that of vegetation quality highs in Betpak-dala; <i>Today:</i> livestock leave for north later than periods of highest vegetation quality. |
| Metrics of livestock distribution and resource density across zones: site specific | | |
| 4 | There is a positive relationship between livestock density and resource density at sites used in 2003 and 2012 | Patterns evident only between zones and, for the Chu, only close to settlements. No site-level resource matching. |
| 5 | In 2003 and 2012, taking the group of used sites only, occupation of sites in a given month can be predicted by monthly measures of relative resource density. | No evidence |
| 6 | In spring, sites where livestock are present in 2003 and 2012 have highest rates of biomass accumulation. | No evidence |
| Metrics of livestock distribution and other bio-physical variables across zones | | |
| 7 | Other environmental factors may also explain between-zone livestock distributions. | <i>Pre-Soviet:</i> water availability and snow cover interacted with resource density to drive movements. <i>Soviet:</i> Snow cover remains important driver, but importance of water availability reduced; some evidence for push factors such as insects, but factors related to resource density dominate. <i>Today:</i> summer temperatures, spring emergence of flies and ticks, and water availability and quality issues contribute to the decision of certain owners to locate stock in zones of relatively low resource density. |

Methodologically, the use of a 'classic' IFD approach based on forage resource density is helpful in the sense that it illustrates the extent to which forage-related drivers of movement are now combined with many other factors. The small number of used sites; interactions between site and zone; combinations of push and

pull factors; and dependence of each factor on herd size preclude multivariate analysis which might determine the relative importance of each driver, but combining quantitative analysis with literature and interview analysis enable the identification of those combinations of factors likely to be important in each season and for different types of user. The natural experiment made possible by the comparison with the past tells us what systems closer to resource matching might have looked like.

A major factor behind the observed changes is institutional transformation in terms of the unit of decision making and the rules governing pasture access. In the pre-Soviet period households moved with their livestock and the unit of movement was groups of households known as *aul*. The broad limits of migratory systems were set by clan boundaries, each migrating ‘within an established geographic zone’ (Olcott, 1995). These clans were grouped into three loose political affiliations known as ‘hordes’. The middle horde, present in the study area, was split into over 20 clans, each of which typically used a large scale migratory route and typically contained between 1000 and 10,000 households with many tens of thousands of animals (Mansurova, 1984, Masanov et al., 2001). Ploughing up of the northern steppe contributed to the loss of these lands for grazing – a process which began during the Russian conquest of the 1800s and greatly accelerated during the Soviet period in the 20th century.

During the latter Soviet period, movements were entirely directed by the state, to which the bulk of livestock belonged. Economic constraints to movement were weak due to subsidies, whilst provision of imported winter feed limited livestock losses caused by *dzhut*. Organisational units were large, with each *sovkhoz* holding up to 50,000 head of sheep (or more in some cases). *Sovkhoz* flocks and herds followed a single migratory system; the broad ‘universe’ within which livestock could move was set by boundaries of state farms and land allocations made by the state.

Both clans and state farms were large scale units within which members dispersed across the landscape according to established decisions and patterns influencing the group as a whole. Pre-Soviet clans were looser than state farms, inequalities were large and movement patterns affected by wealth and herd size (Kazakh Academy of Sciences, 1980), but the grouping of households into nomadic *aul* both pooled stock and increased labour availability. In the modern context, each owner is part of a (mostly sedentary) household, upon which the costs of herd management, pasture access arrangements and movement now fall (see also Kerven et al., 2008). The fact that, although some flocks have now reached Soviet-period sizes, none had yet returned to Sary Arka at the time of the study, is telling in this respect.

These changes are by no means restricted to Kazakhstan. The variable impacts of the collapse of state and collective farms on pastoral mobility has been documented across post-Soviet Central Asia (Farrington, 2005, Kerven et al., 2004, Steimann, 2011, Vanselow et al., 2012). The decline of collective management institutions (whether this concerns groups of related households or state farms) has been recorded in Mediterranean Europe (e.g. Manzano-Baena and Casas, 2010) eastern and southern Africa (BurnSilver et al., 2008, Rohde et al., 2006), and Mongolia and pastoral regions of China (Fernandez-Gimenez, 2006, Li et al., 2007), where increasing individualisation of herding, and integration of this activity with markets and land privatisation, have led to declines in mobility (see also Behnke, 2008, Dong et al., 2011, Fernandez-Gimenez and LeFebvre, 2006 for reviews of these trends worldwide).

5. Conclusions

We have seen how seasonal variability in vegetation and water availability in our study system once drove livestock movements across a huge latitudinal range. We then examined how Soviet era well building programmes allowed prolonged use of spring and autumn pastures, whilst highly productive northern pastures were lost to agriculture, reducing the biomass dividend attained through summer migration. Today, organisation of herding occurs at the household level, characterised by highly variable animal ownership distributions. Movements are shorter than in the Soviet period, highly dependent on herd size, and appear to

respond to a range of ‘push’ factors such as insects, heat and winter feed costs in addition to differences in resource density.

The Kazakh government is currently designing policies concerning the regulatory environment for pasture access and forms of support for the livestock sector. The 2020 Agricultural Development Programme recommends a package of measures to incentivise mobile sheep production (Ministry of Agriculture of the Republic of Kazakhstan, 2013). These policies will need to consider the obstacles preventing livestock from using areas of peak forage availability in different seasons. Some barriers concern water availability, already the subject of government well-building programmes, but institutions which can create economies of scale are also clearly a factor. Today, new forms of organisation are emerging in the form of large commercially-oriented private herds, but these are still subject to considerable risk. Over 65 % of livestock (11 million small stock and 4 million cattle) are held in households with no registered pastureland (Kazakhstan Statistical Agency, 2013). It remains to be seen whether a combination of increasing livestock numbers, consolidation and economic change will lead to the evolution of a livestock sector to which the vast and remote pastures of central Kazakhstan may once again contribute.

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