Title: Complexity in the Spatial Utilization of Rangelands: Pastoral Mobility in the Horn of Africa

Chuan Liao[1,2,*], Patrick E. Clark[3], Stephen D. DeGloria[4], Christopher B. Barrett[5]

[1] School for Environment and Sustainability, University of Michigan, 440 Church Street, Ann Arbor, MI 48109 USA

[2] School of Sustainability, Arizona State University, 800 Cady Mall, Tempe, AZ 85281 USA

[3] Northwest Watershed Research Center, USDA Agricultural Research Service, 800 E. Park Boulevard, Suite 105, Boise, Idaho 83712 USA

[4] School of Integrative Plant Science, Crop and Soil Sciences Section, Cornell University, 1014 Bradfield Hall, Ithaca, NY 14853 USA

[5] Charles H. Dyson School of Applied Economics and Management and Department of Economics, Cornell University, 301G Warren Hall, Ithaca, NY, 14853 USA

[*] Corresponding author email: lchuan@umich.edu

Abstract

Extensive movement is a key strategy for pastoralists to ensure adequate forage intake for livestock while distributing grazing pressure throughout the landscape. However, the complexity of pastoral mobility was overgeneralized in previous research, which often leads to sedentarization-oriented policy-making. Based on continuous GPS-tracking of cattle movement over seven months and pastoralist knowledge of mobility, we investigated spatial rangeland utilization patterns in five study sites across the Borana Zone of southern Ethiopia. By quantifying the extent of movement, density of utilization, and recursive use of rangelands, we found highly diverse mobility patterns and resource-use strategies even within a single study region. Rather than the central-place model, pastoral mobility patterns in Borana can be characterized using restrictive, semi-extensive, or extensive herding models. The research findings suggest that sedentarization largely results in compromised mobility. Thus, we recommend both intra- and inter-community coordination to reduce recursive use of rangelands and mitigate degradation.

Key words: mobility; pastoralism; spatial utilization pattern; GPS-tracking; Ethiopia

1. Introduction

Being mobile is an important strategy adopted by millions of pastoralists worldwide to ensure adequate forage intake for livestock while maintaining rangeland ecosystem sustainability (Brown, 1971; Coughenour et al., 1985; Coughenour, 1991; Homewood, 2008; Smith, 1992). Forage quality and productivity within a single patch of arid or semi-arid land (ASAL) can vary vastly both intra- and inter-annually in response to changes in precipitation and other environmental conditions (Behnke et al., 1993). Consequently, rather than fixed control of a specific piece of land, pastoralists in ASAL typically require flexible access to multiple pastures in well-dispersed and strategic locations in order to meet the nutritional demands of livestock and better distribute grazing pressure throughout the landscape (Marin, 2010; Turner et al., 2014).

Early attempts to study pastoral mobility yielded conceptual models based on long-term field observation and ethnographic investigation (Coppock, 1994; Spencer, 1973). These models largely assumed forage distribution as the global driver of broad-scale migration, and daily herding management as the local driver of grazing pressure distribution (Coppolillo, 2001). One of these models proposed that grazing intensity is evenly distributed within a defined distance from pastoral settlements (Homewood & Rodgers, 1991) (Figure 1a). This means that grazing intensity is uniform with regard to direction from settlement. Another model predicted that grazing intensity decreases as it gets farther away from settlement, and the rate of change in grazing intensity is uniform regardless of direction from settlement (Spencer, 1973) (Figure 1b). In this case, pastoral resource-use patterns could be characterized by the central-place model (Coppolillo, 2001) or as a piosphere (Lange, 1969). The area near settlement is subject to heavy and recursive livestock use, thus becoming a ‘sacrifice zone.’ A ‘transition zone’ occurs farther from settlement and is represented by steadily decreasing grazing pressure. At distant locations from settlement, grazed zones gradually give way to areas which are rarely visited or influenced by livestock grazing. A third model added environment variables such as water into consideration, and proposed that grazing intensity decreases as it gets farther away from settlement, but livestock move between the settlement and a point source of drinking water as they need to be watered on a regular basis (Western, 1975) (Figure 1c).

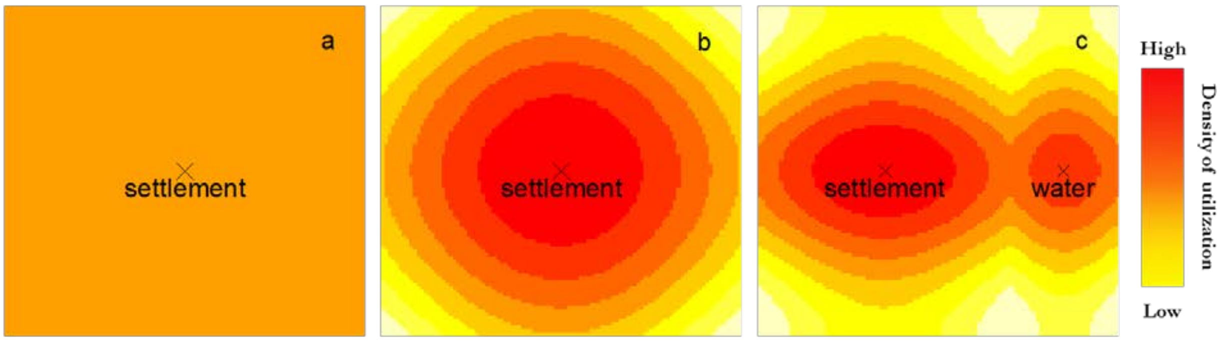

Figure 1. Three conceptual models of pastoral mobility with distinct patterns of spatial utilization.

By synthesizing the above pastoral mobility models, a diachronic model of grazing pressure was proposed to characterize the spatio-temporal variations in grazing pressure as a response to resource availability variations within the year (Moritz et al., 2010). This diachronic model predicted that after the rain season starts, pastoralists would first use the patches of rangelands with better forage quality and less travel cost from settlement. However, by the end of dry season, cumulative grazing pressure would be evenly distributed within their extent of movement.

The conceptual models above provided valuable insights into rangeland management and pastoral policy-making in ASAL; however, these models were largely confined to characterizing livestock herding around settlements. Empirical research suggests that pastoralists move far beyond their settlement areas in search for greener pasture, exhibiting more complex mobility patterns than described in the models above (Brottem et al., 2014). For example, in the Borana pastoral system of southern Ethiopia, a mixture of home-based herding (known as *worra*) and satellite-based herding (known as *forra*) has been practiced for centuries (Coppock, 1994; Wario et al., 2016). *Forra* herding is a key strategy for Boran pastoralists to make use of distant under-utilized rangelands during dry seasons.

However, sparse evidence was collected to investigate extensive movement beyond settlement areas, which is commonly practiced on the rangelands in Africa and Asia (Liao et al., 2014; Niamir-Fuller, 1999). Although indirect measurements derived from observations, interviews, participatory mapping, and household surveys could be used to infer pastoral mobility at multiple scales (Brottem et al., 2014; Homewood & Lewis, 1987), data collected using these approaches was usually of limited accuracy and reliability. While revealing broad-scale seasonal migration routes, details of fine-scale movement and cumulative rangeland utilization patterns can hardly be derived from such data.

Often due to the lack of sufficient understanding of pastoral mobility and spatial patterns of rangeland utilization, government entities have used partial, anecdotal, and perhaps erroneous evidence to design policies to sedentarize pastoralists and transform their livelihoods. Pastoralists are commonly accused of being collectively ‘irrational’ – albeit individually rational – assuming that each individual attempts to maximize livestock production from limited rangelands without considering environmental consequences (Hardin, 1968). Correcting such accusation about pastoralists requires more accurate models of pastoral mobility, in which quantitative monitoring data is crucial to reveal and predict pastoral resource-use patterns under current and projected socio-environmental conditions.

With the emergence of GPS-tracking technology and spatial analysis tools, tremendous progress has been made in the study of pastoral mobility. Portable GPS instruments were installed on domesticated animals to study their movement patterns under the free-ranging, unfenced situations typical of the African and Asian rangelands (Adriansen & Nielsen, 2002; Butt et al., 2009; Coppolillo, 2000; Kawamura et al., 2005; Moritz et al., 2010; Schlecht et al., 2004). These efforts generated valuable information on how livestock moved within their unique contexts.

Significant shortcomings, however, still exist in the modeling of pastoral mobility. This is primarily because extensive movement behaviors (e.g. camp relocation) were rarely captured in previous studies. Short battery lifespan required frequent recapture of livestock, data downloading, and battery recharging or replacement. Intensive labor was required, and there were substantial risks to personnel who regularly followed livestock into potentially dangerous areas (Butt et al., 2009). Therefore, the collected data was generally limited in space and time. Without continuous and intensive tracking data on livestock movement, it is impossible to assess the cumulative resource-use patterns and camp relocation strategies practiced in the extensive ASAL grazing systems.

The goal of this paper is to evaluate the complexity in spatial utilization patterns by pastoralists and investigate the socio-environmental factors which drive and shape this complexity. Our research seeks to address the knowledge gaps on pastoralist extensive herding practices by using custom-built, high-performance GPS collars (Clark et al., 2006) deployed at multiple study sites to monitor livestock movement. This advanced GPS-tracking technology allowed intensive and continuous collection of livestock movement data at relatively low cost, which made it possible to examine fine-scale, cross-season movement patterns and compare how mobility strategies vary in different herding contexts. The specific objectives are to: 1) determine how and why pastoral mobility vary across different socio-environmental contexts in the Borana Zone of southern Ethiopia; 2) test the validity of the central-place model by examining the relationship between density of utilization by livestock and distance from settlements; and 3) investigate how the extents of livestock movement increase on a daily basis and their implications on recursive use of rangelands.

2. Methods

2.1. Study area and sample selection

Our empirical research was conducted in the Borana Zone of southern Ethiopia, an arid and semi-arid region where pastoralism in the primary livelihood strategy. About 43000 km^2 in size, this region is home to over 350000 people with a livestock population around one million (Coppock, 2016). The vegetation is mainly mixed savanna, which is increasingly encroached by *Acacia* and *Commiphora* woody species (Angassa & Oba, 2008). Elevation ranges from 500 m to 2500 m, with terrain varying from steep highland slopes to flat, dry river and lake beds in the lowlands. Mean annual rainfall ranges from 300 mm in the lowlands to 1000 mm in the highlands. Annual precipitation distribution is bimodal, with 60% in the primary rain season (April to May) and 30% in the secondary rain season (October to November) each year (Coppock, 1994).

Livestock herding, as the major livelihood strategy of Boran pastoralists, is generally practiced in two forms. Home-based herding (*worra*) involves the herding of lactating cows, calves, and ruminants close to settlements. In this form of herding, livestock are herded to nearby grazing sites during the day, and taken back to settlement villages in the evening on a daily basis. Satellite-based herding (*forra*) involves multiple temporary camps to graze livestock at substantial distances beyond one-day reach and have access to better forage that what is available near settlements. One household can practice both forms of herding simultaneously through herd splitting.

The selection of study sites was conducted at the *reera*[1] level. The selection process accounted for representativeness of local pastoral system, accessibility by four-wheel-drive vehicles, and size of cattle herds. In addition, it was also ensured that selected study sites had at least 50 households in order to draw household samples from sufficiently large populations (International Livestock Research Institute, 2011). Based on these criteria, five *reera*, namely Siqu, Shomo, Irbi, Taka Bulti and El Dima, were selected as study sites to represent the diversity of socio-environmental contexts across the Borana Zone (Figure 2).

[1] Administrative units in Ethiopia follow the descending order of extent: nation, region, zone, district (*woreda*), and sub-district (*kebele*). *Kebele* is further sub-divided into sub-*kebele* as *reera* in the Borana Zone.

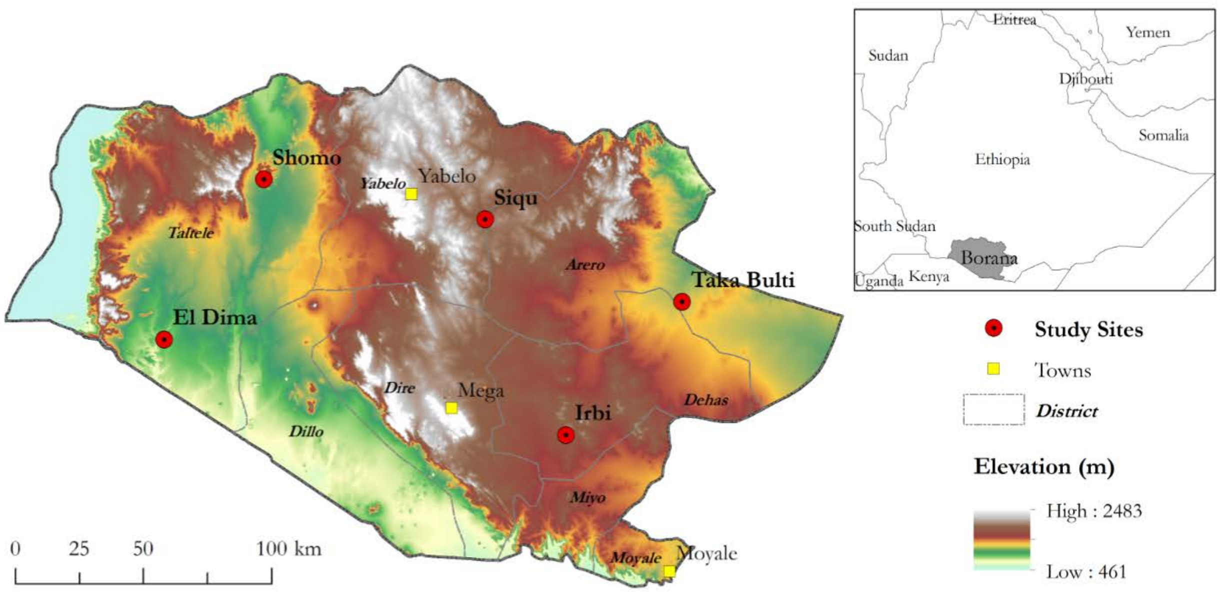

Figure 2. The Borana Zone and the five selected study sites in southern Ethiopia.

Selection of participant households in each study site was based on herd size. Households were first stratified according to the number of cattle owned. In order to restrict the sample to households relying primarily on livestock herding as a livelihood, those whose cattle herd sizes fell within the bottom 35% of the *reera* population were excluded from sampling. In addition, the households within the top 5% of cattle ownership were also excluded to avoid the inclusion of commercial producers. The remaining households from each *reera* were divided into four herd-size groups: 35-50%, 50-65%, 65-80%, and 80-95% of the maximum herd size for the corresponding *reera*. One household was then randomly selected from each group from the five *reera*.

2.2. GPS-tracking

In August 2011, three mature cows from 20 selected households were fitted with custom-built GPS-tracking collars. These collars were capable of recording geographic locations every five minutes for six months or more without service or battery refit. The high-performance collars were also lightweight, with each accounting for less than 0.3% of the body mass of a mature cow in Borana, thus having minimal impact on cattle movement. Of the 60 deployed collars, 58 collected viable data, with an average data set being 135 days in length. Twenty of these collars collected data for periods exceeding 200 days. Since the principal aim of this research was to assess cumulative spatiotemporal utilization patterns and recursive use of rangelands, it is necessary to choose collars that were functional throughout the entire tracking period spanning. Because there were only two long-standing collars in two sites, we decided to choose two collars that collected data for the longest period in each site to make cross-site comparison consistent. This subset of data, collected from August 2011 to March 2012, spanned both wet and dry seasons and included 582542 GPS locations. Collection of continuous, herd movement data across multiple sites and seasons allowed us to develop a broader and deeper understanding of pastoral mobility than would have been possible without this advanced technology.

2.3. Participatory mapping and interview

Although pastoral mobility patterns can largely be inferred from the intensively sampled GPS-tracking data described above, well-rounded interpretation of these patterns requires substantial input from pastoralists. In order to obtain in-depth understanding of pastoral mobility patterns in Borana, we interviewed household heads, and conducted participatory mapping with these pastoralists and three community elders at each study site in July 2013. During the interviews, we validated the movement patterns inferred from GPS-tracking data, such as camp locations, travel distances, and extent of movement that were typical for these herds and the *reera* they represented. In addition, we investigated the factors affecting pastoralist decision-making in each *reera* including environmental conditions, conflicts within and among communities, the practice of crop cultivation, settlement patterns, and development interventions by government agencies and non-government organizations. Follow-up validation interviews and mapping were conducted in May 2014 to correct any misinterpretation of herding strategies we inferred from mobility pattern assessments.

2.4. Data processing and analysis

We use the term ‘pastoral mobility’ to refer to the movement pattern, which is produced by a combination of cattle-dominated behaviors (i.e., freely grazing) and human-driven behaviors (i.e., actively herded or night-corralled). Since the Boran cattle herds are gregarious and tightly herded, we assumed the movement of a single collared individual represented the mobility patterns exhibited by the entire herd (Moritz et al., 2012).

Data processing began by first identifying and removing erroneous GPS locations using a travel distance threshold of 1000 m for each 5-min interval between observations. This threshold represents a sustained velocity of collared cattle traveling at least 12 km/h. The Boran cattle (*Bos indicus*) rarely run at this velocity for a sustained period of time. Thus, data indicating this excessive rate of movement almost certainly contained substantial location error and thus were dropped from the dataset.

Rather than using minimal convex polygon that is likely to overestimate the extent of movement, we performed a vector-based analysis to calculate the extent of movement for each collared cow. First, each location point was buffered to accommodate a conservative estimate of location error (< 50 m). By doing so, each location point was converted to a circular polygon with a 50-m radius. Then we dissolved these individual polygons into an aggregated polygon to represent the observed movement extent for each cow.

We used a mixed raster-vector approach to quantify the density of utilization for each cow, which is defined as the number of observations per unit of space (Adriansen & Nielsen, 2005). First, the movement extent polygon of the cow was rasterized into 50 m by 50 m cells. We assumed this 2500-m^2 cell size would approximate the area traversed by the Boran cattle during a 5-min interval while actively foraging. Next, this raster was overlain with the point-location data and the number of locations occurring within each raster cell were counted. Finally, these raster patterns in density of utilization were compiled for display and reported in terms of points/km^2.

By overlaying density of utilization images with features mapped by pastoralists, we found clear linkages between GPS-based density of utilization and pastoralist-reported land use patterns such as base and satellite camp locations, travel corridors, and principal foraging areas. While at camp during the nighttime hours, about 22:00-04:00 local time, cattle were typically enclosed within night-corrals or circular bush fences about 20-50 m in diameter to reduce predation and theft losses. Consequently, with cattle movement constrained to these small areas, it was a straightforward process to identify camp locations based on the density of utilization data alone. Base camp locations at all study sites typically exhibited a density exceeding 100000 points/km^2 (2500 points/cell), and potential camp locations could be located by identifying sets of adjacent raster cells with the highest density of utilization. In contrast, density of utilization at satellite camp locations was orders of magnitude lower than that of base camps. Their locations were determined by specifying that the tracked cow returned to the same place for over three consecutive days. We then used high-resolution satellite imagery available for display through Google Earth™ and Bing Maps™ to confirm the presence of night-corral and dwelling structures at these camp locations.

In order to investigate the relationship between the density of utilization and distance from base camp locations, we extracted cell values from density of utilization images, and estimated the distance of each cell to base camps. We first performed a logarithm transformation on the response variable so that the regression model assumptions held. Then, we tested the central-place model prediction that as distance from base camp increases, density of utilization will decrease. We applied both ordinary least squares (OLS) models and general additive models (GAM) (Wood, 2013) in each study site to accomplish this test. The OLS model can be represented as:

$$log(Density) = \beta_0 + \beta_1 \, Distance + \varepsilon \qquad (1)$$

where β_0 is intercept; β_1 is coefficient of distance; ε is the error and ε ~ N(0, s^2). The GAM can be represented as:

$$log(Density) = \beta_0 + f(Distance) + \varepsilon \qquad (2)$$

where β_0 is intercept; $f(Distance)$ is non-linear and is subject to smoothing splines; ε is the error and ε ~ N(0, s^2).

Recursive use and subsequent adverse environmental impacts could be indicated by stability in cumulative extent of cattle movement over time (Benhamou & Riotte-Lambert, 2012). In other words, if cattle are herded over the same areas day after day, their cumulative movement extent would tend to remain fairly stable in size. We used a vector-based approach to calculate the cumulative extent of movement for collared cattle over time at the daily level. For each cow, we first derived a polygon representing the movement extent from each day of tracking. Next, for first two days, we merged the first two polygons; for first three days, first three polygons; and so until finally, for the entire tracking period, all polygons were merged. In order to compare across study sites, we converted the response variable into percentages of the maximum movement extent of each cow. Then we used GAM to investigate how tracking duration and study site are correlated with the percentage of cumulative movement range. The model can be represented as:

$$Percentage\ of\ Cumulative\ Movement\ Range = \beta_0 + f(Duration) + \beta_1\ Site + \varepsilon \qquad (3)$$

where, percentage of cumulative movement range is the response variable; β_0 is the intercept; $f(Duration)$ is a non-linear predictor; β_1 is coefficient of site; ε is the error and ε ~ N(0, s^2). All data analysis in this research was performed in the R statistical software (R Development Core Team, 2014).

3. Results

3.1. Pastoral mobility patterns

The 10 cows in this study were monitored by GPS collars over a continuous tracking period ranging from 205 to 218 days. We acquired 55809 to 60196 location observations (i.e. coordinates, date, time, GPS fix quality info, etc.) for each collared cow (Table 1). The extent of movement of collared cows ranged from 20 km^2 in Siqu to 116 km^2 in Taka Bulti. Larger movement extents allowed for more dispersed utilization patterns. Correspondingly, the mean density of utilization observed in Siqu (2983 points/km^2) was nearly six-fold larger than that observed in Taka Bulti (500 points/km^2).

Table 1. Summary of GPS-tracking data acquired from cows of two pastoral households in each study site in Borana, Ethiopia.

Cow ID	Start	End	Duration (days)	Observations	Movement Extent (km^2)	Density (points/km^2)
Siqu1	20-Aug-11	25-Mar-12	218	60196	20	2983
Siqu2	20-Aug-11	21-Mar-12	214	56602	35	1630
Irbi1	27-Aug-11	24-Mar-12	210	57800	42	1364
Irbi2	21-Aug-11	13-Mar-12	205	55809	43	1284
Shomo2	22-Aug-11	23-Mar-12	214	58749	52	1125
Shomo1	22-Aug-11	24-Mar-12	215	58749	54	1081
El Dima2	25-Aug-11	24-Mar-12	212	58852	52	1133
El Dima1	25-Aug-11	25-Mar-12	213	58194	56	1042
Taka Bulti1	21-Aug-11	25-Mar-12	217	59839	59	1008
Taka Bulti2	28-Aug-11	25-Mar-12	210	57752	116	500

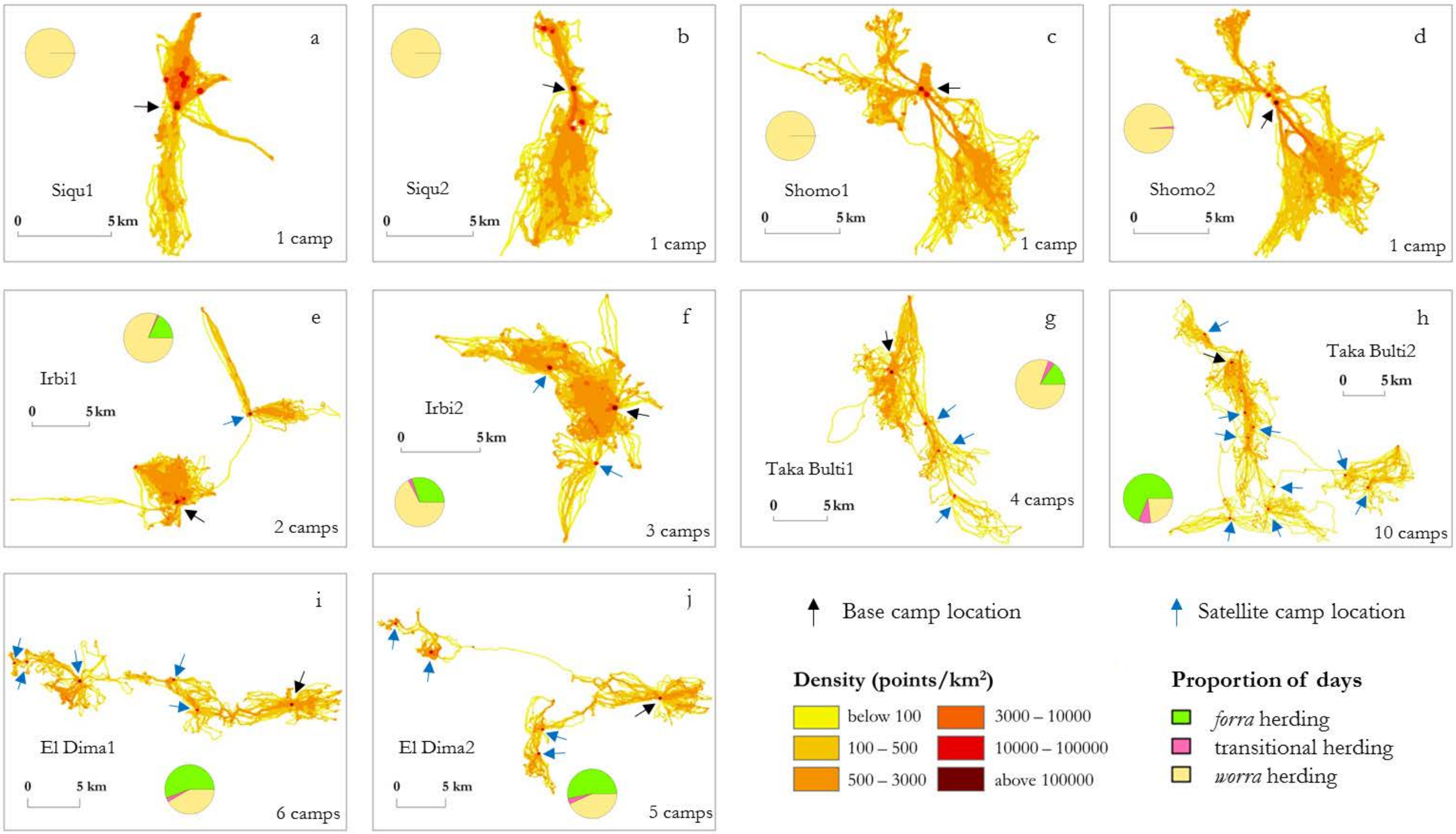

Figure 3. Spatial patterns of density of utilization by cows from two pastoralist households in five study sites in Borana, Ethiopia. Locations of base and satellite camps are identified by arrows.

Pastoral mobility patterns varied substantially across study sites (Figure 3). This variability was reflective of different herding strategies practiced across sites. In Siqu, the two households practiced a *worra*-only herding strategy (Figures 3a and 3b). Consequently, no satellite camps were employed and the herds returned to their base camps each evening after grazing at distant foraging areas (Figure S1). Contrary to the simple mobility models in the literature, directionality of movement relative to the camp location was rarely uniform. Leaving their base camp, Siqu pastoralists either herded their animals towards north or south. This obvious north-south pattern was largely driven by government sedentarization efforts that had occurred in past decades, in which pastoralists were settled along the main road extending east-west between Yabelo and Arero (Watson, 2003). Due to the presence of neighboring settlements and their designated grazing areas, there were few foraging opportunities to the east or west of base camps. Consequently, density of utilization within these north-south travel corridors reached up to 5000 points/km^2, suggesting heavy recursive use on these lands.

Similar to Siqu, well-used travel corridors were also evident in the spatial utilization maps of Shomo pastoralists (Figures 3c and 3d). For most of the study period, the collared cows traveled each day to and from foraging areas in the southeast along fixed corridors which were nearly 4 km in length. These corridors were displayed in Figure 3c and 3d as linear, dark orange features radiating from the base camps towards southeast and indicated a density of 3000-10000 points/km^2 before the cattle dispersed into their principal foraging areas. This pattern of using travel corridors to and from distant foraging areas and little grazing activity occurring near base camps was largely due to the human settlement pattern in and around the community center. Village dwellings, livestock corrals, fenced crop fields, and rangeland reserves occurred as clusters around the community center, strongly confining the available area for livestock use to these narrow travel corridors between camps and distant foraging areas to the southeast. The overall direction of movement shifted, however, under the drier conditions, which occurred late in the tracking period. At those times, pastoralists herded their animals in the opposite direction towards higher elevation foraging areas in the hills to the northwest of base camps.

Like Siqu, only *worra*-herding was practiced in Shomo (Figure 3c and 3d). Although Shomo2 household changed their base camp location, the relocation was within the same village, which could not be considered evidence of *forra* herding. Average movement extent of Shomo pastoralists, however, was almost twice that of their Siqu counterparts, which resulted in lower overall density of utilization (Table 1).

In contrast to Siqu and Shomo, pastoralists in Irbi practiced a different herding strategy that included both *worra* and *forra* herding (Figures 3e and 3f, Figure S1). Since there were fewer fenced crop fields and rangeland reserves in this site, the herds did not have to follow fixed travel corridors starting from base camps. The collared cow of Irbi1 spent 17% of the entire study period at the household's only satellite camp, which was about 12 km from base camp (Figure 3e). The cow of Irbi2 spent almost a third of its time at two satellite camps, which were both about 6 km from base camp but in opposite directions (Figure 3f). The movement extents of both cows in Irbi appeared to be smaller and the overall density of utilization greater than those of Shomo (Table 1). This was probably because Irbi pastoralists had more directional choices in their *worra* herding practices and did not have to follow fixed corridors to reach distant foraging locations.

Cattle from the two households in Taka Bulti exhibited an extensive movement pattern (Figures 3g and 3h). Drier environmental conditions common in this area forced pastoralists to utilize rangelands far from their base camps. Consequently, Taka Bulti households practiced both *worra* and *forra* herding. Most satellite camps were set along seasonal migration routes leading towards their most distant grazing areas, which were over 25 km away from their base camps. The density of utilization by Taka Bulti pastoralists was distinct from the other study sites, as their extent of movement was larger, resulting in highly dispersed utilization patterns within the extents of movement. It is also important to recognize the intra-site variation in movement patterns, in which Taka Bulti2 moved more extensively than Taka Bulti1. This highly-dispersed movement pattern exhibited by Taka Bulti2 with over two thirds of the entire tracking period at nine different satellite camps, consequently, resulted in the lowest overall density of utilization among the 10 households in this study (Table 1).

Extensive movement patterns were also observed for pastoralists in El Dima. Cattle from both households spent over half of the study period at satellite camps (Figures 3i and 3j, Figure S1). In contrast to Taka Bulti where satellite camps were set along migration corridors, in El Dima, *forra* grazing opportunities largely existed in the hills as far as 30 km west of their base camps. During the dry seasons, rangeland condition in the hills was much better than in the lowland plains surrounding the base camps. In addition, there were no human settlements and associated *worra* herds in these hills to compete for resources, making this area ideal for *forra* herding.

3.2. Density of utilization

Density of utilization within the extent of movement differed substantially among the five study sites. The shapes of violin plots showed that Taka Bulti had the widest bottom part, suggesting that cells of low density accounted for a large proportion in their extents of movement (Figure 4a). This was followed by El Dima where, although the movement extent was smaller, a large proportion of that extent exhibited low density of utilization. Violin plots for the three remaining study sites demonstrated much narrower bottom parts. Although Irbi pastoralists practiced *forra* herding, most of their livestock herding was conducted around base camps. While Shomo and El Dima pastoralists had similar movement extents, distribution of density of utilization was different, in which the top part of violin shape of Shomo is wider and bottom part narrower than El Dima. This indicates that although Shomo pastoralists had a relatively large extent of movement, the rangelands were still subject to recursive use as the households were largely sedentarized and livestock were herded over the same travel corridors and principal foraging areas on a daily basis. The bottom part of Siqu violin plot is the narrowest, while top widest. In addition to being sedentarized, households in Siqu had smaller extent of movement compared to Shomo, which resulted in clear evidence of a recursive use pattern.

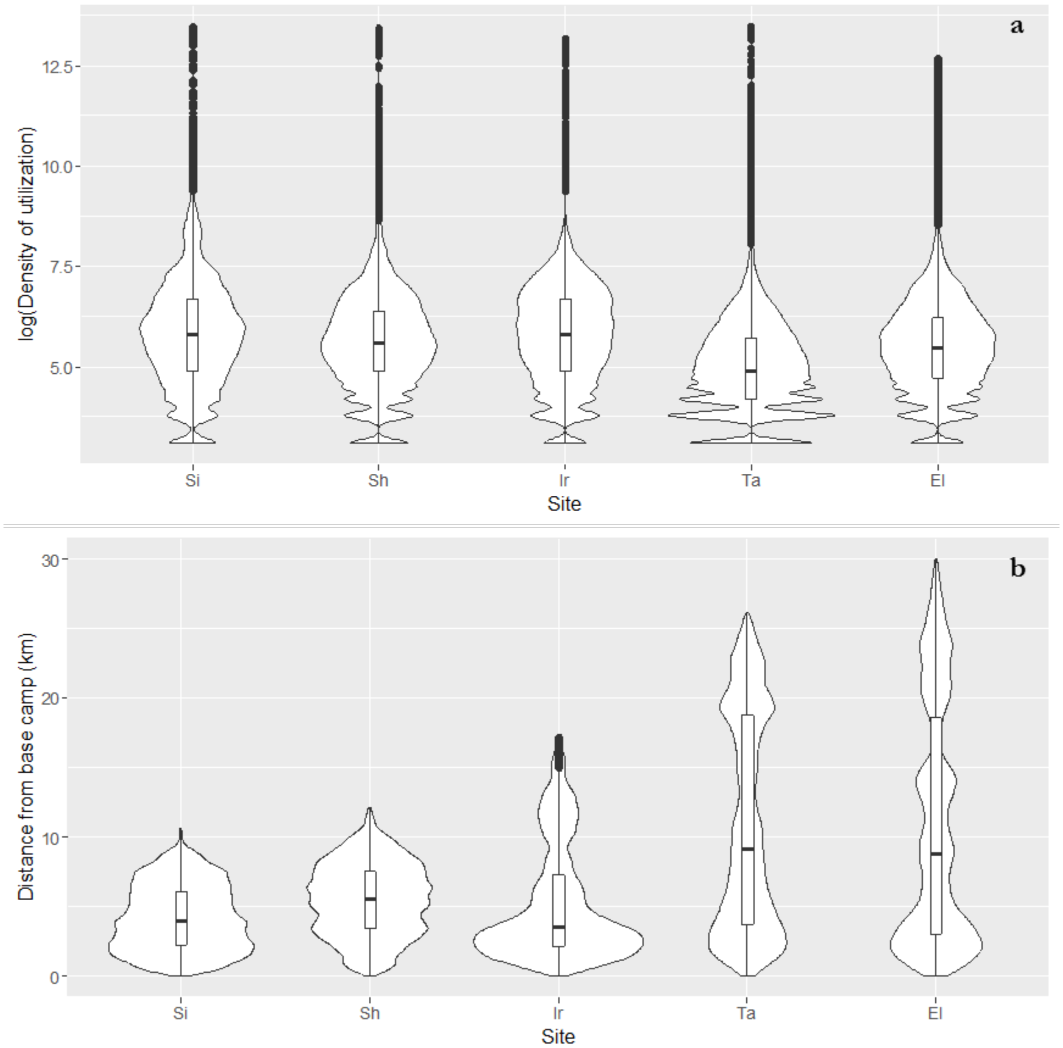

Figure 4. Violin plots of density of utilization (a) and distance from base camp locations (b) of each utilized raster cell within the movement extents of GPS-collared cows in the five study sites.

Density of utilization relative to distance from the base camp also differs vastly among study sites. El Dima pastoralists practiced herding in places up to 30 km from base camps (Figure 4b). Similarly, Taka Bulti pastoralists also herded livestock in places more than 25 km from base camps. In contrast, pastoralists in other three sites herded livestock closer to their base camps. Despite Irbi pastoralists practicing *forra* herding, they mostly set up satellite camps within 17 km from base camp. In addition, the majority of herding revolved around base camps, resulting in a wide-bottom violin shape. The cases of Shomo and Siqu were more similar to each other and clearly different from the other three sites. These sedentarized pastoralists confined their movements to areas within 12 km of their base camps. However, there were some differences between Shomo and Siqu. The heavily utilized rangelands in Siqu appeared at about 2-km distance from base camp, while in Shomo it ranged from 4 km to 8 km.

Earlier models of spatial utilization of rangelands by pastoralists suggested distance from base camp locations could be used as an important predictor of density of utilization. Areas farther away from the base camp would be less likely to be used, indicating a central-place utilization pattern. However, according to our OLS models, both significant positive and negative correlations between density of utilization and distance from base camp can occur (Table 2). In four out of five sites, density of utilization decreased as it got farther away from base camps. However, in El Dima, density of utilization was higher at locations that are more distant from base camps. Nevertheless, the correlations did not seem to be linear as evidenced by low R-squared values in the OLS models.

Table 2. Estimation of density of utilization using OLS models.

	Siqu		Shomo		Irbi		Taka Bulti		El Dima	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	6.63E+00	1.11E-02	6.29E+00	7.84E-03	6.27E+00	6.37E-03	5.54E+00	4.27E-03	5.44E+00	5.57E-03
Distance	-1.93E-01	2.31E-03	-1.26E-01	1.29E-03	-9.80E-02	9.70E-04	-4.99E-02	3.20E-04	5.22E-03	4.09E-04
R-sq	0.10		0.08		0.10		0.11		0.001	
AIC	207579.3		365758.9		306696.9		574688.9		379635.5	

Note: all estimates are significant at 0.001 level.

Table 3. Estimation of density of utilization using GAM.

	Siqu		Shomo		Irbi		Taka Bulti		El Dima	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	5.82E+00	5.42E-03	5.59E+00	3.25E-03	5.77E+00	3.69E-03	4.99E+00	2.38E-03	5.49E+00	3.31E-03
	edf	Ref.edf	edf	Ref.edf	edf	Ref.edf	edf	Ref.edf	edf	Ref.edf
s(Distance)	8.925	8.998	8.968	9	8.99	9	8.999	9	8.993	9
R-sq	0.11		0.12		0.20		0.17		0.08	
AIC	207166.9		359442.4		294774.4		562390.8		370274.5	

Note: all estimates are significant at 0.001 level.

In order to improve the prediction, we applied GAM, which can effectively smooth the predictor. The results indicated distance was a significant predictor of density of utilization (Table 3). The adjusted R-squared values in the GAM were higher than OLS models, and the AIC values of GAM were lower than those in OLS models, indicating that GAM was generally a better fit than OLS. However, R-squared values are still low in GAM, suggesting that distance from base camp can only partially explain the variation in density of utilization within the extent of movement.

Predictions from GAM revealed that density of utilization exhibited a non-linear relationship with distance from base camps, and the relationships are different across sites (Figure 5). In Siqu and Shomo, density of utilization generally decreased as it became farther away from base camps within the extents of movement, but there were some minor fluctuations along the distance gradient (Figure 5a and 5b). Since pastoralists in these two sites only conducted *worra* herding, their utilization of rangelands rarely appeared beyond 12 km from base camps.

In contrast, utilization of satellite camps in Irbi, Taka Bulti, and El Dima resulted in more substantial fluctuations of density of utilization along the distance gradient. Camp relocation allowed Irbi pastoralists to access resources up to 17 km from base camps (Figure 5c). In Taka Bulti, as pastoralists set up satellite camps along the migration corridor until the most distant location, density of utilization generally decreased along the distance gradient (Figure 5d). In El Dima where multiple satellite camps were set up at strategic locations, there were substantial fluctuations in density of utilization along the distance gradient (Figure 5e). There were little grazing opportunities at locations that were about 17 km from base camps. However, density of utilization beyond 20 km was even higher than the locations near base camps, and such trend reflected the increasing foraging opportunities presented in areas remote from human settlement.

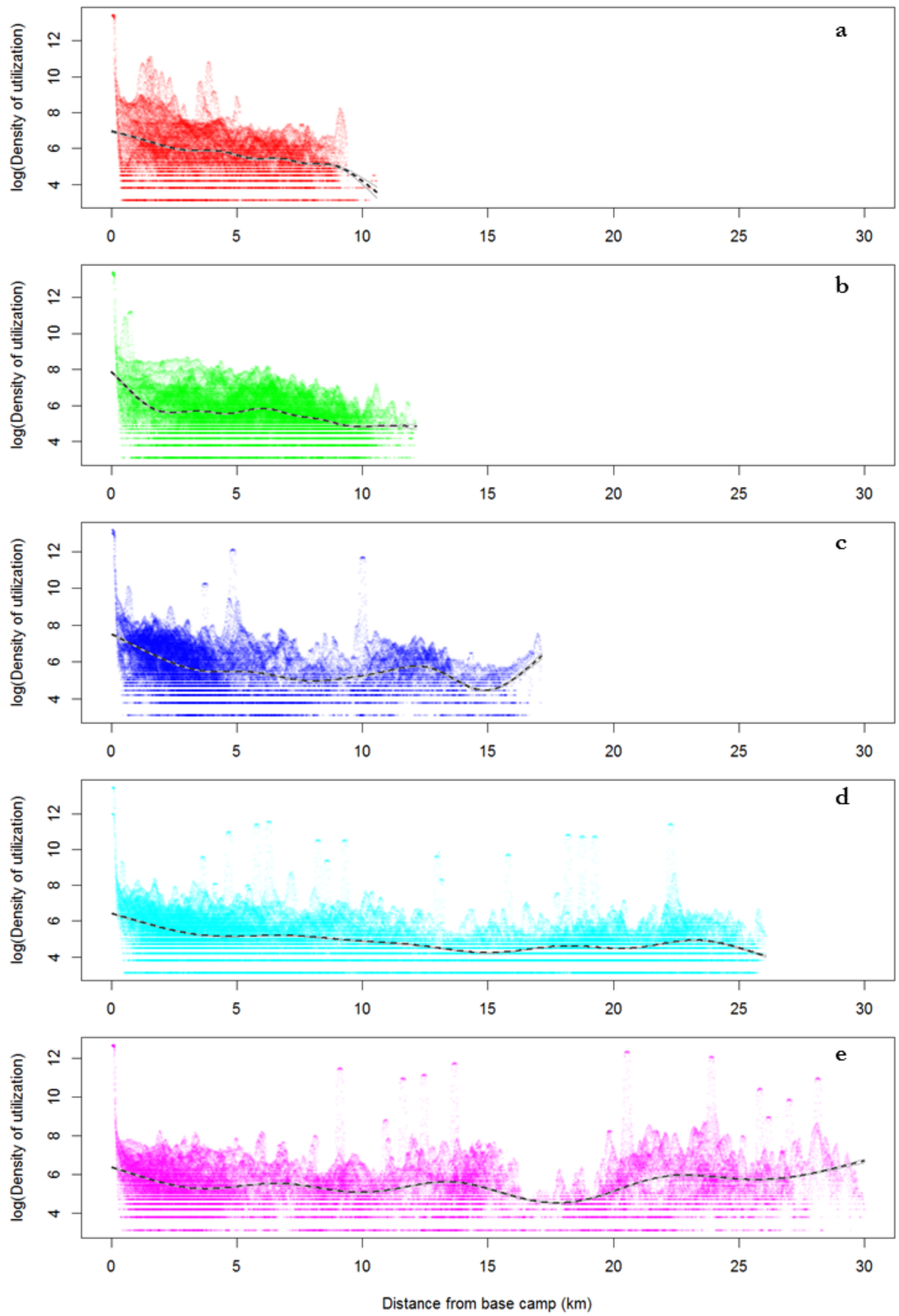

Figure 5. The relationship between density of utilization and distance from base camp locations in Siqu (a), Shomo (b), Irbi (c), Taka Bulti (d), and El Dima (e). The black dotted lines represent predicted density from GAM. The grey lines represent 95% confidence intervals from model prediction.

3.3. Recursive use of rangelands

We investigated the degree of recursive use of rangelands by livestock in the five study sites using GAM. The results indicated cumulative movement extent increased over time, but there were clear differences in the degree of recursive use across sites (Table 4). Specifically, there are two patterns in the cumulative use of rangelands (Figure 6). First, there was an overall trend that the extent of movement expanded as the tracking duration proceeded. Second, the rate of increase reduced as the tracking continued, suggesting that it is likely to reach the maximum extent of movement after the 7-month tracking which included both wet and dry seasons.

Table 4. Estimation of cumulative herding range using GAM.

Variables	Estimate	SE
Intercept	0.503	0.003
Irbi	0.155	0.005
Shomo	0.144	0.005
Siqu	0.180	0.005
Taka Bulti	0.143	0.005
s(duration)	Edf	Ref.df
Duration	5.711	6.865

Note: all estimates are significant at 0.001 level.

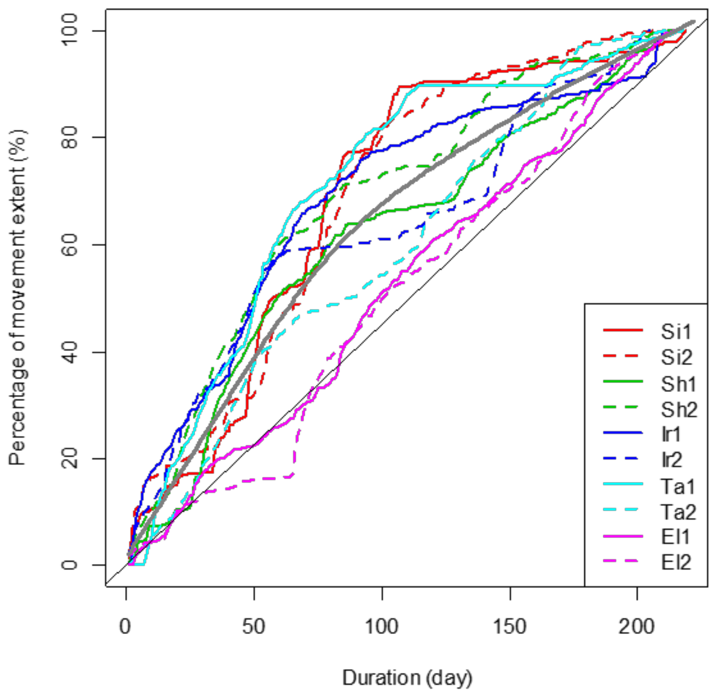

Figure 6. Movement extent and its relationship with duration of tracking. The grey curve represents prediction from GAM. The diagonal line represents perfect non-recursive use of rangelands that for every unit of duration, movement extent increases by one unit. The closer the plotted curves to the diagonal line, the less likely recursive utilization will occur.

Pastoralists in El Dima exhibited the lowest degree of recursive use. As illustrated in Figure 5, the relationship between cumulative movement extent and tracking duration in El Dima is the closest to the perfectly non-recursive use pattern denoted by the 45° diagonal line on the plot. This result suggests El Dima households were constantly searching out and using new foraging areas throughout the tracking period. Despite the greater movement extent mentioned above, Taka Bulti pastoralists showed a higher degree of recursive use that those in El Dima, the reference site in the GAM. This recursive use was likely because Taka Bulti pastoralists had to return to places closer to permanent water facilities at the end of the dry season when surface water sources in their *forra* grazing lands had been exhausted. Other sites showed even higher degree of recursive use. The highest was observed in Siqu, largely because of its constrained movement extent.

The above results also suggest that extent of movement alone may not determine the degree of recursive use. Pastoralists in El Dima and Shomo exhibited similar movement extents but demonstrated very different levels of recursive use of rangelands. Differences in herding strategies between these two sites can explain the observed differences in recursive use. Pastoralists in El Dima were engaged in an extensive form of *forra* herding, while those in Shomo practiced only *worra* herding. These differences in recursive use were clearly evidenced in the spatial distribution of utilization density (Figure 3). In El Dima, pastoralists used multiple small patches of rangelands, which were connected by lightly-used migration routes. In contrast, the Shomo pastoralists attempted to mitigate the disadvantages of giving up *forra* herding by dispersing their livestock in a larger patch of distant rangeland by following fixed corridors between base camps and principal foraging areas. Therefore, the mobility strategy seems to play a more important role in determining the level of recursive use of rangelands.

4. Discussion

The spatial rangeland utilization strategies of pastoralists on ASAL landscapes of the Horn of Africa are demonstratively more complex than suggested by the central-place model and others. In our study, intensive GPS-tracking of cattle herds across seasons and at multiple study sites revealed a complexity in daily and seasonal movement and camp-relocation patterns not captured in previous pastoral mobility research. We addressed the challenge of accurately interpreting herding strategies from GPS-tracking data by conducting multiple rounds of interviews and mapping sessions with participant households. We found the integration of GPS-tracking and direct input from pastoralists essential for a comprehensive study of pastoral mobility and resource-use patterns. Our research was conducted in five study sites which contained sufficient socio-environmental variations in the herding contexts across the Borana Zone of southern Ethiopia. Consequently, the results revealed pastoral mobility patterns that can be generalized across a broader region in the Horn of Africa and, perhaps, other ASAL pastoral regions of the world.

Our research findings indicated the mobility patterns exhibited by Boran pastoralists can be quite diverse. The spatial utilization patterns we observed, however, did not fit well into any existing conceptual models of pastoral mobility (Figure 1). Therefore, we proposed a suite of three new pastoral mobility models which we believe captures the variability in space use by Boran pastoralists (Figure 7).

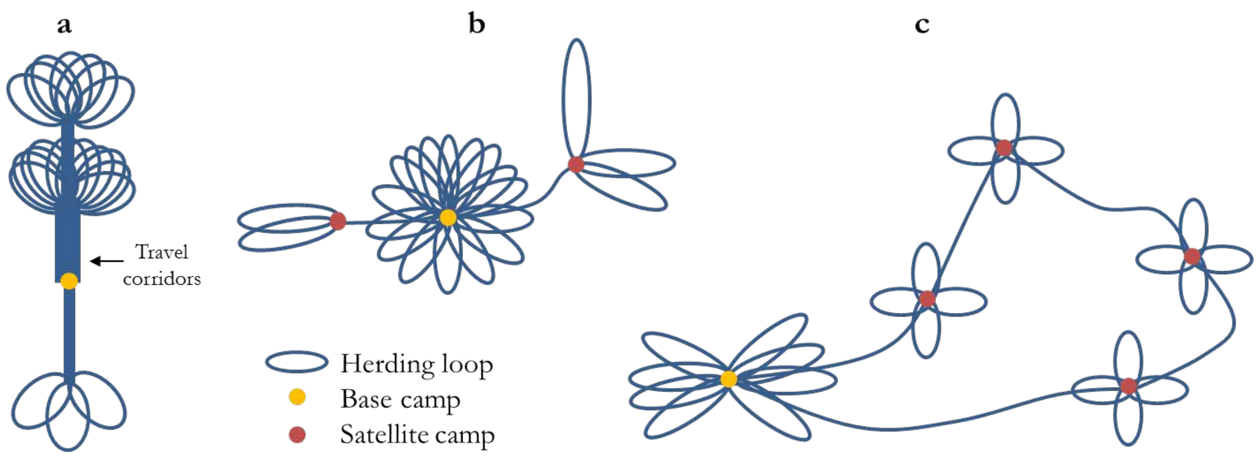

Figure 7. Three conceptual models of pastoral mobility patterns in Borana, Ethiopia.

The first one is a restrictive herding model, which primarily involves linear movement between base camp and the principal foraging areas (Figure 7a). This model describes the *worra*-only herding strategy practiced by pastoralists in Siqu and Shomo. Due to the existence of villages, crop fields, and community rangeland reserves around settlement areas, pastoralists must herd their livestock at a considerable distance away from base camp to find adequate forage. Given these general constraints associated with sedentarized communities, fixed travel corridors were developed between base camps and principal foraging areas, and these corridors could be 3 km or more in length. Due to the lack of foraging opportunities along these corridors, cattle were typically herded at a relatively fast pace on route to the foraging areas in the mornings and back to base camp in the evenings. Because of relatively high population densities and consequent competition for resources among neighboring households, these foraging areas tend to be quite constrained in size and their boundaries are fairly rigid.

The second model in this suite is a semi-extensive herding model, which involves the use of both base and satellite camps (Figure 7b). Although pastoralists may have more than one satellite camp location at their disposal, they usually do not move directly between these camps. Instead, before relocating to another satellite camp, they usually spend some time back at the base camp. The mixture of *worra* and *forra* herding strategies observed in Irbi fits into this semi-extensive model. Lower settlement density and higher resource availability near base camps allowed pastoralists to herd livestock in foraging orbits rather than following heavily-used travel corridors to and from fixed foraging areas as would be observed under the restrictive herding model. Under the semi-extensive model, *forra* herding from satellite camps was practiced when resources around settlements become temporarily depleted. The use of a satellite camp allowed forage near settlement areas time to recover and thus become available for use when the base camp was revisited.

The third model is an extensive herding model, which is founded on a distributed network of satellite camps (Figure 7c). This model best characterizes the mobility patterns observed in Taka Bulti and El Dima. Similar to the semi-extensive model, pastoralists under the extensive herding model used foraging orbits rather than fixed travel routes while herding around base camps. However, in contrast to the semi-extensive model, pastoralists operating under this model moved directly from one satellite camp to the next without an intermediate stop over at their base camps. Pastoralists generally kept their herds at their satellite camps for a large proportion of time in the year, and their extents of movement were typically larger than those under the other two models. Due to relatively low population densities and less competition for resources among pastoralists, the foraging areas under this model tend be larger in size and their boundaries are fairly flexible.

Our observed relationship between density of utilization and distance from base camp disputes the simplistic prediction made by the central-place model or piosphere model. While in four out of five study sites, results from OLS modeling suggests negative relationship between distance from settlement and density of utilization, in El Dima, there is a slight positive correlation between these two variables. The result from GAM, which represented a better fit, suggested the relationships are largely non-linear. The peaks and valleys on predicted curves from GAM showed evidence of multiple grazing opportunities along the distance gradient from base camps, especially in sites where camp relocation was practiced. In addition, as revealed in Figure 3, the directionality of rangeland utilization relative to base camp was not uniform as assumed in previous studies. Pastoralists in our study demonstrated clear directionality preferences in their daily herd movements relative to camp locations. Therefore, pastoral mobility patterns in the Borana Zone are much more complex than can be described by a linear model assuming uniform directionality of utilization pressure.

Recursive heavy livestock use is one of the most important contributors to rangeland degradation (Vetter, 2005). While the extent of movement is certainly an important factor that determines the degree of recursive use, the herding strategy adopted by pastoralists also plays a crucial role to mitigate overgrazing. Although pastoralists practicing either restrictive or extensive herding strategies may demonstrate similar extent of movement, extensively herded livestock exhibit less recursive use because they move in herding orbits that aim to avoid overlapping with previous use. Conversely, resource use under the restrictive strategy tends to be intensely recursive along fixed travel corridors and at the principal foraging areas.

It is also important to recognize that pastoral mobility is inherently complex and resistant to simplistic prediction. Both converging and diverging mobility patterns are observed in the five study sites, which result from many interacting factors at different scales. The distribution and availability of water and forage resources can greatly influence pastoral mobility (Adriansen & Nielsen, 2002). Similar herding strategy practiced by different households in the same community, as shown in the case of El Dima, is primarily a response to the spatio-temporal variation of forage availability within the extent of movement. At the household level, labor availability, composition of livestock species in the herd, and wealth status can also affect how pastoralists make use of rangelands (Boru et al., 2014), which is reflected in the divergent herding strategies adopted by the two pastoralist households in Taka Bulti. Although rare, ethnic conflicts resulting in livestock rustling and even violence can also constrain mobility and increase competition for the remaining grazing resources (Kaimba et al., 2011; Tache & Oba, 2009).

Understanding pastoral mobility patterns can be potentially improved by extending the duration of GPS-tracking studies. Although our tracking period covered both wet and dry seasons, the extent of movement in some cases continued to increase even at the end of the tracking period, albeit at a slower rate (Figure 6). It is likely that mobility may have cyclic patterns extending beyond our study duration, which is beyond the results that can be revealed based on 7-month tracking data. Our GPS-tracking was implemented during normal precipitation conditions, but it is crucial to understand whether sedentarized pastoralists will adopt camp relocation as a coping strategy when extreme drought hits the pastoral system. Therefore, a longer, multi-year study is needed to fully understand and articulate the nature of mobility patterns in the ASAL environment.

5. Policy Implications

Our research findings shed light on the complexity of mobility strategies employed by pastoralists under the varying socio-environmental situations across the Borana Zone of southern Ethiopia. This information is critically needed for the design of effective management policies, which can facilitate sustainable utilization of rangelands by pastoralists and their livestock. It has long been recognized that the key to successful herd management in ASAL environments is the freedom of movement (Niamir-Fuller, 1999), which promotes continuous redistribution of livestock grazing pressure across broad landscapes, thereby reducing the chance of overgrazing and rangeland degradation. However, given a projected warmer and drier climate (Funk et al., 2008) and a surge in human population in the Borana Zone (Coppock, 2016), the future of pastoral livelihoods and their associated need for mobility is indeed complicated. On the one hand, drier climate necessitates extensive movement as a coping strategy. On the other hand, population increases continue to reduce the availability of grazing lands per capita, which constrains livestock movement. And if climate change brings increased incidence of drought, it could reduce typical household herd size and induce a significant shift in herd species composition (Barrett & Santos, 2014). Therefore, pastoral policy-making needs to account for this existing complexity and be flexible enough to accommodate increased complexity as climate-change predictions unfold.

We recommend that future pastoral policy making should prioritize the maintenance and protection of the herding sector so crucial to the livelihoods of Boran pastoralists. Planning and development of crop fields and rangeland reserves should avoid impinging on the directionality options for livestock herd movement. This kind of consideration and forethought could reduce the potential for recursive livestock use and establishment of heavily-impacted travel corridors. In cases where sedentarization is being and will be voluntarily adopted by pastoralists, policy-makers should allow pastoralists to herd livestock within a movement extent that is expansive enough to effectively distribute grazing pressure throughout the landscape. It is crucial to limit the density of settlement clusters and prevent or slow the contraction of available grazing areas to the point where heavy and recursive use of rangelands begins to occur. At a broader spatial scale, grazing resource-sharing agreements among pastoral communities based on the principle of reciprocity need to be promoted and facilitated as a strategy to cope with drought (Kamara et al., 2005). Policies which remove impediments to these agreements would allow drought-stricken pastoralists to migrate to distant, less impacted lands and then reciprocate in turn by sharing their grazing lands with migrant herds. These agreements would foster extensive herd movement patterns that are similar to those illustrated under our third conceptual model at a broad scale (Figure 7c). This increased herd mobility would lessen the stresses of excessive and recurrent herbivory on drought-impacted vegetation, allow more rapid recovery of plant vigor, and decrease mortality losses. Combined efforts to enhance fine- and broad-scale herd mobility can help enhance pastoral system resilience and make pastoralists more prepared to cope with the challenges of overpopulated rangelands, tendencies toward sedentarization, and increases in drought stress brought on by climate change.

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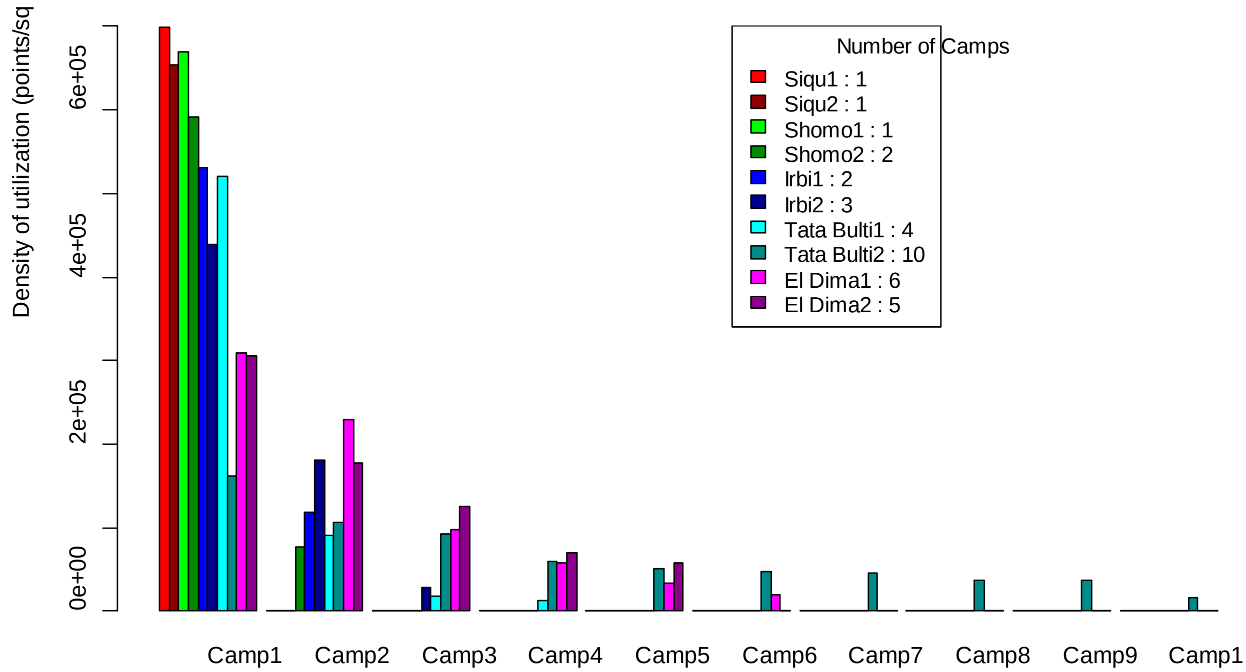

Figure S1. Density of utilization at each camp location of ten cows. Pastoralists in Siqu and Shomo herded their around settlement (Shomo2 used two camps, but the relocation was within the village), while those in Irbi, Taka Bulti and El Dima were engaged in camp relocation. Base camp (Camp 1) showed higher density of utilization, while satellite camps (Camp 2-10) were associated with lower density. In general, the more number of camps used by a cow, the lower the density of utilization will be at the base camp.