COMPLEXITY IN THE OPEN GRAZING SYSTEM: RANGELAND ECOLOGY, PASTORAL MOBILITY AND ETHNOBOTANICAL KNOWLEDGE IN BORANA, ETHIOPIA

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Chuan Liao

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Chuan Liao, PhD

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Abstract: The Borana rangeland was considered one of the most sustainable grazing systems in East Africa until early 1980s; however, intensifying environmental stresses, external development interventions and weakening indigenous institutions are threatening pastoral livelihoods in this region. This dissertation examines these issues by studying the resource base, resource users, and their complex interactions in the open grazing system in Broana, Ethiopia. A mixed method approach was applied in this interdisciplinary research, including plant survey, GPS-tracking, videography, participatory mapping, focus group discussion and in-depth interviews. In terms of resource base, the findings suggested that the Borana rangelands are highly diverse, and the encroachment of woody plants has been stabilizing in the past decade. Although the cover of herbaceous plants generally decreases as grazing intensity increases, woody plant cover could be maintained at a lower level given intermediate grazing pressure. In terms of mobility, pastoralists' spatial utilization of rangelands is highly diverse across the five study sites in Borana, which could be summarized by three conceptual models: sedentarized herding, semi-extensive herding, and extensive herding. Camp relocation, as a crucial strategy to cope with environmental stresses, is largely determined by the broader socio-ecological context of herding, rather than household characteristics. Cattle's resource selection behaviors are strongly driven by environmental covariates, herd management strategies and seasonality. However, other sociocultural and institutional factors also influence cattle behaviors, and the issues of climate change, population increase, and sedentarization further complicate how cattle move in the open grazing system. Pastoralists have accumulated rich ethnobotanical knowledge, which allowed them to assess rangeland quality and palatability, and then adjust their livestock portfolios. Adding more camels and small ruminants into their herds effectively mitigates the negative impact of woody plant encroachment. My research findings also demonstrated how resilience is operationalized in pastoral settings. Future research needs to investigate collective resource-use behaviors, the complex feedback loops between resource base and resource users, and how to truly engage pastoralists in capacity building.

BIOGRAPHIC SKETCH

Chuan Liao grew up near the Yangtze River in the city of Chongqing in southwestern China. He obtained an undergraduate degree in Resource Science and Engineering at Beijing Normal University in 2010. After that he moved to Ithaca, New York, USA to pursue his MS/PhD degree in the Department of Natural Resources at Cornell University. His research interest lies at the intersection between resource conservation and community development. As an interdisciplinary environmental scientist, he worked with Boran and Kazak pastoral communities in East Africa and Central Asia to study their risk perception, livelihood diversification, ethnobotanical knowledge, and interaction with external development agencies. His research also investigates vegetation states and transition pathways in the rangeland ecosystem at multiple spatio-temporal scales. He worked with the Index-Based Livestock Insurance (IBLI) team to deploy GPS collars on livestock to examine pastoral mobility and explore evidence of collective actions in the open grazing system. Chuan joined International Forestry Resources and Institutions (IFRI) and Environmental Spatial Analysis (ESA) Lab in the School of Natural Resources and Environment at the University of Michigan – Ann Arbor as a Postdoctoral Research Fellow in the fall of 2015.

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I would like to first thank the participant pastoral households in Borana, Ethiopia. The household heads in these five study sites are Bidu, Diqa, Godana and Gufu in Siqu; Elema, Jarso, Jirga and Guyo in Shomo; Dida, Kane, Nura and Roba in Irbi; Sasure, Diqa, Wario, and Xache in Taka Bulti; and Abduba, Abudo, Adi and Danbaba in El Dima. Together with their community members, they provided shelter and food whenever I needed. Such hospitality made me feel at home while I was in the field conducting research. Their generosity to hosting me and sharing knowledge is the basis of this dissertation. In addition to the research activities such as interview, focus group discussion and participatory mapping, I also had substantial informal interaction with these pastoralists. All these experiences were crucial in my research. Whenever I was analyzing data or writing dissertation chapters, I always kept in mind of what I observed in the field and what pastoralists told me. Thus, the GPS-tracking data is not just geo-referenced and time-tagged points to me. They are intimately connected with my memory in these pastoral communities.

I am grateful to my dissertation special committee members. I really appreciate Dr. Karim-Aly Kassam's advice to guide me throughout my graduate studies at Cornell over the past five years. His generosity and patience made me feel at home while studying in the US. I thank his support and guidance in pursuing my academic interests. As my special committee chair, he trained me into a well-rounded young scholar who is able to integrate natural and social sciences to investigate the complexity in the real world. It is due to his encouragement and support that I went to Xinjiang to conduct my MS research on pastoralism, which opened a wonderful and exciting research topic that I will stick to in the rest of my academic career.

I appreciate the advice I received from Dr. Christopher Barrett. Thanks to his support, I was able to conduct my dissertation research in Ethiopia. Working in Africa for eight months is definitely a life-changing event in my academic career. Before the start my PhD, I never imaged that I could conduct any research in Africa. Dr. Barrett connected me to the fantastic IBLI research team and made my research plan work in Ethiopia. He also offered tremendous guidance while I was developing my PhD proposal and early drafts of dissertation chapters.

I am also thankful to the advice from Dr. Patrick Sullivan. I took three semesters of his classes, from which I developed essential quantitative data analysis skills. I also appreciate the time he spent on advising me to how to formulate specific research questions and fit the original data into appropriate models in which hypotheses could be tested. Learning these skills and ways of thinking are crucial to me as a scholar.

I equally appreciate the support I received from Dr. Stephen Morreale. I thank his generosity in helping me to develop the research ideas. When I got stuck in my research, he was always so willing to help. He was full of innovative ideas, which broadened my thinking while I was analyzing the data. He also taught me fundament field ecology research skills, which are essential to conduct fieldwork in Borana.

I am so fortunate to have Dr. Patrick Clark as my external committee member. He not only trained me on rangeland ecology theory through directed reading, but also taught me how to conduct field research while we were together in Borana, Ethiopia and Idaho, USA. In addition, he spent a substantial amount of time to guide me in proposal writing and development of dissertation chapter drafts. His advice on how to develop a clear logic flow is invaluable in my academic career.

My dissertation research also highly relies on the logistic support and guidance I received in the field. I am so grateful to the IBLI team based at International Livestock Research Institute (ILRI). I thank Andrew Mude for his leadership and coordination of my fieldwork, and Mohamed Shibia, Birhanu Tadesse and Wako Gabu for their valuable support in Addis Ababa and Borana. I also appreciate Alemayehu Nigussie and Yoseph Gebre, who drove me to the distant study sites where roads were almost non-existent. I am thankful to my field assistant, Galma Shiki, who helped with interviewing pastoralists and collecting voucher specimens. I also appreciate the support from the National Herbarium of Ethiopia at Addis Ababa University. I thank Dr. Ensermu, Dr. Zemede, Mr. Melaku, Mr. Wagee, and Mr. Degafa for their advice on plant identification, and Mr. Ayenu and Tadesse for their assistance on logistics.

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In addition, I also received tremendous support and advice from other professors at Cornell University. I attended two semesters of Dr. Stephen DeGloria's classes on GIS and spatial modeling. He provided valuable support and advice on analyzing NDVI images and GPS-tracking data. I also had access to his lab facilities to process and analyze geospatial data. I took one semester of Dr. Davydd Greenwood's class and had an independent study session with him. He was so patient to help me develop the first drafts of my PhD proposal, and teach me how to conduct ethnographic research in the field. I also appreciate the knowledge I learned from Dr. Melissa Luckow, who introduced me into the field of taxonomy in such a rigorous, intensive and fun approach. Even taking her exams was an enjoyable experience.

Teaching is not part of my dissertation research by definition, but is an essential component in my academic career. I was fortunate enough that in my last year at Cornell, I attended Dr. David Way's class on teaching, which helped me to develop my teaching philosophy and a professional career portfolio, which eventually led to the creation of my personal website. Such training directly fed into my own teaching under the supervision of Dr. Marc Goebel and Dr. Paul Rodewald on Introductory Field Biology and Dr. Richard Stedman on Society and Natural Resources. Experiences of teaching both natural and social sciences not only informed me how to become a versatile teacher, but also fed back into my own research.

I am deeply indebted to the support from family. My wife, Ding Fei, has always been the source of motivation throughout my graduate studies over the past five years. She traveled with me to both Xinjiang and Borana and helped me with my fieldwork. The companion and support from her are indispensable in my academic career. I also thank my parents for supporting my graduate studies in the US. Their encouragement helped me to go through the hardships in my research and other business.

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CHAPTER 1 INTRODUCTION

The Borana rangeland was considered one of the most sustainable herding systems in East Africa until early 1980s (Cossins & Upton, 1987). The past success of livestock herding could be largely attributed to the customary rangeland management institutions, which regulated both fine- and broad-scale seasonal migration activities. The open grazing systems in Borana are common property by definition (Agrawal, 2001; Ostrom, 1990), because it is costly to exclude potential beneficiaries from using the forage resources given the vast size and varying conditions of rangelands. Although there are no fences to delineate boundaries of rangelands for each community, the membership to access the forage resources is always recognized. When drought hits the grazing system, pastoralists typically seek beyond their community herding boundary on the basis of negotiation and reciprocity. Therefore, the open grazing system in Borana does not equal to open access or unmanaged common-pool resources. In fact, there are complex indigenous institutions to regulate access to forage resources, facilitate inter-community resource sharing, and resolve conflicts when tension arises (Legesse, 2000). Access to diverse forage resources distributed in sub-humid, semi-arid and arid environments throughout the entire Borana Zone ensured both rangeland sustainability and livelihood security.

However, three emerging issues are challenging pastoral livelihoods and rangeland sustainability in Borana. First, pastoralists have been experiencing increasing environmental stresses. Drought has been hitting the grazing system more frequently and severely in the past decade, and such trends are projected to intensify in the future (Funk et al., 2008). Although the Boran pastoralists deal with the challenge of dry seasons on a regular basis, the failure of expected rain has usually translated into severe drought. Adding further complication to this issue is woody plant encroachment, which has suppressed the growth of herbaceous forage plants. Once established, bush cover has significantly accelerated the decline in grass cover (Scholes & Archer, 1997). Fire used to perform an essential ecological role in shaping the structure and composition of vegetation on these tropical rangelands. However, a bush burning ban that lasted for 30 years since 1970s (Angassa & Oba, 2008), accompanied with the intensification of grazing, resulted in the failure of thinning the woody plant layer and the depletion of herbaceous plants in the understory.

Second, external interventions, mostly implemented by NGOs in recent decades, have imposed tremendous impacts on the Borana pastoral system (Watson, 2003). With more development interventions flowing into this region, pastoralists have become more dependent on external aid and less likely to develop their own capacity to deal with the socio-ecological challenges. This can largely be attributed to the fact that NGO interventions were generally preoccupied with an objective of generating immediate impacts on the targeted population, which could be showcased to their donors. Accordingly, their projects tended to span a short period of time. In addition, these short-term projects largely overlooked their unintended negative impacts on the pastoral society and rangeland ecosystem. For example, paying pastoralists to manage rangelands and water facilities boosted short-term investment on the grazing lands. However, when these incentives disappeared, pastoralists became unwilling to organize their own labors to clear the bushes on communal rangelands or develop/maintain water facilities. Rather than building community capacity, such development interventions could potentially jeopardize what has been functioning in the Borana grazing system for centuries.

Third, given increasing human and livestock population and declining forage resource quality and quantity, the customary regulations on rangeland management were being compromised or even violated in recent decades (Watson, 2003). As more pastoralists became sedentarized, the traditional resource-use patterns were affected, as well as the ability to endure crisis. Fencing small patches of communal rangelands as private crop fields or rangeland reserves was a likely cause of the collapse of common property resource management institutions. Pastoralists easily ran into conflicts due to competition for limited forage within a confined herding extent. In addition, some pastoralists took cattle into community-owned rangeland reserves at the wrong time of year and violated the collective agreement on access to reserved resources. Water facility management rules were also becoming weaker, largely because the government started interfering by putting pressure on the administrators of the wells, who were no longer permitted to punish those who do wrong. These changes in resource-use pattern were clearly going against the principles of common-pool resource management institutions in Borana in recent decades.

The above three challenges to the Borana pastoral system fundamentally motivated my dissertation research. Although various research has been conducted in Borana over the past decades, efforts to investigate and address the above three challenges remain sparse. There is a lack of systematic evidence to quantify how pastoralists make use of resources and how changes in the environment feed into pastoralists' decision-making on livestock herding. Rigorous research needs to be conducted to reveal the complex feedback loop between resource base and resource users in open grazing systems.

Comprehensive investigation of the above complex issue in the Borana pastoral system is certainly beyond the scope of my PhD dissertation. Consequently, I narrowed down to three specific aspects, namely rangeland dynamics, pastoral mobility, and ethnobotanical knowledge. Starting from these different perspectives, all of my dissertation chapters shed light on one central theme, which is how to maintain the sustainability and resilience of the grazing system.

The next two chapters center on the resource base, namely rangelands. In the past decades, rangelands in the Horn of Africa have been undergoing a rapid shift from herbaceous to woody plant dominance, a phenomenon known as bush encroachment. Quantification of vegetation shifts and mechanisms of transition pathways, however, remained largely unexplored. In Chapter 2, I mapped and quantified, for the first time, the state and the process of woody plant encroachment in the Borana Zone. The results indicated that in 2013, nearly 80% of landscape has been dominated by woody plants. By comparing the scenarios in 2003 and 2013, it is shown that over 70% of landscape remained in the same land cover classes, suggesting that stable encroached states have been established in both high and low lands. In the less dominant land cover classes, there have been substantial shifts in which the canopy layer is thickening. Meanwhile, encroached lands situated at a higher elevation have been converted into crop fields, which have doubled their size in the past decade. This chapter represents a significant advance in our understanding of tropical rangelands as a complex evolving ecosystem.

Disturbance factors, especially livestock grazing, strongly affect rangeland vegetation conditions at the local scale. However, the mechanism of how the understory and canopy of rangelands respond to livestock utilization that is regulated by complex indigenous resource management institution is yet to be explored and articulated. Through intensive plant survey and GPS-tracking of livestock movement, Chapter 3 investigated rangeland vegetation composition and structure, grazing distribution, and the relationship between livestock utilization of rangelands and vegetation cover. The results showed that vegetation structure and composition are significantly different given three distinct land use strategies. Community rangeland reserve exhibited high vegetation cover in terms of herbs, shrubs and trees. Major herding area had moderate herbaceous but low woody plant cover. In contrast, settlement area, which was subject to intensive utilization, demonstrated low herbaceous cover but moderate-to-high woody cover. Analysis of vegetation cover along a livestock utilization gradient suggested that higher grazing pressure generally resulted in lower herbaceous cover. However, woody plant response to grazing was quadratic – an intermediate grazing intensity was associated with the lowest woody cover. The findings implied that moderate grazing pressure appears to be the optimal strategy to balance livestock production and controlling woody plant encroachment.

The next three chapters revolve around resource users, namely pastoralists and their cattle. I was fortunate to work with the IBLI team who deployed GPS collars on 60 cows of 20 households in five study sites that contained sufficient socio-ecological variations within the Borana Zone. Using these data, I first examined and identified general mobility modes, and developed conceptual mobility models to characterize the movement patterns. Built on that, I investigated the camp relocation patterns of Boran pastoralists, which is a crucial strategy to cope with uneven resource distribution in space and time. Then I explored cattle behaviors and their resource selection patterns.

Pastoralists' mobile way of live has long intrigued researchers in multiple disciplines; however, due to the lack of quantitative, continuous and intensive monitoring data, how pastoralists move on the open rangelands is largely unclear. Chapter 4 investigated the spatial rangeland utilization pattern by pastoralists. GPS collars were deployed on cows to monitor their movement, and two rounds of participatory mapping and interviews were conducted with pastoralists to seek their direct input on mobility. Drawing on the quantification of extent of movement, density of utilization and recursive use of rangelands, I found highly diverse mobility patterns in Borana. Given different socio-ecological contexts and constraints, pastoralists employed distinct strategies to manage their herds and have developed different approaches to cope with environmental stresses. Pastoral mobility in Borana can be summarized using three conceptual models: restricted herding model, semi-extensive herding model and extensive herding model. The research findings suggested that sedentarization largely resulted in compromised mobility and led to recursive use of rangelands.

Camp relocation is crucial for pastoralists to track greener pastures in open grazing systems in arid and semi-arid environments throughout the world. However, camp relocation has been rarely studied rigorously due to the lack of intensive and continuous monitoring of livestock movement. Chapter 5 aimed at addressing this gap by modeling pastoralists' camp relocation through an integrated approach. The analysis was based on GPS-tracking of 60 collared cows in five study sites across the Borana Zone in southern Ethiopia, with additional data input from household survey, participatory mapping and interviews. I applied linear mixed-effect models to examine the relationship between camp relocation and a series of ecological and socioeconomic factors at multiple temporal scales. The findings revealed that the three daily herding strategies, namely *worra*, *forra*, and transition herding, were significantly different from each other in terms of travel distance. Community-level factors including resource conditions, resource users and external environment significantly affected pastoralists' camp relocation strategies, while household-level factor such as herd size did not. The results suggested that the broader herding context largely predetermined pastoralists' camp relocation strategy.

Cattle behaviors are crucial to infer fine-scale resource selection patterns in the open grazing system; however, both cattle behaviors and resource selection patterns are poorly understood due to the lack of quantitative, continuous and cross-season monitoring of cattle movement. Based on integration of GPS-tracking and ground-truth evidence, Chapter 6 aimed at linking cattle behaviors with statistical parameters of movement, analyzing spatio-temporal dynamics of behaviors, and predicting resource selection patterns. The research findings indicated that different cattle behaviors were associated with distinct levels of movement velocity, which made it possible to differentiate behaviors from GPS-tracking data. Distribution of the five identified cattle behaviors varied significantly within the time of day and along the distance gradient from camp locations. Results from generalized linear mixed-effects model suggested that resource availability, topography, study site, herding strategy, and seasonality had a significant impact on how cattle select resources. Future modeling of cattle's resource selection needs to incorporate other socio-ecological, institutional and cultural factors to better interpret the complex causal mechanisms in open grazing systems.

The seventh chapter drew on pastoralists' ethnobotanical knowledge to examine the dynamics of rangeland vegetation and livestock production. Pastoral livelihood is largely supported by varieties of forage species on the rangelands. However, the impact of encroaching woody plants on livestock production is yet to be explored. Chapter 7 investigated the implication of bush encroachment by seeking pastoralists' direct input in terms of forage plant species and their palatability to cattle, sheep, goats and camels in Borana, Ethiopia. I interviewed pastoralists regarding their ethnobotanical knowledge and perception of bush encroachment, collected voucher specimens, and identified 252 plant species. Based on their unique palatability to cattle, sheep, goats and camels, these plants can be grouped into six functional categories via the k-means clustering algorithm. I further simulated the dynamics of bush encroachment process and its implications on livestock production. The results indicated that bush encroachment will have most negative impact on cattle, and sheep to a less extent. Camel will be better off as woody plants replace the herbs. Goats are less sensitive to vegetation shifts, as they are generalists rather than pure browsers. Pastoralists have been actively adapting to the bush encroachment process by adding more camels and small ruminants to their herds, while gradually reducing reliance on cattle. Such practices could potentially mitigate negative impacts of bush encroachment on livestock production.

The last chapter summarized the findings of my research on pastoralism and discussed the implication on pastoral resilience. Specifically, I drew upon comparative case studies of pastoral communities in East Africa and Central Asia to operationalize the concept of socio-ecological resilience. I first derived a local subjective definition of resilience based on focus group discussions with pastoralists in Borana, Ethiopia and Altay, Xinjiang, China. Pastoralists generally considered resilience as being able to maintain decent living standard throughout time by keeping viable livelihood strategies. Three surrogate indicators of pastoral resilience were proposed, namely mobility, land use pattern and livelihood diversification. I also analyzed the socio-ecological challenges to resilience in these two pastoral settings. By investigating “resilience of what” and “resilience to what,” this chapter demonstrated that the operationalization of pastoral resilience is highly context-specific. Future pastoral policy-making needs to balance between traditional livestock herding and the emerging demand for livelihood diversification to enhance pastoral system resilience.

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CHAPTER 2 RANGELAND STATES AND TRANSITION PATHWAYS IN BORANA, ETHIOPIA: PHENOLOGY-BASED RANGELAND CLASSIFICATION USING RANDOM FOREST ALGORITHM

1. Introduction

Encroachment of woody plants on open grasslands and savannas has been one of the major threats to the livelihoods of Boran pastoralists and their ecosystems (Oba et al., 2000; Tefera et al., 2007a; Angassa, 2012). Quantitative research has indicated that in the context of East African rangelands, a 10% increase in woody plant cover would reduce grazing capacity by 7% (Oba et al., 2000). On a substantial proportion of the Borana landscape, increasing woody plants density and cover have crossed a certain threshold and entered into an encroached condition. The abundance of woody plants are found to be aggravating the deterioration of rangeland productivity, as they are negatively related to the ecological condition index or weighted palatability composition, while positively related to bare ground cover. This is because the proliferation of woody plants significantly suppress the growth of high-value herbaceous forage plants in the understory (Tefera et al., 2007b). The plausibility of shifting from an open to closed landscape highlights the necessity to map and quantify rangeland types and their distribution, as well as articulate the mechanisms that promote transitions between different land cover classes.

Various efforts have been made to investigate the issue of woody plant encroachment and its impact on the ecosystem. Survey methods were commonly applied to collect ground evidence of rangeland vegetation, in which controlled experiments were usually set up to examine the causal mechanisms between plant growth and environmental gradients (February et al., 2013; Fensham et al., 2014). While providing valuable information on species composition and vegetation structure at a fine spatial scale, these methods can hardly be applied to assess land cover change throughout the landscape due to intensive labor requirement and logistic challenges.

Satellite images provide an efficient alternative approach to investigate rangeland conditions at a broad spatial level (Gartzia et al., 2014). Among them, the Normalized Difference Vegetation Index (NDVI) imageries derived from the red and near-infrared radiance have proven to be effective to analyze rangeland vegetation condition and dynamics (Piao et al., 2006; Kawamura et al., 2003, 2005; Lee et al. 2002; Mueller et al., 2008). In particular, consistently derived time-series NDVI can effectively reveal the phenological features of vegetation, such as the timing, duration, and intensity of growth and senescence (Kerr & Ostrovsky, 2003; Reed et al., 2009). However, land surface vegetation conditions revealed by satellite images were rarely validated with extensive ground evidence in different seasons, especially in remote regions of the world (Reed et al., 2009).

In fact, equating remote sensing based vegetation indices to contextualized measurements has always been a challenge (Jones et al., 2011). This is particularly true in the bush-encroached landscape of Borana Zone in southern Ethiopia, where greener pixels on satellite images actually correspond to encroached bushlands of little grazing value, rather than open grasslands with palatable graminoids and other herbs. Therefore, NDVI must be interpreted with caution, and ground evidence needs to be collected to classify land cover classes and validate research findings. There is a strong need to couple field observations, ecological data and satellite collections to better understand the dynamics of vegetated landscape (Reed et al., 2009). However, in the Borana Zone of southern Ethiopia where infrastructure is extremely poor, logistic challenges resulted in a shortage of ground-truth evidence to map and validate rangeland classification outcomes.

In addition to a poor connection between satellite images and field data, previous mapping efforts rarely interpreted findings based on rangeland ecology theories. Lacking theoretical foundation to guide the rangeland classification efforts has resulted in difficulties in deriving implications from vegetation mapping results. For example, the land cover map by FAO (2007) classified the Borana landscape into 16 land cover classes. However, there was no explanation about the differences between shrubland, bushland and woodland in terms of canopy and understory cover, not to mention their ecological relationships and species composition. Despite providing general information of Borana vegetation, such mapping effort has little value to guide rangeland utilization and management practices. Evolutionary relationships among these identified rangeland types is yet to be articulated to allow for inferring the mechanisms that contribute to an encroached landscape.

Recent rangeland ecology theory has been converging to agree with the disequilibrium hypothesis (Behnke et al., 1993). Built on the Clements (1916) and Gleason (1926) debate started nearly a century ago, scholars pointed out that natural vegetation communities indeed have a multiplicity of stable states (Laycock, 1991; May, 1977; Whittaker & Levin, 1977). Accordingly, rangeland dynamics can be better described as a set of discrete “states” of the vegetation on a specific site and a set of discrete “transitions” between states (Westoby et al., 1989). Transitions from one state to another often require a combination of climatic circumstances and management actions (e.g. fire or grazing) to bring them about. Circumstances which allow favorable transitions represent opportunities, while those threatening favorable transitions represent hazards. Thus, the implication of state-and-transition model for rangeland management is to seize opportunities and evade hazards, with emphasis on timing and flexibility rather than on establishing fixed rules of regulation (Briske et al., 2005).

The application of state-and-transition model for analyzing arid and semi-arid rangelands in Africa is yet to be explored. However, there are a few pilot examples. The model developed by Milton & Hoffman (1994), although crude, represented an advance on understanding the processes that determined the composition of rangeland vegetation types in South Africa. The model was also applied to interpret land cover change in Borana, but was limited to the highland areas in the north-central part of the zone based on plant survey results (Angassa & Oba, 2008). Although it provided preliminary insights into the rangeland dynamics in Borana, it is yet to be validated with empirical evidence at a broader spatial scale.

In order to address the knowledge gaps in rangeland mapping and mechanisms of vegetation transition, this chapter aims at classifying rangeland types throughout the Borana Zone using time-series satellite images and examining the transition pathways among different land cover classes over the past decade. There are two specific research questions: 1) what are the land cover classes and their spatial distribution; and 2) how did rangeland vegetation states shift from 2003 to 2013. I integrated time-series NDVI data and field observations to perform supervised classification using the random forest algorithm. Then I constructed a land cover change matrix, and investigated the transition of vegetation states for each cell in the satellite images. The results indicated that nearly 80% of landscape has been dominated by woody plants in 2013. Over 70% of landscape remained in the same land classes over the past decade, suggesting stable encroached states have been established in Borana.

2. Study Area

The research is conducted in the Borana Zone (43000 km^2) in the southernmost part of Ethiopia (Figure 1). Elevation in this area ranges from 500 to 2500 m above sea level with terrain varying from steep highland slopes to flat, dry river and lake beds in the lowlands. The climate is largely semi-arid with relatively cool annual temperatures (19-24°C) in a tropical setting, and a mean annual rainfall ranging from 300 mm in the lowlands to 1000 mm in the highlands. The annual precipitation distribution is bimodal, with 60% occurring during the long-rain season (April to May) and 30% during the short-rain season (October to November) (Coppock, 1994; Desta & Coppock, 2002).

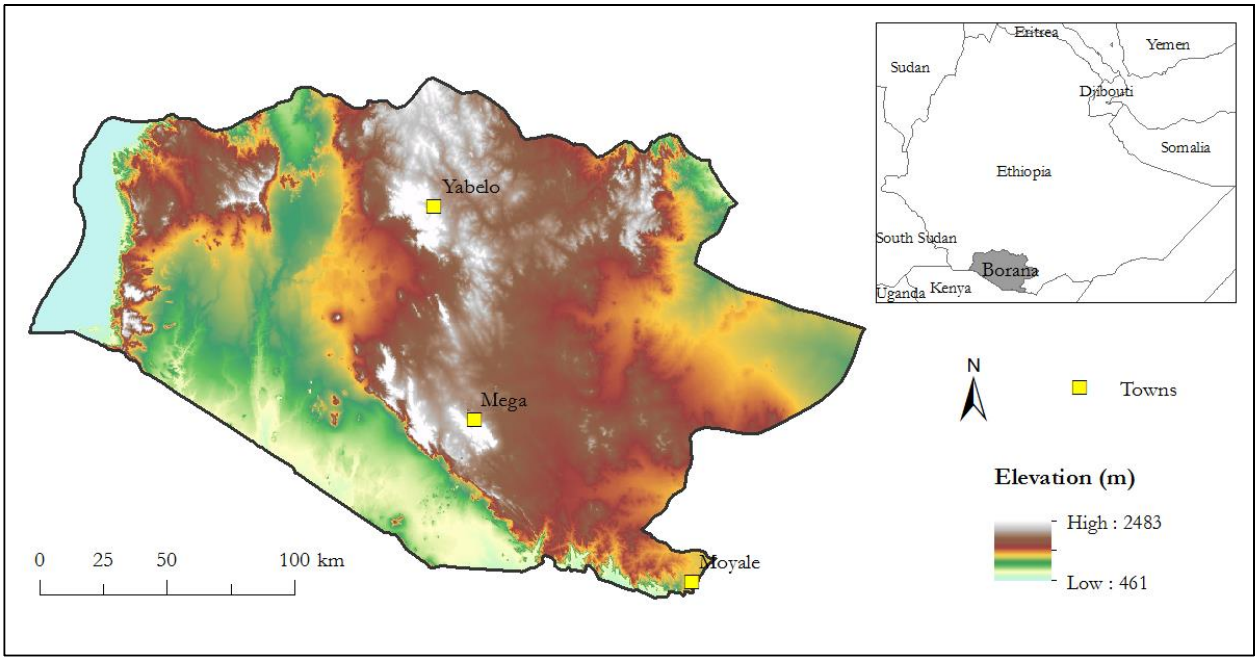

Figure 1. Location and elevation of the Borana Zone in southern Ethiopia.

The vegetation in Borana is co-dominated by herbaceous and woody plants, and its ratio variation results in mosaics of different land cover classes, forming a complex landscape typical in the Horn of Africa (Huntley & Walker, 1982; Sinclair & Norton-Griffiths, 1979). Different combinations of environmental factors interact with each other and result in a spectrum of woody plant cover ranges from 5% to 75% (Coppock, 1994). The ecosystem is endowed with a high potential to shift, as it spans two unstable states among grassland, savanna and woodland (Mayer & Khalyani, 2011). At the higher end of fire frequency and lower end of precipitation, the transition occurs between savanna and grassland. At the lower end of fire frequency and higher end of precipitation, the ecosystem shifts between savanna and woodland with a significant amount of woody plants.

Multiple classification approaches have been developed to distinguish land cover classes in the African rangeland ecosystems. Based on the growth type and relative contribution of woody and herbaceous plants, vegetation could be classified as 1) bushland; 2) woodland; 3) grassland; 4) bushed grassland; 5) wooded grassland; and 6) dwarf shrub grassland (Pratt et al., 1966). According to floristic composition, these lands could be classified as 1) *Acacia drepanolobium*-*Pennisetum mezianum*; 2)

Bidens hildebrandtii-Chrysopogon aucheri; 3) *Chrysopogon aucheri-Commiphora Africana*; 4) *Cenchrus ciliaris-Chrysopogon aucheri*; 5) *Acacia bussei-Pennisetum mezianum*; 6) *Commiphora erythraea-Sansevieria ehrenbergii*; 7) *Acacia melliphera-Setaria verticillata*; and 8) *Heterpogon contortus-Hildebrandtia obcordata* (Dalle et al., 2005). In addition to scientific classification systems, indigenous pastoralists also developed their own classification approach by considering vegetation physiognomy, soil and topographic features. These classes included 1) *Wayama*: red soil bushy vegetation; 2) *Chaari*: basement complex heterogeneous uplands; 3) *Kobe*: sandy-clay upland wooded grassland; 4) *Malbe*: volcanic soils bush climax; 5) *Booji*: lime stone grassland; and 6) *Kooticha*: bottom land-vertisol soils (Oba et al. 2000). All these classification approaches were complementary to each other and provided valuable information on interpreting vegetation characteristics in Borana.

3. Methods

3.1. Rangeland classification criteria

In order to establish context-specific rangeland classification criteria, I conducted pilot fieldwork in February, 2013. Built on the United Nations Food and Agriculture Organization standards (Di Gregorio, 2005), I came up with 8 land cover classes to describe the variation of rangeland vegetation in the Borana Zone, in which I considered both physiognomic features and species composition (Table 1).

Table 1. Land cover classes, codes and brief descriptions. Land cover classes are summarized according to the order of decreasing woody plant coverage in general.

Land cover	Code	Description
Closed Canopy Woodland	CCW	A stand of trees with an interlaced canopy, usually with shrubs interspersed, and a tree canopy cover over 50%. CCW is usually distributed above 1500 m. Dominant tree species include *Juniperus procera*, *Combretum molle* and *Terminalia brownie*.
Dense Scrubland	DS	An assemblage of woody plants, mostly of shrubby habit, having a shrub canopy cover over 50%. The basal cover by grasses and herbs is at a low to intermediate level, between 20% and 40%. DS is usually distributed above 1000 m with a relatively wet climate. Dominant woody species include *Acacia drepanolobium, A. nilotica* and *A. hockii*.
Bushland	BU	Land dominated by shrubs with scattered trees. The basal cover is usually less than 30%. BU is usually distributed below 1000 m with a relatively dry climate, but it has the potential to shift into DS as canopy closes. Dominant woody species include *A. mellifera* and *A. reficiens*.
Open Canopy Woodland	OCW	A stand of trees with open canopy, usually with few shrubs interspersed, and a canopy cover less than 40%. The basal cover by grasses and herbs is at an intermediate level between 20% and 50%. Dominant tree species include *A. tortilis* and *Commiphora africana*.
Sparse Scrubland	SS	Land with scattered or grouped shrubs. The shrubs are always conspicuous, but trees are sparse, with a canopy cover between 10% and 30%. Growth of grasses is somewhat suppressed, with a basal cover between 10% and 20%. This type of land cover represents the state between GR and DS. Major woody species include *Solanum giganteum* and *Hibiscus boranensis*.
Cultivated Land	CL	Land being used for crop cultivation. Common crops include *Zea sp, Sorghum sp* and *Erogrostis tef*. CL is usually fenced and located at higher elevation, and sometimes close to seasonal rivers.
Grassland	GR	Land dominated by grasses and occasionally other herbs, with a basal cover over 40%. The widely scattered trees and shrubs can contribute to a canopy cover that rarely exceeds 10%. Major herbaceous species include *Cenchrus ciliaris*, *Chrysopogon auheri*, *Enneapogon persicus* and *Panicum maximum*.
Sparsely Vegetated Land	SV	Land poorly covered by either herbaceous or woody plants. The basal and canopy covers rarely exceed 10%. SV either represents the result of heavy grazing on the newly established grassland, or merely bare ground dominated by rock, sand or lava. The top soil is usually lost due to low basal cover.

3.2. Rapid vegetation assessment

In contrast to previous land cover research that primarily used indirect evidence as training points in supervised classification (Gartzia et al., 2014), I conducted rapid vegetation assessment to link remote sensing based vegetation indices with contextualized land cover classes. The majority of ground evidence was collected in May-September, 2013, with additional data obtained in April-August 2014. These data collection periods covered both wet and dry seasons. I used the Nikon GPS camera to take pictures of rangelands along major roads and in specific study sites (see Chapter 4). In addition to a picture of land cover class, the camera also recorded geographic coordinates and time. This approach allowed for rapid vegetation assessment and collection of a large sample size. In comparison to other land cover mapping efforts that predominantly used various forms of climate data to validate satellite-derived measures, I obtained sufficient field observations in both wet and dry seasons. Therefore, the ground-truth evidence, coupled with satellite imagery, was intended to effectively address a gap in land cover mapping in one of the most remote regions of the world.

In addition to the ground-truth pictures, I included 39 locations at the far west and southwest corners of Borana Zone, which is inaccessible by a four-wheel drive vehicle. For these remote areas, I used Google Earth and Bing Map images to determine the land cover class. In addition, I validated those land cover types with participant pastoralists who visited these areas in my third round of fieldwork in 2014.

Using the above two approaches, a total of 1866 valid training points were collected. Pictures taken in the field were classified based on the criteria in Table 1. Picture details, including time and location, were extracted using Nikon ViewX2 software. Among the 1866 training points, I identified the following land cover classes: 85 CCW, 278 OCW, 615 DS, 256 SS, 388 BU, 68 GR, 172 CL, and 4 SV. These training points are mostly distributed along major roads in Borana, and covered both high and low land areas of the entire zone (Figure 2).

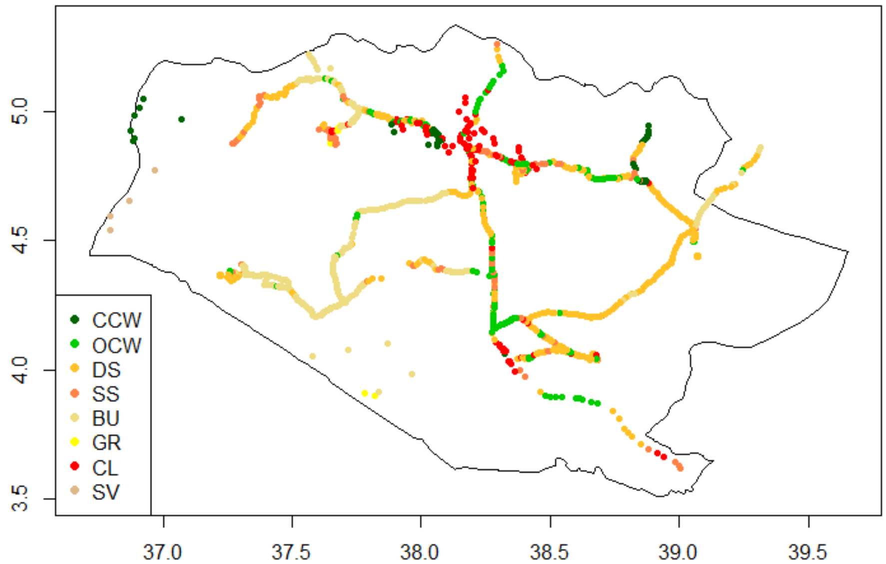

Figure 2. Locations of field data collection and land cover classes

3.3. Satellite images

Satellite images were used to quantify the spatio-temporal changes of land cover in Borana. Multi-temporal data sets such as those from Moderate-resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite, which is available for worldwide coverage since 2000, have made it possible to study land cover change in the most remote regions of the world. Specifically, I used the MODIS NDVI data, with a spatial resolution of 250 m and temporal resolution of 16 days acquired from MODIS, as the data input for rangeland classification. Since the majority of training points were collected in the year of 2013, I used the 23 images from that year in my classification. I also obtained the 23 images in 2003 to investigate the vegetation states a decade ago.

3.4. Data analysis

I conducted supervised classification using the non-parametric random forest classifier. The random forest algorithm is not constrained by parametric restrictions and is not sensitive to collinearity and overfitting of the data, allowing the use of layers with potential collinearity issues (Rodriguez-Galiano et al., 2012). The method takes random subsets from a training dataset and constructs classification trees using each of these subsets. Trees consist of branches and leaves. Branches represent nodes of the decision trees, which are often thresholds defined for the measured variables in the dataset. Leaves are the class labels assigned at the termini of trees. Sampling many subsets at random results in many trees being built. Classes are then assigned based on classes assigned by all of these trees based on a majority rule, as if each class assigned by a decision tree is considered a vote. The classification was performed using the randomForest package in the R software environment (Liaw & Wiener, 2002; R Development Core Team, 2014).

In this study, the 23 images available throughout the year were considered 23 predictor variables. Rather than using a signal snapshot or an average of annual NDVI, these 23 images characterize the periodic life cycle events of rangeland vegetation, including the seasonal timing of growing seasons, canopy growth and senescence that can potentially distinguish each land cover class. In this way, the phenological features of land covers were taken into consideration in the supervised classification (Brandt et al., 2013). I used three quarters of ground-truth evidence as training data, and the rest was used to generate confusion matrix[1] for accuracy assessment.

I also investigated the spatial distribution and phenological features of each land cover class. Specifically, I extracted the elevation and slope information for each cell in the satellite image to examine the topographic niche of each class. I conducted Analysis of Variance (ANOVA) to test whether the niches are different for each land cover class. The general additive model (GAM) was used to investigate the phenological features of land cover classes. The response variable is NDVI. The predictors include

[1] Confusion matrix contains information about actual and predicted classifications done by a classification system. It is a specific table layout that allows visualization of the performance of an algorithm, typically a supervised learning one.

date in the year (continuous) and land cover class (categorical). The analysis was conducted at the cell level. However, there is a total of 688100 cells within the Borana Zone. Such a sample size is beyond the computational power of R. Therefore, I randomly selected 1% of the cells to perform GAM. Since the mean NDVI curve of open canopy woodland is the closest to sample mean, I used it as the benchmark land cover class in the model.

In order to identify land cover transition pathways from 2003 to 2013, I constructed a land cover change matrix from the two classified land cover raster images. The analysis was at the cell level as well. This approach made it possible to not only identify which part of rangelands changed their land cover features, but also reveal the pathway of transition.

4. Results

4.1. Land cover classes

The classification results indicated substantial variation in the distribution patterns of eight land cover classes across the Borana Zone (Figure 3). These land classes occupy different topographic niches in terms of elevation ($F_{7,\ 687894} = 58939$, p-value < 0.001) and slope ($F_{7,\ 687894} = 26224$, p-value < 0.001) (Figure 4). Overall, the entire zone is highly encroached by woody plants. In 2013, the two land cover classes that were dominated by woody plants contributed to over 80% of total land area. As the most expansive class, dense scrubland covered 57.8% of the zone. This scrubland class was mainly distributed in the eastern and northern part of Borana, with an average elevation around 1350 m. The other type of dominant land class, bushland, covered 23.2% of landscape. In contrast to dense scrubland, the bushland was mostly distributed in the lowland in the southwest with an average elevation that is approximately 400 m lower.

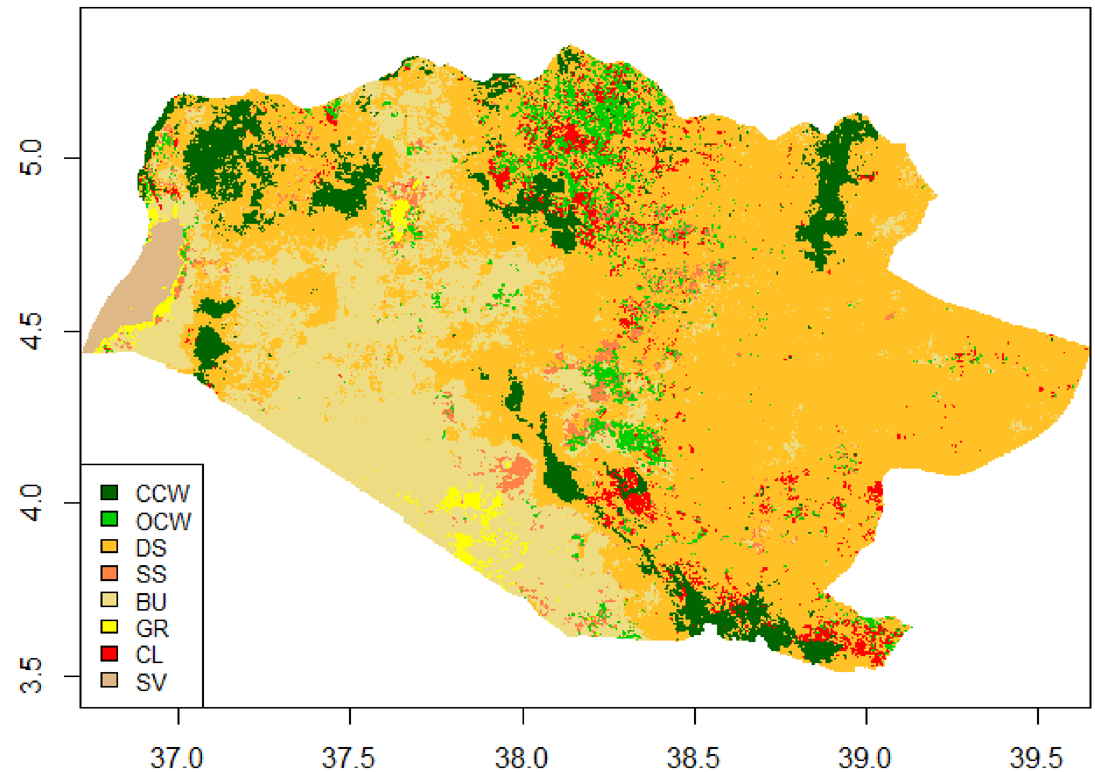

Figure 3. Rangeland classes and distribution in 2013. Dense scrubland and bushland dominated the landscape, accounting for over 80% of Borana Zone.

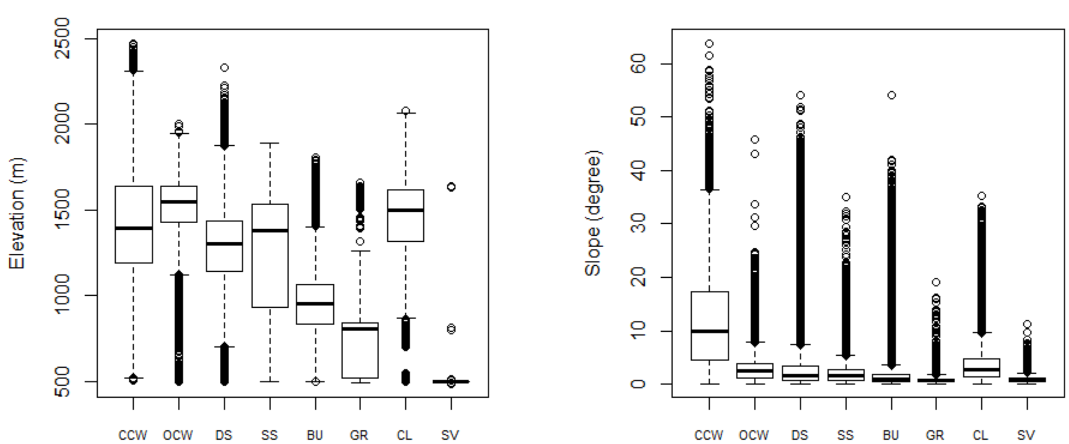

Figure 4. Elevation and slope of each land cover class.

The remaining 20% of the zone was covered by the other six classes. Closed canopy woodland, representing 7.6% of the total area, primarily occupied the highland area above 1400 m. However, this type of woodland had the potential to span across a wide range of elevation given favorable environmental conditions, as it stretches from 511 m at 10% value to 2300 m at 90% value (Figure 4). In contrast to other classes, closed canopy woodland was more likely to occur in the hilly areas. Its average slope is over 10 degrees, which was three times of the sample mean.

Open canopy woodland, which was the typical savanna-like class, represented merely 3.8% of landscape. Once the dominant land cover type on the Borana rangelands, it was restricted to the north and central part of the zone. Its spatial distribution was also very patchy, often nested within dense scrubland, cultivated land and closed canopy woodland.

Cultivated land was the next prevalent land cover class, which represented 3.0% of landscape. In general, cultivated land tended to appear in the highland, with a mean elevation around 1500 m. It was also more likely to occur in relatively hilly areas. Such a topographic niche might be more favorable for crop cultivation. In terms of spatial distribution, most cultivate land appeared near townships such as Yabello, Mega and Moyale.

Sparse scrubland represented scattered shrubs that occupied 2.2% of total area. It was more likely to occur in the highlands around 1400 m, although it had a wide altitudinal range of distribution. This land cover class had a potential to shift into dense scrubland due to sharing a similar topographic niche.

Sparsely vegetated land, which represented 1.4% of total area, was mostly distributed in the far western corner of Borana Zone. It had the lowest average elevation at 510 m. Largely occurring as an entire patch, this land cover class occupied a dried lake bed that was barely covered with any plants. On the edge of it there was a belt of grassland and bushland. Farther away from the flood plain up the hill, dense scrubland and closed canopy woodland dominated the landscape.

Grassland was the least common land cover type in Borana. It occupied 1.1% of landscape, and was mainly distributed in the lowland flat area. Its mean elevation was approximately 750 m, with an average slope at 3 degrees, which were the lowest except sparsely vegetated land.

Validation of classification results indicated that the overall accuracy of classification was 76.1% (Table 2). Among the eight land cover types, grassland and sparsely vegetated land were perfectly validated according to producer's accuracy. Closed canopy woodland had an accuracy over 95%. The two dominant land cover classes, namely dense scrubland and bushland, were also well classified, with an accuracy index over 85%.

Table 2. The confusion matrix of classification results. Producer's accuracy presents the fraction of correctly classified cells with regard to all cells of that ground-truth class. User's accuracy is the fraction of correctly classified pixels with regard to all cells classified as this class in the classified image.

Land Cover	CCW	DS	BU	OCW	SS	CL	GR	SV	Producer's Accuracy
CCW	20	0	0	0	0	1	0	0	95.2%
DS	0	133	6	7	6	4	0	0	85.3%
BU	0	8	82	2	2	1	1	0	85.4%
OCW	0	22	6	37	5	2	0	0	51.4%
SS	0	8	3	9	39	3	1	0	61.9%
CL	0	5	0	4	4	23	0	0	63.9%
GR	0	0	0	0	0	0	16	0	100.0%
SV	0	0	0	0	0	0	0	1	100.0%
User's Accuracy	100.0%	75.6%	84.5%	62.7%	69.6%	67.6%	88.9%	100.0%	76.1%

The remaining three classes were less accurately classified. Among the 36 cultivated land validation points, 13 were misclassified as open canopy woodland, dense or sparse scrubland. This was likely because cultivated land was usually converted from these three land cover classes, thus often nested within them. In addition, since the size of cultivated land was usually less than the NDVI cell size (6.25

hectares) in many cases, they were more difficult to distinguish at that resolution. Sparse scrubland showed a similar accuracy index, which was likely because it was often confused with open canopy woodland and dense scrubland. The lowest accuracy was observed with open canopy woodland, which was the typical savanna-like type. It was most likely to be confused with dense scrubland, into which this land cover class was shifting.

4.2. Phenological features of land cover classes

Land cover classification by random forest algorithm revealed distinct phenological features for the eight classes. Regression results from GAM suggested that NDVI values varied significantly throughout the year (Table 3). In addition, all land cover classes were significantly different from open canopy woodland, although the degree of difference was different. In general, land cover classes with higher woody plant coverage than open canopy woodland demonstrated positive coefficient, while those with less woody plants showed negative estimates. The only exception is cultivated land, which is largely managed by people.

Table 3. General additive model regression results

Variables	Estimate	Std. Error	t value
Intercept	0.309^{***}	0.002	147.830
Date	0.003^{***}	0.000	45.797
CCW	0.215^{***}	0.002	90.553
DS	0.094^{***}	0.002	45.978
BU	0.025^{***}	0.002	12.000
SS	-0.015^{***}	0.003	-4.492
CL	0.054^{***}	0.003	19.097
GR	-0.121^{***}	0.004	-30.506
SV	-0.243^{***}	0.004	-68.488

Note: *** indicates significant at 0.001 level

Mean NDVI curves of eight land cover classes illustrated their distinctive phenological features (Figure 5). Among these eight curves, sparsely vegetated land and grassland did not intersect with any other ones and represented the two land cover classes with consistently low mean NDVI values throughout the year. In contrast to other curves that exhibited a bimodal distribution pattern, the NDVI curve of sparsely vegetated land fluctuated around a value of 0.1. The two rains in the year did not green up this class as they did for all others. Grassland showed a bimodal curve as other six classes, but its mean NDVI value was consistently lower than others at all times of year. Arguably, the lack of woody layer in grassland resulted in relatively low NDVI. The unique phenological feature of grassland ran counter to the common perception that higher NDVI values indicate better quality forage.

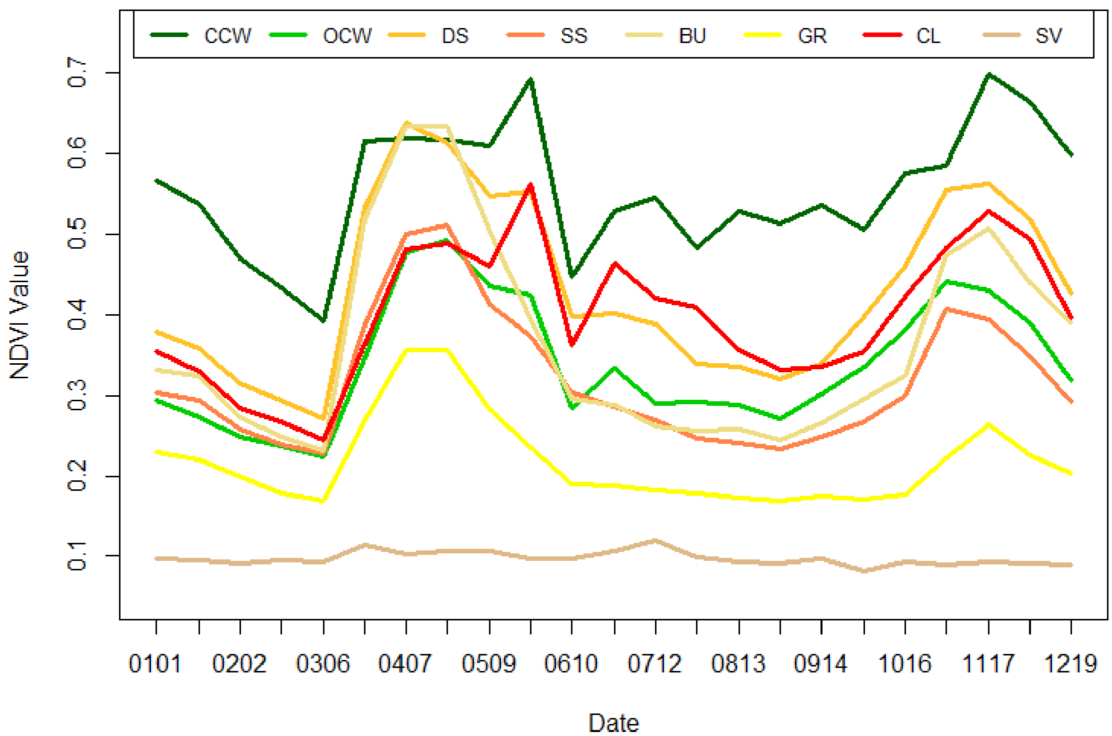

Figure 5. Mean NDVI curves of eight land cover classes

Contrarily, closed canopy woodland stood out of the others because of its high overall mean NDVI value. Except for a few periods in the major rain season, its NDVI value was consistently higher than all other classes. It is likely that dense tree canopy contributed to the observed high NDVI values throughout the year.

The other five classes largely intersected with each other. However, certain phenological features allowed the random forest algorithm to distinguish them. Dense scrubland was characterized by two high peaks in the two rain seasons. During dry season, it still maintained a high NDVI value. In contrast, bushland, which was also dominated by shrubs, exhibited lower NDVI values during the dry season despite its high greenness in the rain season. Dominated by deciduous woody plants such as *A. mellifera* and *A. reficience* that drop their leaves soon after the wet season, high NDVI values could not be maintained for a long period. Sparse scrubland, with highly scattered shrub layer, demonstrated much lower NDVI in contrast to dense scrubland and bushland throughout the year.

Open canopy woodland exhibited a very similar phenological feature to sparse scrubland. According to GAM estimates, these two classes were the closest to each other. However, because of its intermediate tree layer cover by species such as *A. tortilis*, it had higher NDVI values in the dry season. Thus, it was the distinct signals from June to October that distinguished it from sparse scrubland.

Cultivated land was the only land class that was largely tended by human beings. The scattered trees on these crop fields made it less green. However, since it was under human management, it exhibited the second highest NDVI values during the dry season, only after closed canopy woodland. This distinct dry season window distinguished it from all other land cover classes.

4.3. Land cover change

In order to detect land cover change in the past decade, I also classified the 2003 land cover classes using the same algorithm and training data. Comparison between 2003 and 2013 land cover maps indicated that over the past decade, while the rank of dominance largely remained the same, substantial transitions were happening in the rangeland ecosystem (Table 4). The chi-square test of the composition of land cover classes suggested significant differences between these two years ($\chi^2_{7,\,699243}$ =11618, p-value < 0.001).

Table 4. Land use change from 2003 to 2013

Land Cover	Area Changed (km^2)	Proportion of Change	2003 Area (km^2)	2013 Area (km^2)
DS	1809.05	7.85%	23045.62	24854.67
CL	669.45	105.50%	634.54	1303.99
CCW	64.07	2.01%	3186.29	3250.36
SV	-3.92	-0.63%	624.73	620.81
GR	-167.64	-26.73%	627.14	459.50
SS	-653.42	-40.97%	1595.04	941.62
BU	-857.11	-7.92%	10818.55	9961.44
OCW	-860.48	-34.78%	2474.09	1613.62

Overall, land classes such as dense scrubland, cultivated land and closed canopy woodland expanded, while open canopy woodland, sparse scrubland, bushland and grassland diminished to varying degrees from 2003 to 2013. The greatest net gain occurred to dense scrubland, the already dominant land cover class with substantial woody plant coverage. The increment in this land cover class represented over 70% of positive land cover change, suggesting that the landscape is being further encroached. Substantial positive change also happened to cultivated land, with a net gain of 669 km^2. This man-made landscape replaced sparse scrubland and became the fifth most common land class in Borana. Closed canopy woodland experienced slight positive change, with a gain of merely 64 km^2. In terms of loss, the greatest decline happened to open canopy woodland, the typical savanna-like land class. A total of 860 km^2 in this class was lost, representing over 34% of change. A similar area of bushland also disappeared, but this represented only 8% loss. Sparse scrubland experienced the third greatest loss, with a deduction of over 650 km^2, but it represented the highest proportion of loss at over 40%. Grassland, despite of its small total area, continued to reduce an area of 167 km^2. In contrast to the other seven vegetated classes, sparsely vegetated land showed negligible change over the past decade.

The rate of change varied substantially among the eight types. In general, greater rate of change happened to the less dominant land classes. Among them, cultivated land doubled its size, increasing from less than 1.5% in 2003 to over 3% in 2013. In contrast, sparse scrubland reduced over 40%, open canopy woodland declined nearly 35%, and grassland decreased by more than 25%. Changes in closed canopy woodland and sparsely vegetated land were minimal. The two dominant land cover classes demonstrated minor changes in terms of proportion. While dense scrubland increased about 8%, bushland decreased about 8%.

Directions of land cover shifts revealed more details on the pathways of transition. Comparison between 2003 and 2013 land cover map at the cell level suggested that 30% of the land in the entire Borana Zone changed their cover (Table 5). Among the eight land cover classes, sparsely vegetated land was the most stable class. Over 98% of land area in this class remained the same. After that, dense scrubland, bushland and closed canopy woodland also maintained over 70% of their area from 2003 to 2013. Since the two dominant classes were stable, the overall land cover change throughout the Borana Zone was not drastic. However, it is worth pointing out that although bushland was diminishing, this land cover class was shifting into dense scrubland, which is a more encroached vegetation state.

Table 5. Land cover transition matrix in the past decade (unit = km^2)

Land Cover	CCW	DS	BU	OCW	SS	CL	GR	SV	2003 Total	% Remained in 2003
CCW	2318	823	35	1	5	39	0	0	3221	72%
DS	935	19093	1690	578	233	871	33	0	23433	81%
BU	29	3077	7367	121	221	28	158	1	11003	67%
OCW	10	1191	248	629	236	185	16	0	2514	25%
SS	1	709	379	189	237	72	27	0	1613	15%
CL	2	355	18	124	19	129	1	0	647	20%
GR	0	0	398	6	7	1	218	7	637	34%
SV	0	0	0	0	0	0	11	622	634	98%
2013 Total	3295	25248	10134	1648	957	1325	464	631	43703	70%
% Remained from 2003	70%	76%	73%	38%	25%	10%	47%	99%		

Note: The rows show the sum are of each land cover class in 2003, and the last column summarizes the percent of lands that remained for each class in 2003. The columns show the sum area of each class in 2013, and the last row summarizes the percent of lands remained from 2013.

However, for the remaining less dominant four classes, no more than 40% of land area stayed the same. The general transition pathway is from a less encroached state to a more encroached state. For grasslands, only 218 km^2 out of 637 km^2 remained in the same class. The greatest loss was the transition into bushland, representing a net decrease of 240 km^2. For open canopy woodland, 629 km^2 out of 2514 km^2 remained the same. A total of nearly 625 km^2 land area shifted into dense scrubland, representing the greatest decline in this class. Another approximately 125 km^2 of this class transitioned into bushland and 63 km^2 lost to cultivated land. Sparse scrubland maintained less than a quarter of its land area from 2003. Transitions into dense scrubland and bushland represented the greatest loss of this class. Cultivated land is the lowest group – less than 10% of land area remained from 2003. Expansion of this class was sustained by converting dense scrubland, open canopy woodland, and sparse scrubland into crop fields.

5. Discussion

The above findings indicate that rangelands in Borana can be effectively classified into eight land cover classes using the random forest algorithm. Each land cover class was associated with a unique topographic niche and exhibited distinct phenological features. Different species composition and vegetation structure made it possible to distinguish these land cover classes that are nested within each other. The results suggested that greener cells do not necessarily represent high quality rangelands for the purpose of cattle grazing. In fact, rangelands with higher woody plant cover were typically associated with higher NDVI values. In contrast, open grassland had consistently lower NDVI values than all land cover classes other than the sparsely vegetated.

In the past decade, there has been a significant change in land cover classes in the Borana Zone. Woody plants continued to establish themselves, which contributed to a denser canopy layer on the already encroached landscape. Multiple socio-ecological factors that interacted with each other influenced the transition pathways among the land cover classes. Before the official ban on fire, the rangeland, under moderate grazing pressure, was dominated by open canopy woodland. Its transition into open grassland was usually facilitated by the use of fire, although the process might take up to 30 years or more (Coppock, 1994). In the traditional grazing system, one site could be abandoned with a smaller social cost, and physical energy would be slowly gained by a rebound of herbaceous plants and associated litter previously suppressed by the combination of shrub competition and grazing. Over time, fine fuels would reach to the point at which fire could spread. Low-intensity fires would occur at first, reopening the bush canopy, thus facilitating understory production. Once in several decades, a stand-replacement fire would reset the system back to open grassland. As a result, the Borana rangeland was long considered the most productive type in the Horn of Africa (Cossins & Upton, 1988).

However, given the fire regulation started in the 1970s and increasing human population, site abandonment can hardly be an option to facilitate the above transition process. The declining condition of rangeland is becoming evident in recent decades. Increasing densities of human population denied the possibility of free relocation as previous generations did after resources were depleted in certain locations. Recent research indicated that grazing disturbance has already exceeded a certain threshold of degradation, as the vegetation variables along the distance gradient from settlement or water sources showed no significant differences (Tefera et al., 2007a). Although the government recently realized the importance of fire and has encouraged pastoralists to burn woody plants, the fuel load required to initiate canopy fire had been diminished due to heavy grazing pressure and woody plant proliferation.

Based on directions of land cover change in the Borana rangeland system, and by considering both broad-scale climatic factors and local-scale disturbance factors, I proposed the following transition pathways among the eight land cover classes (Figure 6). Overall, the Borana rangelands are no longer subject to the common perception that rangelands are dominated by open grasslands. On one hand, with fire prohibited from 1970s to 2000s, transition pathways from bushland, dense or sparse scrubland to grassland were cut off. On the other hand, grazing pressure and woody plant recruitment facilitated the transition of grassland into other shrub-encroached landscapes.

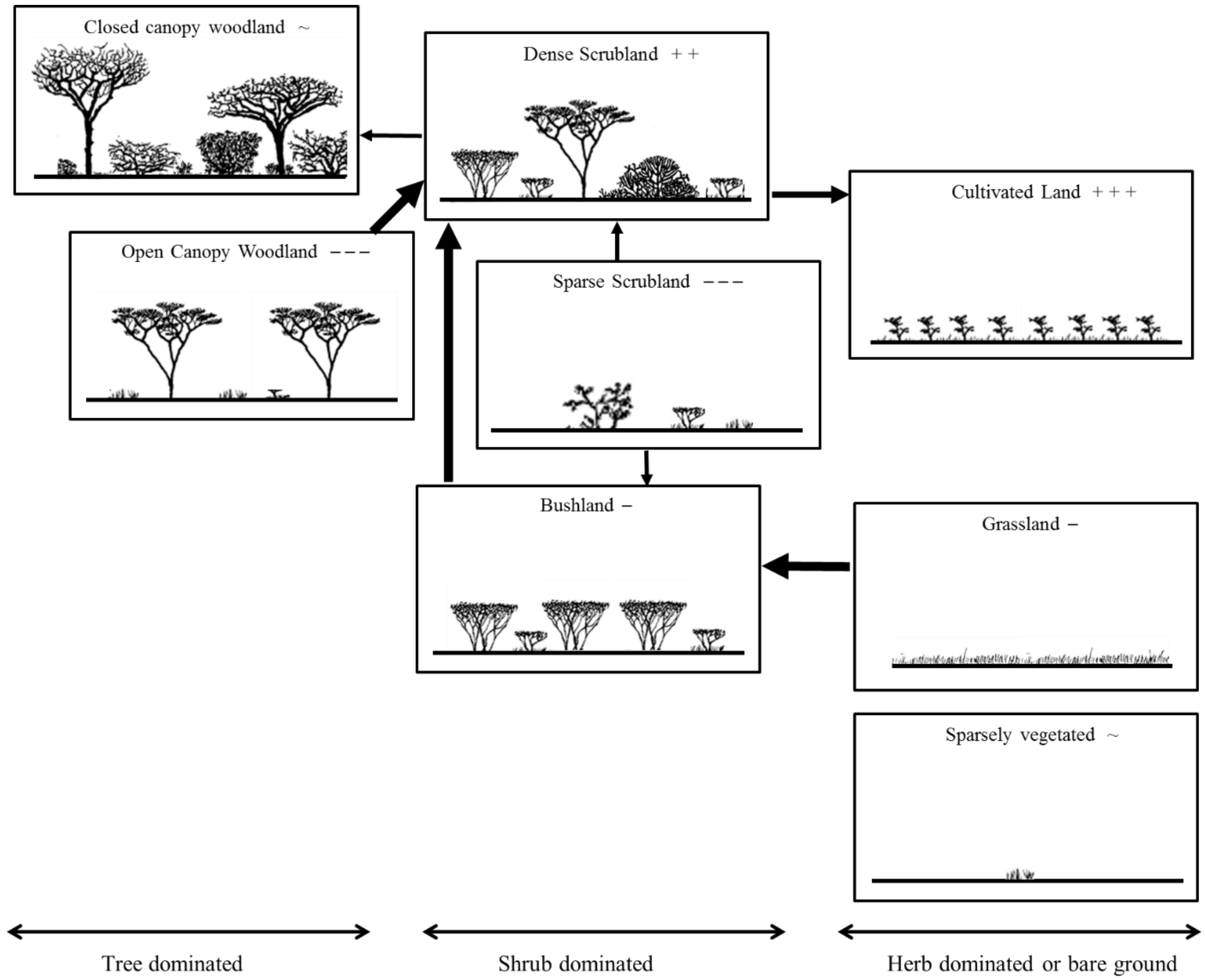

Figure 6. States and transition pathways of land cover types in Borana, Ethiopia from 2003 to 2013. Width of arrow indicates relative intensity of transition.

Based on land cover change analysis, multiple transition pathways have been going on within the Borana rangeland ecosystem. At a higher elevation, dense scrubland represents the greatest attraction point, drawing substantial transition from open canopy woodland and bushland. As the already dominant land cover class, dense scrubland demonstrated the greatest gain in area over the past decade. This indicates that DS might be the climax land cover class, given the environmental conditions without fire.

Open canopy woodland is rapidly shifting into dense scrubland, because moderate to high grazing pressure removed the understory on one hand, while woody plant recruitment filled the open space between sparse trees. This represents a major transition pathway since fire was banned. The transition is still going on, judging from the calculations that nearly 35% open canopy woodland has disappeared in the past decade, mostly changing to dense scrubland. In addition, the spatial distribution of open canopy woodland is getting patchy, often nested within dense scrubland, cultivated land and closed canopy woodland. This distribution pattern indicates conversion from open canopy woodland to these three classes.

Another primary transition pathway is from bushland to dense scrubland, representing a vegetation shift from the second to the first dominant land cover class. Such transition is more likely to occur in areas at relatively higher elevation. Given the ongoing climate change that is favorable to woody plant establishment (Kulmatiski & Beard, 2013), plant recruitment is facilitating the thickening of woody layer of bushland.

Although dense scrubland represents a successional climax under natural conditions, it could be changed given human intervention. In the past decade, it is being converted into crop fields. Since these lands are situated at a higher elevation, it is likely to receive more precipitation than elsewhere. As revealed in Figure 3, pastoralists selected the dense scrubland at higher elevations to cultivate crops. Until 1950s, crop cultivation on the rangelands was banned by indigenous rules. Changes started in the 1980s, when a severe drought hit the zone. Pastoralists then began to fence rangelands and cultivate maize and teff to make ends meet. The land cover transition matrix showed that only 10% of cultivated land remained the same, which echoed the opportunistic nature of crop cultivation in Borana. Although pastoralists tried to become self-sufficient in grain production, their yields are only 31% of the Ethiopian national average, and grain per capita met only 26% of the annual requirement for each household (Tache & Oba, 2010). In recent years, commercial farming is becoming more prevalent, especially around townships such as Yabello and Mega, which largely drove the pattern of crop field expansion on the rangelands.

A minor transition pathway is from dense scrubland to closed canopy woodland. Given favorable environmental conditions, tree seedlings could grow into mature trees and gradually close the canopy. In addition, the government prohibited grazing in such forested areas for conservation purposes. Therefore, both the canopy and understory tend to remain constant for this class. In addition, sparse scrubland is also shifting into dense woodland or bushland. At a higher elevation, it shifts into the former, while at lower elevation, it is more likely to become the latter.

In the lowlands, the primary transition occurring is the change from grassland to bushland. The above quantitative evidence showed that over a quarter of grasslands were lost over the past decade, making it the rarest land cover among the eight. Once the dominant landscape in the lowlands, it is being encroached by invasive species such as *A. mellifera* and *A. reficience*, which could potentially change soil features and make it more difficult for grasses to grow (Rundel et al., 2014). Sparsely vegetated land is hardly linked to other land cover classes, as it showed negligible changes over the past decade.

The findings in this chapter imply that multiple stable vegetation states can potentially occupy individual ecological sites. Ecological states are neither steady nor in equilibrium; rather, they are characterized by a defined range of deviations from a mean condition over a prescribed period of time. It has been well documented that ecological systems on many scales can shift abruptly and irreversibly from an existing state to a radically different state (Briske et al., 2005; Scheffer et al., 2009). Theoretical research on transition mechanisms has revealed that the state shift is relatively abrupt and could lead to new mean conditions outside the range of fluctuation evident in the previous state (Barnosky et al., 2012). Once a critical transition occurs, it is extremely difficult or even impossible for the system to return to its previous state. Large ecosystem changes such as shifts among vegetation types often come as surprises because there is a lack of leading indicators to predict regime shifts. However, increases in variability of ecosystems have been suggested to foreshadow ecological regime shifts (Carpenter & Brock, 2006).

6. Conclusion

This chapter applied mixed methods to investigate land cover change in the Borana Zone of Ethiopia. Based on time-series NDVI data and rapid rangeland assessment, I performed supervised classification to categorize the landscape into eight land cover classes using the random forest algorithm. The time-series NDVI data made it possible to distinguish these land cover classes by examining their unique phenological features. The mapping and classification results suggested that over 80% of rangelands are dominated by woody plants. Dense scrublands proliferate in the highland, while bushlands prosper in the lowland of the zone. The findings contributed to closing a knowledge gap regarding the distribution pattern and transition pathways of different rangeland types.

Results from land cover change analysis echoed earlier research findings that rangelands in Borana have entered a state of bush encroachment. In the most recent decade, the proportion of woody plant-dominated landscape began to stabilize, despite a continuing trend toward encroachment. This is evidenced by the fact that over 70% of landscape remained its land cover class over the past decade. The greatest net gain occurred to the class of dominant dense scrubland, suggesting that the landscape is being further encroached. Even part of bushland thickened its canopy and shifted into dense scrubland. In contrast to these two dominant classes whose proportional change was minimal, substantial alterations happened to the less dominant land classes. In particular, the size of cultivated land doubled from 2003 to 2013, primarily taking place near townships. Other less dominant land cover classes continue to decline. Grasslands, once the defining land cover of rangelands, represented only 1% of the Borana landscape, and was the rarest land cover class in 2013. The results also suggested that on rangelands with substantial woody plant cover, higher mean NDVI values do not necessarily translate into better quality forage, because valuable open grasslands demonstrated consistently lower NDVI than encroached land cover classes that are less desirable for livestock production.

Vegetation changes can hardly be accurately predicted because of their dependence on multiple variables. However, models that incorporate vegetation life history and environmental stochasticity are more likely to approach reality than those based on the deterministic concepts. It is considered that state-and-transition model is useful in conceptualizing alternative states of vegetation and the transition factors that transform one state to another. Further research needs to build on the theories of vegetation succession model (Whittaker & Levin, 1977) and state-and-transition model to interpret vegetation dynamics on the tropical rangelands. This approach allows vegetation evaluation procedures to explain continuous and reversible, as well as discontinuous and non-reversible vegetation dynamics, because both patterns occur and neither pattern alone provides a complete assessment of vegetation dynamics on the rangelands. The construction of the models could also generate testable hypotheses and point to gaps in our understanding of tropical rangeland dynamics.

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CHAPTER 3 EFFECT OF GRAZING ON VEGETATION COMPOSITION AND STRUCTURE ON THE BORANA RANGELANDS IN SOUTHERN ETHIOPIA

1. Introduction

Savanna ecosystems, defined by the co-dominance of trees and grasses, cover one-fifth of the world's land surface and are of great ecological and socioeconomic importance (Riginos, 2009). However, in recent decades, the species composition and vegetation structure of savanna have gone through significant transitions throughout the world (Anadón et al., 2014; Briggs et al., 2005; Buitenwerf et al., 2012; Gartzia et al., 2014; Gillson & Hoffman, 2007; Naito & Cairns, 2011). The establishment of woody plants on open rangelands has strong impacts on ecosystem processes, influencing nutrition cycling, carbon sequestration and eco-hydrology, while leaving edaphic legacies that would persist even if woody plants could be removed (Rundel et al., 2014).

On the rangelands of the Borana Zone in southern Ethiopia, the trend of bush encroachment has been intensifying over the past decades (Angassa, 2012; Dalle et al., 2005). Increase in woody plant density typically results in impenetrable thickets, which suppress the growth of grasses and other herbs that are valuable for cattle grazing, thus reducing the carrying capacity of rangelands. Such a bush encroachment process has tremendous impact on a large and rapidly growing population on the tropical rangelands (Wiegand et al., 2006). To Boran pastoralists whose livelihoods primarily depend on cattle herding, bush encroachment is likely to affect food security on the vulnerable arid and semi-arid environment.

Recent research has shown that multiple stable states co-exist on the Borana rangelands, with varying combination of understory and canopy covers (Dalle et al., 2005). Any factor that increases woody plant growth or decreases fire frequency will favor canopy closure (Murphy & Bowman, 2012). However, specific factors determining the status of vegetation have long been a matter of debate.

Seasonality of climate, fire, grazing, soil and atmospheric CO_2 concentrations have all been described as crucial in the origin, maintenance and shift of vegetation in the tropical rangeland systems (Archibold, 1995; Bourlière, 1983; Cole, 1986; Huntley & Walker, 1982; Mistry, 2000; Buitenwerf et al., 2012; Eldridge et al., 2011; Wigley et al., 2010).

Vegetation ecologists have long noted that, at large spatial scales, climate largely controls the distribution of vegetation types. However, within a single climate zone, complex mosaics of open and closed canopy rangelands may exist, suggesting the decoupling of climate and vegetation. Such evidence makes it clear that controls other than climate are also important at a finer spatial scale (Beard, 1953; Bowman, 2000). Early quantitative investigation of environmental controls over tropical rangelands indicated that while rainfall and seasonality were significant in separating different community types, grazing and fire are critical factors that contribute to the patches of rangelands with different structural and morphological characteristics (McNaughton, 1983, 1985).

The balance between woody and herbaceous plants is, to a large extent, determined by the interactive effects of herbivory and fire (Van Langevelde et al., 2003). In the Borana rangeland system, humans played a significant role in changing the disturbance factors. For centuries, their active use of fire was critical to maintain an open landscape with scattered trees and shrubs. Fire limited canopy growth and facilitated the coexistence of trees and grasses on the tropical rangelands. However, the official ban on fire, which took effect since 1970s, removed an important disturbance in regulating woody plant growth. Although the ban was lifted in 2000s, the effect of fire on controlling woody plant encroachment has been diminished in the past few decades (Gordijn et al., 2012). Reduced ground litter made it difficult to start a fire that could effectively thin the woody plant layer.

Human choice of livestock species also has a clear influence on the rangelands. An increase in the level of grazing leads to reduced fuel load, which makes fire less intense and, thus, less damaging to woody plants and, consequently, results in an increase in bushes. Similarly, browsers may enhance the effect of fire on trees because they reduce woody biomass, thus indirectly stimulating grass growth.

However, recent household survey throughout the Borana Zone revealed that over 85% of tropical livestock units are cattle (see Chapter 7), suggesting a strong grazing rather than browsing impact on rangelands.

Other than external disturbance factors, herbaceous and woody plants also interact with each other to facilitate their own growth while suppressing the development of the opposite. In particular, grass competition in productive tropical rangelands may limit tree growth as much as herbivory and fire (Riginos, 2009). Woody plant recruitment is particularly difficult in grassy ecosystems. Grasses compete with seedlings and saplings, reducing their growth rate, whereas frequent fires and/or intense herbivory prevent saplings from escaping the grass layer (Bond, 2008). Grasses and other herbs reinforce landscape heterogeneity by excluding trees from ecosystem hotspots and maintain functionally important landscape heterogeneity in tropical rangelands (Riginos et al., 2012). As a result, recruitment into the adult tree stage from seedlings is most likely in drought years when there is little competition from grass for resources and grass fuel loads are low (February et al., 2013). Once established, canopy cover facilitates seedling establishment by reducing stressful environmental conditions. For instance, low irradiance and high litter cover in closed canopy rangelands enhance the recruitment and survival of seedlings relative to open landscape by reducing soil water deficits and increasing nutrient availability in the upper soil layers (Salazar et al., 2012).

The above rangeland ecology theory suggests a hypothesis that grazing reduces herbaceous cover but contributes to woody plant growth, which reinforces the growth advantage of bushes against herbs. Empirical research has been conducted to test this hypothesis. In Borana, based on intensive plant survey, it has been revealed that greater herbaceous species richness was recorded in the lightly and moderately grazed sites than heavily-grazed sites (Angassa, 2012). In addition, herbaceous biomass was higher in enclosures than in the open grazed areas. On one hand, enclosures showed greater diversity and more even distribution of herbaceous species than open grazed areas. On the other hand, enclosures also promoted the regeneration of invasive woody plants (Angassa & Oba, 2010).

However, the grazing intensity gradient is largely derived from secondary sources in previous investigation. Stocking rate was commonly estimated from census data (Allred et al., 2012; Staver et al., 2009). Distance from settlement or enclosure was also used as indicator of grazing intensity, which was qualitatively described as high, medium, and low (Angassa, 2012; Tefera et al., 2007). Consequently, pastoralists' spatial resource utilization pattern is generally summarized as a piosphere (Chamaillé-Jammes et al., 2009), which consists of a "sacrifice zone" that is subject to severe resource exploitation, followed by a "transition zone" that shifts into a nearly homogeneously grazed zone. This grazed zone gradually merges into undisturbed natural vegetation that is hardly influenced by grazing. Other studies defined utilization by livestock as the percentage of forage grown in a year that is consumed, which was also qualitatively determined, as 25% utilization equals light, 50% equals moderate, and 75% equals heavy utilization (Ash et al., 2011). All these measurements, however, could not completely capture the spatial variability of grazing and its impact on tropical rangeland vegetation.

The issue of lacking quantitative measurement of grazing intensity is particularly evident in Borana, because indigenous livestock management by pastoralists is inherently complex. Rather than rushing to the greenest patch of rangelands available in proximity, pastoralists set up specific rules in terms of when to access which patch of pastures. Therefore, a fine-scale grazing intensity map is necessary to investigate grazing intensity distribution at the pastoral community level. In addition, plant surveys also need to be guided by local herders, because outsiders can hardly know how pastoralists practice livestock herding in the communal rangelands. Without such traditional ecological knowledge, there is a lack of solid evidence to infer the relationship between grazing and vegetation cover, and thus it would be difficult to generate any effective contextualized rangeland management policy.

The knowledge gap of how grazing affects herb, shrub and tree cover fundamentally motivated the research of this chapter. Specifically, I aimed to answer the question of how vegetation responds to grazing gradient at the local scale. I hypothesized that heavier grazing will result in lower herbaceous cover, while contributing to higher woody cover. First-hand data were collected by conducting nested quadrat surveys in three land use types defined by indigenous pastoralists. To gain quantitative evidence of grazing intensity, I made use of GPS collars deployed on 12 cows of 4 households in the study site to monitor their movement over 7 months that covered both wet and dry seasons. The results suggested that vegetation structure and composition are distinct under different land use strategies. While heavier grazing is associated with low herbaceous cover, its relationship with woody plant cover is quadratic. The state-and-transition model could potentially explain the shift of vegetation states in the tropical rangeland ecosystem.

2. Study Site

The Borana zone is located in southern Ethiopia, with elevation varying from 500 m to 2500 m. The climate is largely semi-arid with relatively cool annual temperatures (19-24°C) and a mean annual rainfall ranging from 300 mm in the lowland up to 1000 mm in the highland. The precipitation distribution is bimodally distributed within the year, with 60% from April to May and 30% from October to November. Local livelihood is primarily supported by livestock herding, with a total livestock population fluctuating around 1 million.

The major vegetation type in Borana is tropical savanna, which is known for its variation in the proportion of woody and herbaceous plants. Different combinations of various factors result in a spectrum of woody plant cover ranging from 5% to 75% (Coppock, 1994). The Borana rangelands were considered sustainable even until a few decades ago, with surplus stands of perennial grasses (Cossins & Upton, 1987). The issue of woody plants encroachment was first identified in Borana in the 1970s, when human and livestock populations began to increase and concentrate around the newly developed water points and the official fire ban. As the competition from grasses and fire disturbance were largely removed, woody plants enjoyed favorable conditions to proliferate, and thereafter, dominated the landscape. Various plant surveys revealed that common woody genera include *Acacia*, *Commiphora*, *Combretum, Cordia*, *Terminalia*, *Aspilia*, *Albizia*, *Juniperus*, *Rhus*, *Boscia*, *Boswellia*, *Cadaba*, *Balanites*, *Salvadora*, *Dobera*, *Pappea*, *Grewia*, *Delonix* and *Boswellia*. Common herbaceous genera include *Cenchrus*, *Cynodon*, *Themeda*, *Pennisetum*, *Enteropogon*, *Bothriochloa*, *Brachiaria*, *Sporobolus*, *Panicum*, *Chloris*, *Aristida*, *Dactyloctenium*, *Leptothrium*, *Heteropogon* and *Hyparrhenia* (Coppock, 1994; Angassa & Baars, 2000; Gemedo-Dalle et al., 2005).

I conducted the empirical research in Shomo *reera* of Sarite *kebele*, which is approximately 65 km west of Yabello, the administrative center of Borana Zone. The settlement is established on the edge of Rift Valley at an elevation around 1000 m. Pastoralists herd livestock on these lowlands for most of the year, but they have access to pastures at a higher elevation up to 1350 m in nearby hills. The primary reason for selecting Shomo as the study site is because of the existence of extensive open grasslands are rare elsewhere. Such open grasslands can be considered the vegetation state prior to bush encroachment.

3. Methods

3.1. Vegetation survey

Discussions with pastoralists in my pilot field study in February, 2013 indicated that there are three general land use types. The first type, known as *mata tika* in the local language, is the major herding area where most livestock herding practices are conducted. The second type, known as *kalo* in the local language, is fenced patches of communal rangeland reserves that are saved for dry season consumption only. The third type, known as *qaye* in local language, is the land close to settlement where villages were constructed and crop fields were established.

Plant surveys were carried out in July, 2013, which was six weeks after the rain stopped. Realizing that part of predetermined sampling locations generated through a random approach would certainly fall into inaccessible places, I adopted a systematic sampling scheme in the three land use types. In the field, I had two local pastoralists lead me and my research assistant to locations that were characteristic of each land use type. Then I walked 10 steps towards the north as the first sampling plot. I set the plot size as 1 m * 1 m for herbs, 5 m * 5 m for shrubs, and 10 m * 10 m for trees. At each sampling location, I counted the frequency of each species, and estimated the percent of cover for each layer. I also used a handheld GPS to record the coordinates of all sampling locations.

Aiming at sampling 9 plots in each type, I walked 300 steps south to get to the second plot, and another 300 steps to get to the third plot. Then I turned east to measure the fourth plot, then north to the fifth and sixth plots. After that, I turned east again to get to the seventh plot, then south to get to the eighth and ninth plots. Such a sampling strategy worked well in the open *mata tika*. However, in *kalo*, dense woody plants usually blocked the way, and I had to detour frequently to reach the next plot. In *qaye*, although the bush is less dense, existence of crop fields and clustered bushes also made me detour. In total, I encountered 34 species in the 27 sampling plots. A voucher specimen of each species was collected and brought to the National Herbarium of Ethiopia at Addis Ababa University. All species were identified there.

3.2. GPS-tracking

In contrast to previous research that used distance from settlement/enclosure as an indicator of grazing intensity, this chapter used GPS collars deployed on 12 cows from 4 households to estimate their utilization of rangelands. These collars were custom-built, and were configured to record the location of cows every 5 minutes (Clark et al., 2006). Over the 7-month tracking from August 2011 to March 2012, more than a half million geo-referenced and time-tagged points were recorded, which covered both dry and wet seasons. Analysis of movement patterns suggested that the different households tended to follow the same migration pattern and schedule, which was further validated in my discussion with participant pastoralists (see Chapter 4). Therefore, I assumed that the GPS-tracking captured collective utilization patterns by pastoralists in this study site as a whole.

3.3. Data analysis

I conducted floristic analysis to investigate the vegetation composition and structure characteristics. For each land use type, I estimated its species diversity using the Shannon-Weiner Diversity Index[2]. I also calculated the dissimilarity coefficient[3] among the nine plots in each land use type. Abundance-rank analysis (Kent, 2012) was performed to examine the dominant plant species of each land use type. Analysis of Variance (ANOVA) was conducted to statistically test the difference of herb, shrub and tree cover among the three land use types. The floristic analysis was conducted in the R software (R Development Core Team, 2014).

Grazing intensity was determined by calculating kernel utilization distribution (UD) from the GPS-tracking points (Hooten et al., 2013). The conventional perspective in animal space use research is that the UD is a spatial probability distribution based on a spatial point process. It is assumed that there is a surface over a spatial domain (*S*) of interest that specifies the likelihood (*f*) that an animal will occur at any given location (*s*) in the domain. Thus, for a finite set of times at which an animal's location is observed, say t = 1,…,T, there is a statistical model for location where $s_t \sim f(s)$, for s_t belong to *S*.

To estimate the UD, a wide variety of density estimation techniques can be employed to find *f* based on GPS-tracking or telemetry data (s_t). In this study, I applied the kernel density estimation (KDE),

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[2] The Shannon index has been a popular measure of diversity. It is calculated as

$$H = \begin{cases} -\sum_{i=1}^{r} p_i \log p_i, & \text{if } p_i > 0 \\ 0, & \text{if } p_i = 0 \end{cases}$$

where p_i is the proportion of characters belonging to the ith type of livestock in the r-string of interest (i=1,2,…,r).

[3] The dissimilarity coefficient is presented as:

$$S = \frac{2\sum_{i=1}^{m} \min(X_i\,,\ Y_i)}{\sum_{i=1}^{m} X_i + \sum_{i=1}^{m} Y_i}$$

where X_i and Y_i are the abundances of species i, $\sum_{i=1}^{m} \min(X_i\,,\ Y_i)$ is the sum of the lesser scores of species i where it occurs in both quadrats, and m is the number of species. The coefficient ranges from 0 (complete dissimilarity) to 1 (total similarity).

because this is a commonly used technique to estimate animals' utilization distribution. In KDE, one takes a nonparametric approach to estimate *f*. For any location of interest $c = (c_1, c_2)$, in the spatial domain *S*, the estimate of UD is as follows:

$$\boldsymbol{f(c)} = \frac{\sum_{t=1}^{T} \boldsymbol{k((c_1 - s_{1,t})/b_1)k((c_2 - s_{2,t})/b_2)}}{\boldsymbol{Tb_1b_2}}$$

where k represents the kernel (which I assumed to be Gaussian) and the parameters b_1 and b_2 are bandwidth parameters that control the diffuseness of the kernel (Venables & Ripley, 2013). There are various ways to choose the bandwidth parameters, and these are well described in the literature (Silverman, 1986). In this chapter, I chose the adehabitatHR package (Calenge, 2011) in R to perform the analysis. After the raster image of UD was generated, I used the coordinates of plant sampling plots to extract the raster value to derive grazing intensity for each sampled location.

I applied ordinary least squares (OLS) models to test my hypotheses on the relationship between rangeland utilization by livestock and herb, shrub and tree covers. The model can be represented as:

$$Plant\ Cover = \beta_0 + \beta_1\ UD + \beta_2\ UD\text{^}2 + \varepsilon$$

where plant cover, which is between 0 and 1, is the response variable; β_0 is the intercept; β_1 and β_2 are coefficients of first and second order UD; ε is the error and $\varepsilon \sim N(0, s^2)$. The regression was performed in R software.

4. Results

4.1. Vegetation

The three land use types exhibited distinct plant species composition and structure (Table 1). *Mata tika*, as the major herding area, showed the lowest diversity. I only encountered a total of 5 species in 9 plots. The Shannon index also revealed that it had the lowest diversity at a value of 2.11. Plots within *mata tika* were also similar to each other, as the mean dissimilarity coefficient is 0.54. *Kalo*, which is reserved for dry season use, had the highest diversity, with a total of 24 species identified in 9 plots. Its diversity was nearly 5 times of that in *mata tika*. *Qaye*, despite its closeness to settlements, also exhibited high diversity, with 19 plant species found in the survey. Its diversity index is slightly lower than *kalo*. However, the 9 plots are more different from each other, suggesting a highly heterogeneous landscape around settlements.

Table 1. Summary of plant diversity and evenness under three land use strategies

Type	No. of Species	Diversity	Dissimilarity Coefficient
Mata Tika	5	2.11	0.54
Kalo	24	5.67	0.79
Qaye	19	5.00	0.85

Despite low diversity, *mata tika* is associated with moderate herbaceous cover that is crucial to cattle grazing (Table 2). It is almost free of any woody species, with both shrub and tree covers less than 2% on average. In contrast, since the grazing pressure is kept at a minimal level in *kalo*, all three layers showed much higher cover. Not only does herb cover double, but woody plants also find it easier to recruit and establish themselves. Unsurprisingly, *qaye* has the lowest herbaceous cover likely due to its proximity to settlement. In addition to grazing, these lands are also subject to trampling, which made herbs harder to regenerate. However, as herbaceous growth is suppressed, woody plants find opportunities to prosper. Shrub layer in *qaye* is even denser than *kalo*, and it also has a moderate tree cover. Results of the ANOVA clearly indicated that structures of all three layers in the three land use types are significantly different from each other (Table 2).

Table 2. Herb, shrub and tree cover under three land use strategies

Land Use Strategy	Herb Cover	Shrub Cover	Tree Cover
Mata Tika	33.33%	1.44%	1.56%
Kalo	65.56%	11.22%	7.78%
Qaye	15.33%	18.33%	3.78%
ANOVA p-value	< 0.01	0.0296	0.028

Plant species composition revealed distinct plant communities in these three land use types (Figure 1). In *mata tika*, high herbaceous cover is predominantly contributed by a single species: *Sporobolus spicatus*. Its growth type is by stolon, which is highly adapted to grazing. In contrast, the understory cover of *kalo* consists of three major species: *Eragrostis cilianensis* (35%), *S. spicatus* (28%), and *Aristida kenyensis* (24%). In total, the abundance of herbaceous individuals in *kalo* is 320, which is 11% higher than *mata tika*. The most abundant species in *qaye* is also *E. cilianensis*, but it is only a third of the value in *mata tika*. In *qaye*, total abundance is also lowest, which is 40% of that found in *mata tika* and 36% in *kalo*.

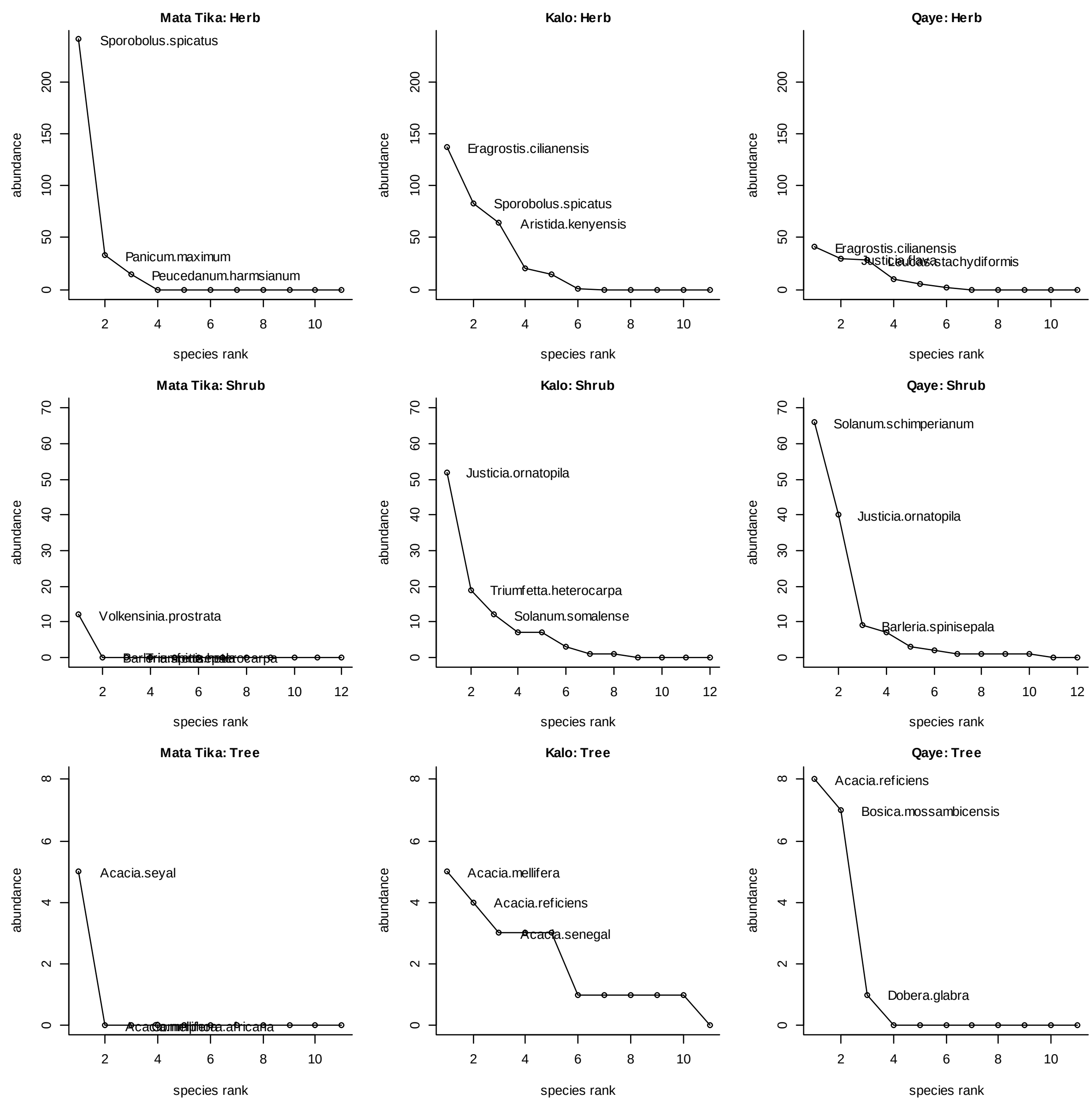

Figure 1. Abundance and rank of each layer in three land use types. The area under the curve represents total abundance

Mata tika is almost free of shrubs. There, the only kind I encountered is *Volkensinia prostrata*, with a total abundance of 11. *Kalo* and *qaye* are covered with more shrubs. Total abundance exceeds 100 in these two land types. Dominant shrub genera include *Justica* and *Solanum*, both had little foraging value to grazers like cattle (see Chapter 7).

Total abundance of trees is similar in *kalo* and *qaye*, but the composition is different. *A. reficiens* and *Bosica mossambicensis* dominate *qaye*, with another single tree of *Dobera glabra*. However, I encountered 9 tree species in *kalo*, with 2 most common species as *A. mellifera* and *A. reficiens*. Another 3 tree species, which include *A. senegal*, *B. mossambicensis*, and *A. oerfota*, have an abundance of 3. In contrast, *mata tika* is free of tree species. The only one I found is *A. seyal*, which is non-existent in the other two land use types. However, the evidence of scattered tree seedlings could be early signs of bush encroachment on the open grasslands.

4.2. Grazing intensity

The kernel density map revealed that UD is much higher around the settlement (Figure 2, left). However, grazing intensity does not decrease linearly from the settlement in all directions. There is a primary herding corridor that stretches from northwest to southeast, displayed as oval-shaped concentric light orange features, before the cattle disperse into their major foraging areas. A secondary herding area is at the opposite direction. As the environment gets drier, pastoralists take their animals towards northwest to make underutilized forage resources in the hills.

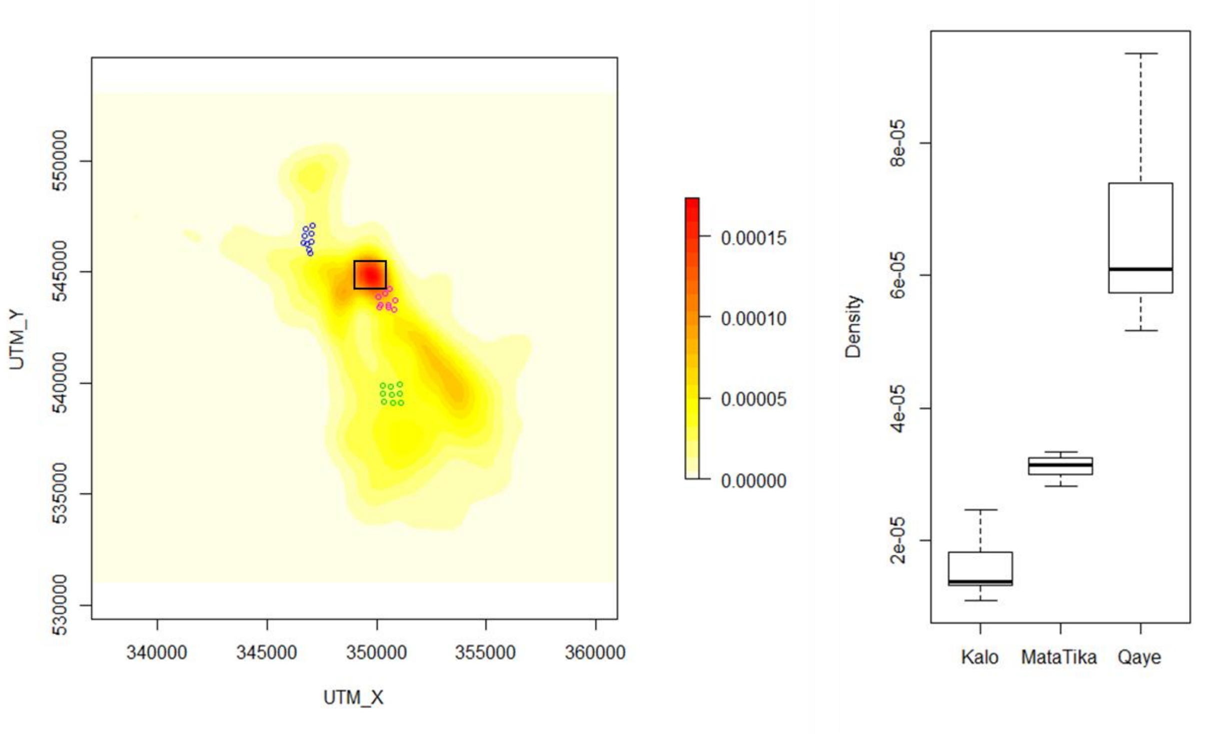

Figure 2. Left: Location of sampling plots on the utilization distribution map by cattle. Plant survey locations are shown as circles. Pink indicates *qaye*, green indicates *mata tika*, and blue indicates *kalo*. The black box indicates settlement area of the pastoral community. Right: Boxplot of UD density of surveyed plots in three land use types.

Results from ANOVA indicated that the 3 land use types received significantly different grazing pressure ($F_{2, 24} = 69.35$, p-value <0.001). Over the 7-month tracking period, the nine plots in *qaye* were utilized most heavily, which was twice higher than *mata tika* and four times higher than *kalo* (Figure 2, right). Livestock herding was primarily conducted in *mata tika*. When reaching this area, livestock were slowed down to graze. In contrast, animals quickly passed through *qaye*, except for a short window in the wet season when forages were available close to settlement area. Compared to *mata tika* and *qaye*, grazing intensity in *kalo* was much lighter. Cattle were only allowed to enter this community-fenced patch of rangelands at the end of dry season. Any violation of this rule would incur a punishment up to 25 US dollars according to the indigenous rangeland management institution.

4.3. Impact of grazing on vegetation structure and composition

I further investigated the relationship between utilization density and rangeland vegetation cover by using OLS models. The estimations are summarized in Table 3.

Table 3. The estimation on the effect of grazing on vegetation cover.

Independent variables	Herb		Shrub		Tree	
	Parameters	SE	Parameters	SE	Parameters	SE
Intercept	88.07***	14.71	15.32	9.00	13.33***	3.15
UD	-1.96E+06**	7.31E+05	-5.03E+05	4.47E+05	-4.61E+05***	1.56E+05
UD^2	1.23E+10	7.29E+09	7.07E+09	4.46E+09	4.29E+09**	1.56E+09
F-statistic	10.78***		2.744*		4.44**	
R-squared	0.4293		0.1183		0.2093	

***: $p < 0.01$; **: $p<0.05$; *: $p<0.1$

The regression estimation indicated that heavier grazing pressure is associated with lower herbaceous cover in general. The model for herb cover is dominated by the first order predictor, but the second order predictor is insignificant in the model. Consequently, the predicted curve shows a downward trend overall (Figure 3). For shrubs, both predictors are insignificant in the model estimation. However, combined together, they contribute to a marginally significant model (p-value = 0.084). When UD is low, shrub cover is maintained at an intermediate level. The cover continues to drop until a density around 4*E-05. After that, shrub cover increases again (Figure 3). Tree cover response to cattle grazing exhibits a similar pattern as shrubs. Both first and second order predictors are significant in the model. Tree cover drops as UD increases until 6*E-05. After that point, tree cover starts to recover (Figure 3).

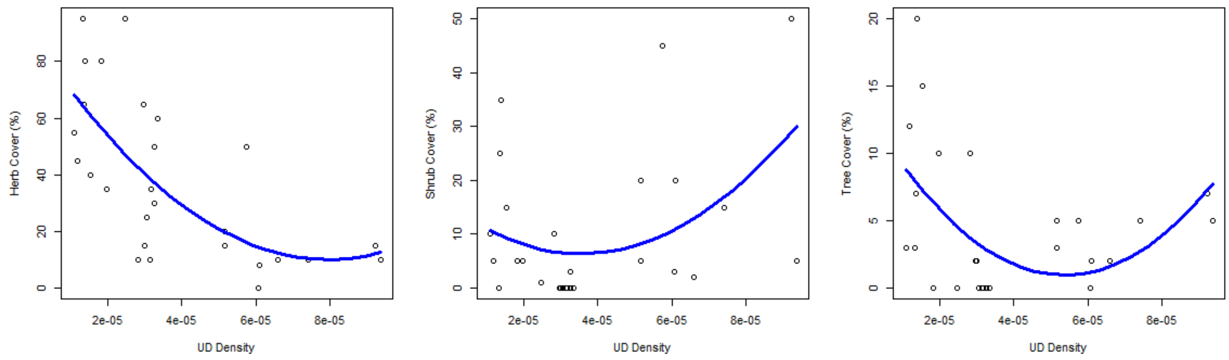

Figure 3. Predicted herb, shrub and tree cover along the gradient of grazing intensity.

5. Discussion

The above results indicated that within a pastoral community, vegetation composition and structure are significantly different given three land use strategies. Livestock herding is primarily conducted on open grasslands. Moderate grazing pressure on these lands is associated with abundant stolon-like grass species and few woody plants. In contrast, the areas near settlements, which are subject to heavy grazing and trampling, are characterized by the lowest herbaceous cover but relatively dense woody plant cover. In places where grazing is kept at a minimal level, both herbaceous and woody plants prosper and result in the highest overall diversity index.

Spatial distribution of grazing intensity is inherently heterogeneous in the study site. Piosphere is not observed according to the GPS tracking data. This is because forage resources on the rangelands are structurally heterogeneous and the intensity of grazing is unlikely to be distributed as piospheres. In a sedentarized pastoral community as my study site, pastoralists' choice of herding location was highly skewed in space. For most of the tracking period, cattle were herded towards the southeast from the settlements. Such a pattern continued until the middle of dry season, when pastoralists drove their animals to nearby hills in the northwest. Pastoralists also set up community rangeland reserves to cope with drought. The heterogeneity of spatio-temporal forage resource distribution resulted in specific land use patterns that are associated with distinct grazing pressures.

The OLS model estimation indicated significant impact of grazing on vegetation cover in terms of herbs, shrubs and trees. Since fire was largely removed from the system, grazing became the primary disturbance factor that was driving vegetation shifts at a fine spatial scale. In order to better examine the current rangeland situation in Borana, it is necessary to understand rangeland conditions in the past. To explain the rangeland history, I adopted the state-and-transition model (Briske et al., 2005) to explain the observed differences in vegetation cover under distinct land use strategies.

In the rangeland system without livestock grazing, fire was historically the major factor that determined rangeland states and transitions (Figure 4). High intensity (but low frequency) fire could change the landscape into a grass-dominated system. With gradual woody plant recruitment, the rangeland contained a mixture of trees, shrubs and grasses. Low intensity fires would periodically burn the grasses, shrubs and tree saplings, but would leave the adult trees undamaged. As a result, open canopy woodland was established as a stable vegetation state. The gradual vegetation recruitment and low intensity fire would keep the open canopy woodland state stable, until the next high intensity fire that brought the entire system back to a grassland state.

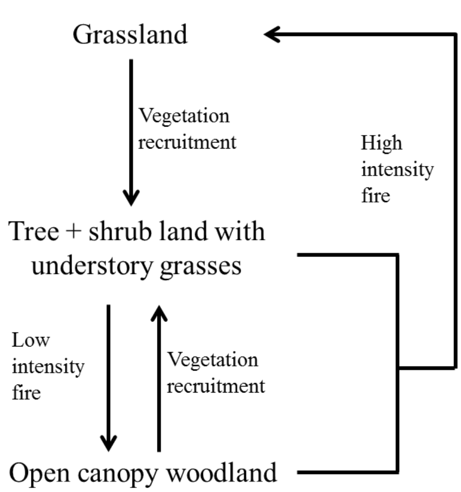

Figure 4. Rangeland states and transitions with fire and negligible grazing

When livestock were added to the rangeland system, transition pathways in the rangeland system were similar to that of the previous system because fire continued to play a significant role (Figure 5). A major difference was that pastoralists were actively involved in the rangeland management. They largely determined when and where to graze and burn. Light to moderate grazing reduced understory cover of grassland, and the system shifted into a mixture of trees, shrubs and grasses given ongoing plant recruitment. As the canopy got denser, pastoralists would set up low intensity fire to burn the rangelands, which only left the highly fire-resistant trees. Grasses and other herbs usually first established themselves after fire, while later woody plant recruitment and grazing would bring the system back to the mixture state. High-intensity fire, either started by lightening or pastoralists, would bring the rangelands back to the grassland state. This factor contributed to a closed loop that allowed the grazing system to continue to be sustainable.

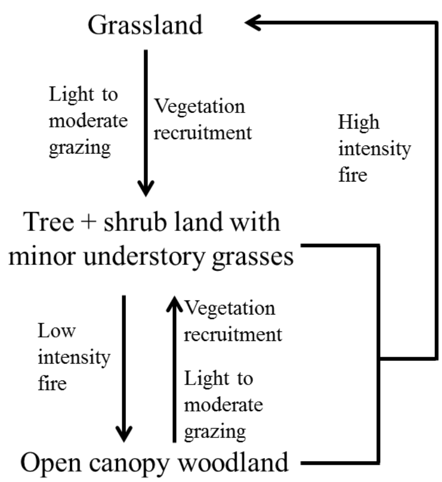

Figure 5. Rangeland states and transitions with fire and livestock

It is worth pointing out that although the pastoralists in Borana were semi-settled, they could be highly mobile when the need arises. In a sparsely populated context, encampments usually change location once every 5 to 8 years and this was commonly related to the search for better foraging areas (Coppock, 1994). In addition, removing grazing pressure facilitated faster recruitment by grasses and other herbs after fire.

The rangeland system with livestock but without fire likely better reflects the current situation in Borana (Figure 6). The last high-intensity fire set the rangeland state as grassland. With moderate grazing and plant recruitment, the system would slowly shift into a mixture of woody and herbaceous plants. This is supported by above findings from plant surveys. Although *mata tika* was characterized as open grasslands, a few plots showed early signs of bush encroachment as *A. seyal* and *V. prostrata* were encountered.

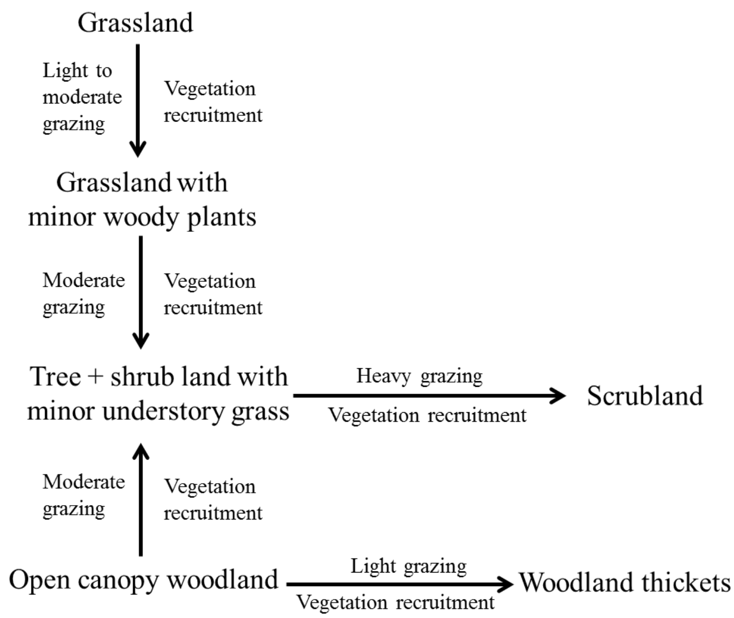

Figure 6. Rangeland states and transitions with livestock but without fire

In places with a mixture of woody and herbaceous plants, heavy grazing could quickly remove the forage in the understory, thus releasing the scattered tree seedlings from competition. This process would eventually lead to an increase in woody cover, which is typical of *qaye*. Although the bush burning ban has been lifted since 2000s, there was little herbaceous biomass in the understory and fuel loads would not build up and could not set the stage for fires to properly thin the woody plant layer. The only possible remaining way to reduce the canopy cover is by bush clearing. However, such manual cutting efforts are far from being effective in a largely encroached landscape.

Without fire, woody plant cover on the open canopy woodland would also become denser. With moderate grazing going on, it would shift into a mixture state as in the previous scenario. In cases where lands were fenced as rangeland reserve, vegetation recruitment would eventually evolve into dense woodland thickets, a state characterized by high cover of herbs, shrubs and trees. This was reflected in the vegetation structure in *kalo*.

Pastoralists indicated that it is getting increasingly difficult to relocate to better grazing sites because of the increase in the numbers of both people and livestock. They are becoming more sedentarized than previous generations and this trend is likely to continue due to the construction of roads, markets and permanent water development that encourage settlement. The changed grazing pattern further exacerbates the degradation issue as the lands are being recursively used as evidenced in *qaye*.

While disturbance factors such as grazing and fire are significant at the local scale, rangeland vegetation structure and composition are certainly subject to ongoing climate change, which makes the interactions in the rangeland system more complex. The main growing-season rainfall has diminished by 15% in food-insecure countries clustered along the western rim of the Indian Ocean (Funk et al., 2008; Williams & Funk, 2011). Accordingly, spring and summer rains in parts of Ethiopia have declined by 15–20% since the mid-1970s. An important pattern of the observed existing rainfall declines coincides with heavily populated areas of the Rift Valley in south-central Ethiopia, and is likely to adversely affect rangeland conditions. Continued rapid population growth and the expansion of crop cultivation under a drier, warmer climate regime could dramatically increase the number of at-risk people in Ethiopia in the next 20 years (Funk et al., 2012). These factors should be included in future investigation of tropical rangelands to reveal and predict the complexity of causal mechanisms within the open grazing systems in Africa.

6. Conclusion

This chapter investigated vegetation composition and structure, grazing intensity and distribution, and the relationships between them in the Borana Zone of southern Ethiopia. The research findings suggested distinct species composition and vegetation structure in these three land use types. Species diversity and plant cover are typically higher in community rangeland reserve, where grazing pressure is kept at a minimal level. The major herding area is characterized by open grassland, with intermediate herbaceous cover but largely free of woody plants. Due to heavy grazing and trampling, the area around settlement has the lowest herbaceous cover. However, as competition is removed by removing herbaceous plants in the understory, woody species are likely to prosper in this area. Therefore, heavy grazing does not necessarily result in lower biodiversity. While understory graminoids are removed, woody species are likely to prosper, leading to even higher overall plant diversity than major herding area.

Specifically, I examined the effect of grazing on vegetation cover using OLS models. The results indicated that the relationship is largely linear for herbs and quadratic for woody plants. For herbs, the prediction is dominated by the first order predictor, suggesting a trend that herbaceous cover decreases as grazing intensity increases. In contrast, woody plants exhibit a different pattern, because the second order predictor played an important role in the model. Both shrub and tree layer cover could be maintained at the lowest level given intermediate grazing intensity. Removal of grazing contributes to canopy thickening when fire is absent, while heavy grazing removes competition from herbs, indirectly facilitating the growth of woody plants.

Vegetation dynamics could be explained by the state-and-transition model. With fire available in the rangeland ecosystem, the transition pathways could form a closed loop, which contributed to the sustainability of the grazing system. However, after the bush burning ban, there was no fire that could bring the system back to an open landscape. Rangelands continued to increase in woody plants abundance, which in turn suppressed the growth of herbs. This trend is very likely to result in compromised livestock production, and potentially threaten livelihood security on the vulnerable rangelands in Borana in the future.

Given that broad-scale environmental factors such as water, temperature, nutrient, and CO_2 concentration are less likely under human control, changes in the disturbance factors such as grazing and fire could potentially help slow down the rate of degradation on the Borana rangelands. While cattle grazing pressure should be maintained at an intermediate level, it is also necessary to safely enhance woody plant use by ruminants in order to make better use of the woody plants that currently dominate the Borana rangelands. While browsing and fire each alone impacted growth, a combination of browsing and fire had much greater effects on tree density (Staver et al., 2009). It is worth trying to adopt flexible rangeland management practices which will facilitate the adaptation to the spatio-temporal variability in forage quantity and quality in the tropical rangelands.

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CHAPTER 4 UNDERSTANDING PASTORALISTS' SPATIAL UTILIZATION OF RANGELANDS USING GPS-TRACKING: A PILOT STUDY IN EAST AFRICA

1. Introduction

Being mobile is an important strategy adopted by pastoralists 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 rangeland can vary vastly within the year in response to changes in plant phenology and available soil moisture in arid and semi-arid lands (ASAL) (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 their livestock and redistribute grazing pressure throughout the landscape (Marin, 2010; Upton, 2012).

In order to understand how pastoralists make use of resources, it is necessary to investigate their spatio-temporal movement patterns. Early attempts to study pastoral mobility yielded conceptual models based on long-term field observation and ethnographic investigation (Coppock, 1994; Coppolillo, 2000, 2001; 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 assumed 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. Another model assumed that grazing intensity decreases as it gets farther away from settlement and that grazing intensity is uniform with regard to direction (Spencer, 1973) (Figure 1b). The third model added environment variables such as water into consideration, and proposed that grazing intensity decreases with it gets farther away from base camp, but that animals move between the settlement and a water source as they need to be watered on a regular basis (Western, 1975) (Figure 1c). By synthesizing the above movement 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 across the year at a broader scale (Moritz et al., 2010).

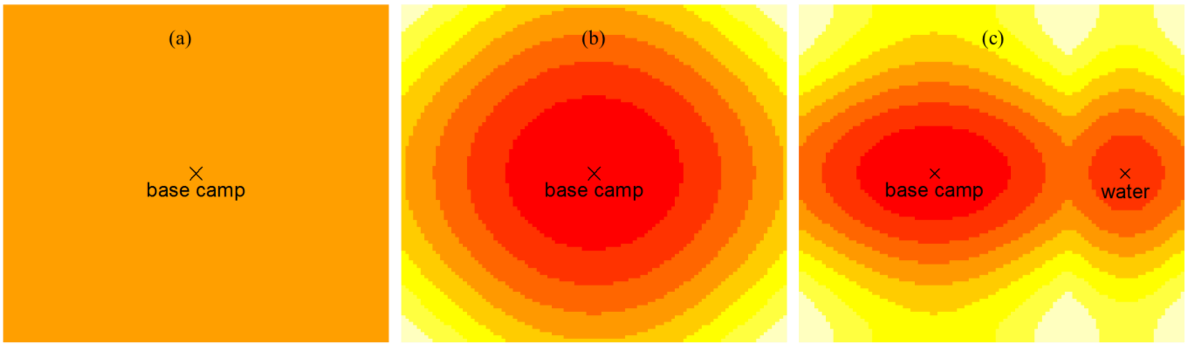

Figure 1. Three models of pastoral mobility. Red indicates high density while yellow represents low density of utilization.

These conceptual models provided valuable insights into rangeland management and pastoral policy-making in ASAL; however, data used for such modeling were acquired with relatively coarse sampling intensity. Thus, these models tended to be oversimplified and could not represent the full range of mobility strategies in the open grazing systems. Later investigation of pastoral mobility applied indirect measurements from observations, interviews, participatory mapping and household surveys to infer pastoral mobility patterns (Homewood & Lewis, 1987; Waters-Bayer et al., 1995). Such indirect measurements were then transformed and geo-referenced using geospatial tools to reveal spatial movement patterns (Liao et al., 2014). Despite the advancement in describing and modeling pastoral mobility, data collected using these methods were usually of low accuracy. While revealing broad-scale seasonal migration routes, details of fine-scale movement and cumulative rangeland utilization distribution cannot be inferred from such models.

Often due to the lack of sufficient understanding on pastoral mobility and rangeland utilization pattern, government entities have, consequently, used partial, anecdotal, and perhaps erroneous evidence to design policies to sedentarize pastoralists and transform their livelihoods. Pastoralists were commonly accused of being “irrational”, given each individual aiming at maximizing livestock production from limited rangelands without considering environmental consequences (Hardin, 1968). Correcting such misconceptions about pastoralists requires contextualized analysis of pastoral mobility, in which quantitative monitoring data is crucial to reveal and predict pastoral resource-use patterns under current and projected socioeconomic and environmental conditions.

With the emergence of quantitative methods such as GPS-tracking technology and associated analytical tools, tremendous progress has been made in the study of pastoral mobility. Portable GPS instruments were installed on domesticated animals to study their movement pattern 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.

However, significant shortcomings still exist in the modeling of pastoral mobility. This is because the tracking data were very limited in previous studies. Short battery life-span required frequent (e.g. daily) 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 generally covered limited geographic areas over a short time period. Without continuous and intensive tracking data on livestock movement, it is impossible to present concrete evidence of cumulative resource-use pattern and camp relocation, which is commonly practiced in the extensive grazing system in the African and Asian rangelands.

This chapters aims at addressing the above knowledge gap by investigating pastoralists’ spatial utilization of rangelands pattern using the GPS-tracking data. With the GPS-tracking technology (Clark et al., 2006) recently evolving to the point where intensive and continuous observation of cattle movement can be collected at a lower cost, it becomes possible to examine fine-scale movement patterns and compare how mobility strategies vary in different herding contexts. My empirical research was conducted in the Borana Zone of southern Ethiopia, which represents the typical open grazing system in the Horn of Africa. The data analysis was based on continuous tracking of ten cows in five study sites with updated animal locations every five minutes from August 2011 to March 2012. Such spatio-temporal data on livestock movement over multiple seasons made it possible to better understand how and why mobility strategies differ in space and time than was previously possible. In addition, qualitative input from pastoralists was combined with the GPS tracking data to complement the interpretation of pastoral mobility and articulate the drivers behind the apparent differences in rangeland utilization distribution. From there, conceptual models of mobility were proposed to summarize pastoral movement patterns.

Specifically, the three research objectives of this chapter are to: 1) estimate the cumulative density of utilization by livestock and explain the factors that affect utilization patterns; 2) investigate the recursive use of rangelands by livestock; and 3) propose conceptual models to characterize mobility patterns. The findings suggested that pastoral mobility patterns in Borana are highly diverse and context/household specific, ranging from sedentarized restricted herding, to temporary away-from-home grazing, to predominantly away-from-home extensive herding. These mobility patterns are associated with distinct distributions of utilization density and recursive use of rangelands, which can be explained by the socio-ecological contexts where livestock herding is practiced.

2. Methods

2.1. Study area and sample selection

The Borana Zone is located in southern Ethiopia north of the Kenyan border. At about 43,000 km^2 in size, this region is home to over 350,000 people with a livestock population fluctuating around a million (Coppock, 2010). The vegetation is mainly mixed savanna, which is increasingly encroached by *Acacia* and *Commiphora* species (Angassa & Oba, 2008). Elevation ranges from 500 m to 2500 m above sea level, with terrain varying from steep highland slopes to flat, dry river and lake beds in the lowlands. The climate is largely semi-arid with relatively cool annual temperatures (19-24°C) and a mean annual rainfall ranging from 300 mm in the lowlands to 1000 mm in the highlands. The annual precipitation distribution is bimodal, with 60% occurring during the long-rain season (April to May) and 30% during the short-rain season (October to November) (Coppock, 1994; Desta & Coppock, 2002).

Pastoralism is the major livelihood strategy for the people in Borana. Cattle herding is generally practiced in two forms. One form is home-based herding, known as *worra* in the Boran local language, which involves the herding of lactating cows, calves, and small stock close to settlements. The other form is satellite herding, referred to as *forra* in the local language, where temporary camps are used to graze bulls, non-lactating cows and immature stock at substantial distances away from base camps. *Forra* herding allows livestock to range more widely and have access to better forage than what might be available near settlements (Homewood, 2008). These two forms of herding are not mutually exclusive, as one household can practice both simultaneously through herd splitting.

Reera[4] was used as the sampling frame for selecting study sites and households by the IBLI team. The selection process accounted for factors such as representativeness of the local pastoral system, accessibility by four-wheel-drive vehicles, and the size of cattle herds. In addition, it is also ensured that the selected study sites had at least 50 households in order to draw household samples from sufficient populations. Based on these criteria, five *reera* were selected, namely Siqu, Shomo, Irbi, Taka Bulti and El Dima, as study sites, which contained sufficient socio-ecological variations across the Borana Zone (Figure 2).

[4] Administrative units in Ethiopia occur in the following descending order of extent: nation, region, zone, district (*woreda*), and sub-district (*kebele*). *Kebele* is further sub-divided into sub-*kebele* to ease execution of daily administrative and extension activities. In Borana Zone, a sub-*kebele* is called *reera*. A *kebele* typically comprises three to five *reera*s. *Reera* is made of geographically adjacent villages called *olla*. *Olla* is group of households settled in a location that consists of as small as three to five households to as large as 20 to 30 households.

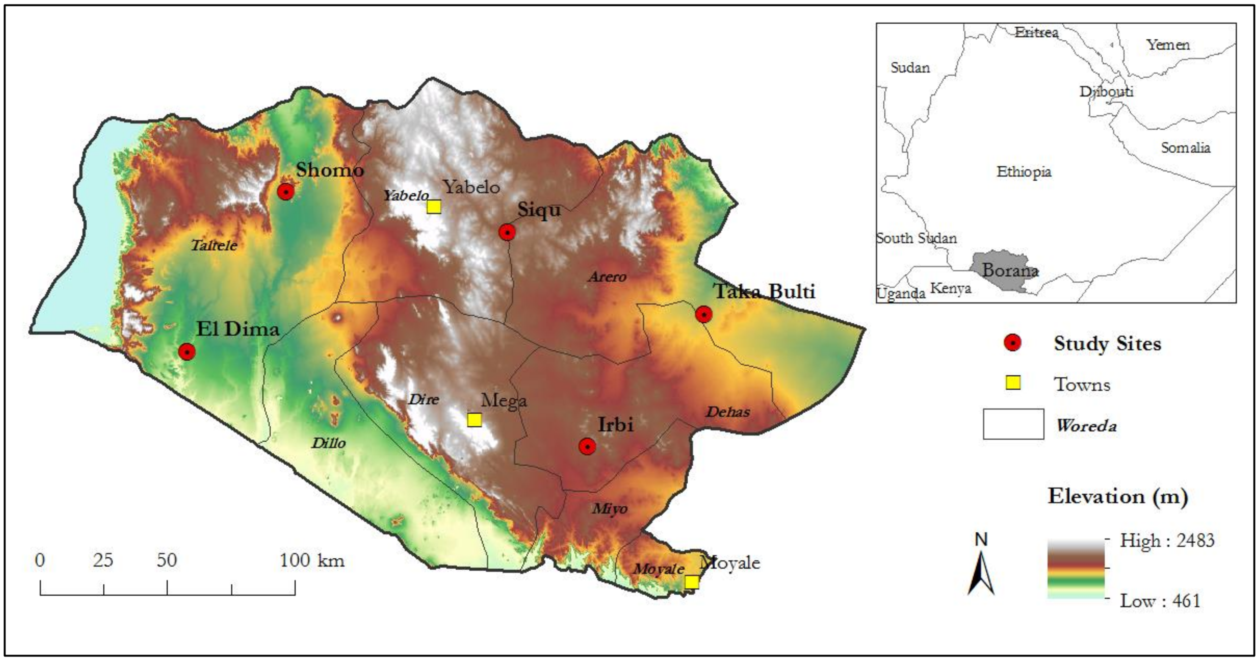

Figure 2. The Borana Zone study area and five selected study sites in southern Ethiopia

Siqu is located in northcentral Borana within a relatively flat area near the border between Yabello and Arero *woreda*. Herds in Siqu are the least mobile among the five study sites and typically migrate only under extremely harsh drought conditions. Shomo is located in Taltele *woreda* in northwestern Borana and is characterized as an area of flat and dry lake beds adjacent to steep hills. When pasture conditions are poor in neighboring areas, pastoralists tend to migrate to Shomo. Consequently, livestock concentrations in Shomo could become very high occasionally. Irbi is situated in southwestern Borana within the Dehas *woreda*. Irbi occurs at relatively high elevation and, during years of normal foraging conditions, commonly receives an influx of pastoralist herds from surrounding lower-lying area. When forage resources are substantially below the normal condition, Irbi households typically split their herds and take their animals to Yabello and Taltele. Taka Bulti is located in eastern Borana within Arero *woreda* and is characterized by dry river beds and flat-to-rolling terrain. Taka Bulti pastoralists are quite mobile, but livestock movement patterns are affected by ethnic conflicts with neighboring Garri and Somali ethnic groups (Tache & Oba, 2009). El Dima is located in southwestern Borana within Tatele *woreda*. While the base camps of El Dima households are situated in the dry lowlands, *forra* herding opportunities mostly exist in the adjacent highlands to the west. El Dima grazing areas border northern Kenya and are periodically affected by ethnic tensions. Pastoralists in El Dima are highly mobile and occasionally migrate into Kenya in search for forage when adequate security prevails.

Selection of participant households at each study site was based on herd size. Households were first stratified according to the relative number of cattle that they owned. In order to constrain the sample to households that relied primarily on livestock herding as a livelihood, those households 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 including commercial producers. The remaining households from each *reera* were divided into four herd-size categories: 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 of these categories in every *reera*.

2.2. GPS-tracking

In August 2011, three mature cows from each of the 20 selected households were fitted with custom-built, research-grade GPS-tracking collars by the IBLI team. These collars were capable of recording geographic locations every 5 minutes for 6 months or more without service or battery refit (Clark et al., 2006). Of the 60 collars deployed, 58 collars successfully collected viable data, with an average data set being 135 days in length. Twenty of these collars collected data for periods exceeding 200 days. From this subset of 20 long-standing collars, I selected two collars from different households in each study site for data analysis in this chapter (N = 10 collars; Table 1). Since the objective of this chapter is to assess cumulative spatial utilization pattern and recursive use of rangelands, it is necessary to choose the collars that worked throughout the entire tracking period.

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 the pastoralists. In order to obtain in-depth understanding of pastoral patterns in Borana, I interviewed household heads and conducted participatory mapping with these pastoralists and other community elders in each study site in July 2013. During the interviews, I validated the movement pattern inferred from GPS-tracking data, such as camp locations, travel distances and extent of movement. Specifically, I investigated the factors affecting pastoralists' decision-making, including environmental conditions, conflicts within and among communities, the practice of crop cultivation, settlement patterns, and development interventions by NGOs and government agencies. Additionally, follow-up validation interviews and mapping were conducted in May 2014 in an effort to correct any misinterpretation of herding patterns. Findings from these qualitative investigations facilitated a better-rounded and more accurate interpretation of GPS-tracking data to infer the spatial resource utilization patterns.

2.4. Data processing and analysis

The GPS-tracking locations were projected to a Universal Transverse Mercator (UTM) grid for distance and area calculation. Location errors were identified and removed by using the rule of thumb that the distance traveled by a collared cow during a 5-min interval should be less than 1000 m (i.e. less than a sustained velocity of roughly 12 kph). The Boran cattle (*Bos indicus*) very rarely run at this velocity for a sustained period of time. Consequently, data indicating this excessive rate of movement almost certainly contained substantial GPS location error and should be dropped from the dataset.

Throughout this chapter, I used the term, pastoral mobility, to refer to the movement pattern observed from the GPS-tracking data, which was 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 were gregarious and tightly herded, I assumed the movement of a single collared individual represented the mobility patterns of the household's entire herd.

I evaluated the extent of movement of individual cattle by first buffering each location point to accommodate a conservative estimate of location error (< 50 m). Each location point was thus converted to a circular polygon with a 50 m radius. Then I dissolved these individual polygons into an aggregated polygon representing the observed movement extent for each collared cow.

Upon visual inspection, density of utilization (i.e. location points per unit area) seemed to differ vastly within a cow's movement extent. I quantified the density of utilization for each cow by first, rasterizing the movement extent into 50 m by 50 m cells. I assumed this 2500 m^2 cell size would approximate the area traversed by Boran cattle during a 5-min interval while actively foraging. Next, I overlaid the raster with the point location data and counted the number of points within each raster cell. Density of utilization results were reported as points/km^2.

An initial examination of point-count values for each cell indicated that the values followed a negative binomial distribution, with most raster cell values falling near the lower end of the density range. Accordingly, for visualization purpose, I classified the cell values into the following six categories with narrower interval at lower end and wider interval at the higher end of the density range: 1) below 100; 2) 100-500; 3) 500-3,000; 4) 3,000-10,000; 5) 10,000-100,000; 6) above 100,000 points/km^2.

By overlaying utilization distribution images with features mapped by pastoralists, I found clear linkages between GPS-based density of utilization and reported land-use patterns such as base and satellite camp locations, travel corridors and principal foraging areas. While at camp during the nighttime hours, 22:00-04:00 local time, cattle were typically enclosed within night-corrals or circular brush 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 the study sites typically exhibited a density exceeding 100,000 points/km^2 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 magnitudes lower than that of base camps. Their locations were determined by the rule of thumb that the tracked cow returned to the same place for over three consecutive days. I 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 potential camp locations. Finally, in my participatory mapping sessions, I asked pastoralists to confirm whether these mapped locations were indeed their camp locations, and to identify which were base camps and which were satellite camps.

In order to further investigate utilization distribution within the extent of movement and its relationship with distance from base camp locations, I extracted cell values from utilization distribution images, and estimated the distance of each cell to base camps. Due to the negative binomial distribution of extracted values, I performed log transformation before any analysis. First, Analysis of Variance (ANOVA) was conducted to test the effect of study site on the utilization of distribution and distance from base camp location. Then I hypothesized that as distance from base camp location increases, density of utilization decreases. To test this hypothesis, I applied both ordinary least squares (OLS) model and general additive model (GAM) (Wood, 2013). The OLS model can be represented as:

$$Density = \beta_0 + \beta_1 \, Distance + \beta_2 \, Site + \varepsilon$$

where β_0 is the intercept; β_1 and β_2 are coefficients of distance and site; ε is the error and $\varepsilon \sim N(0, s^2)$.

The general additive model can be represented as:

$$Density = \beta_0 + f(Distance) + \beta_1 \, Site + \varepsilon$$

where β_0 is the intercept; $f(Distance)$ is non-linear and is subject to smoothing splines; β_1 is coefficient of site; ε is the error and $\varepsilon \sim N(0, s^2)$.

Using a similar approach to estimate movement range of each collared cow, I also calculated their cumulative extent of movement on a daily basis. I first derived the polygon representing each day's movement range. Then for first two days of tracking, I merged the first two polygons; for first three days, first three polygons; for the entire tracking period, all polygons. I used GAM to investigate the increase of movement extent as a response to the duration of tracking. The model can be represented as:

$$Cumulative\ Daily\ Movement\ Range = \beta_0 + f(Duration) + \beta_1\ Site + \varepsilon$$

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

3. Results

3.1. Spatial patterns of utilization

The 10 cows were monitored by GPS collars over a continuous tracking period ranging from 205 to 218 days and included from 55809 to 60196 location observations (i.e. geographic coordinates, date, time, GPS fix quality info, etc.) acquired for each collared cow. The extent of movement of each cow ranged from 20 km^2 in Siqu to 115 km^2 in Taka Bulti. Correspondingly, density of utilization (GPS location points/km^2) for each cow also exhibited a wide range among the study sites. The highest density of utilization was observed in Siqu at nearly 3000 GPS points/km^2, which was nearly six times of the lowest density of utilization as observed in Taka Bulti (500 points/km^2; Table 1).

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

Name	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

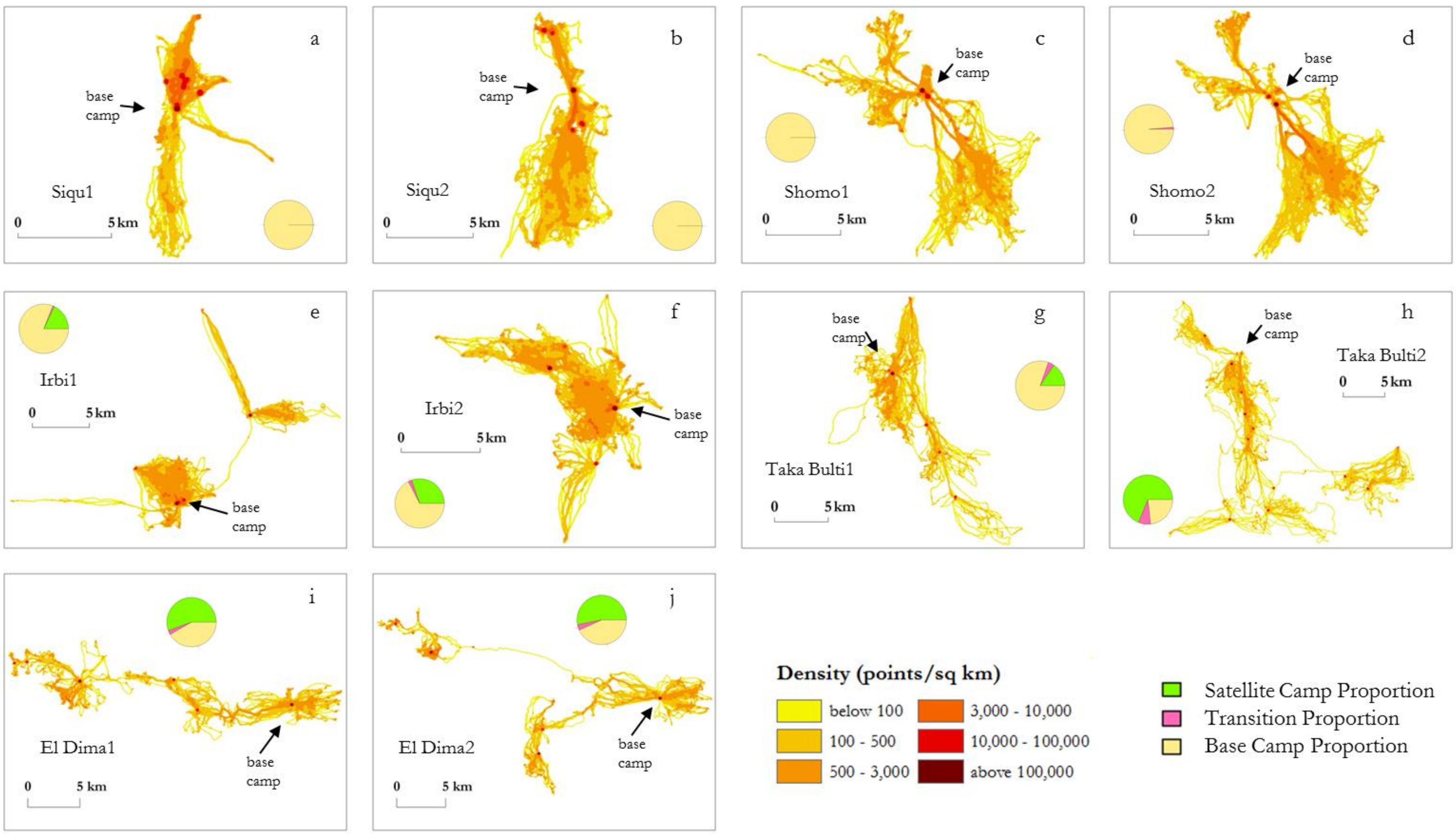

Figure 3. Spatial patterns of density of utilization by cows from two pastoralist households in five study sites of Borana, Ethiopia. Base camp locations are identified for each cow. Satellite camps are those small circular, red (10,000 – 100,000) or dark red (above 100,000) areas representing highly concentrated use at substantial distance from the labeled base camp in e, f, g, h, i and j.

Spatial patterns in density of utilization varied substantially among the study sites (Figure 3). In Siqu, the two households practiced a *worra*-only grazing 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 4). 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 suggested to settle along the main road extending east-west between Yabello and Arero (Watson, 2003). As a result, there were few foraging opportunities to the east or west of base camps because of the presence of neighboring settlements and their designated grazing areas. Consequently, density of utilization within these north-south travel corridors reached up to 5,000 points/km^2, suggesting a clear pattern of recursive utilization.

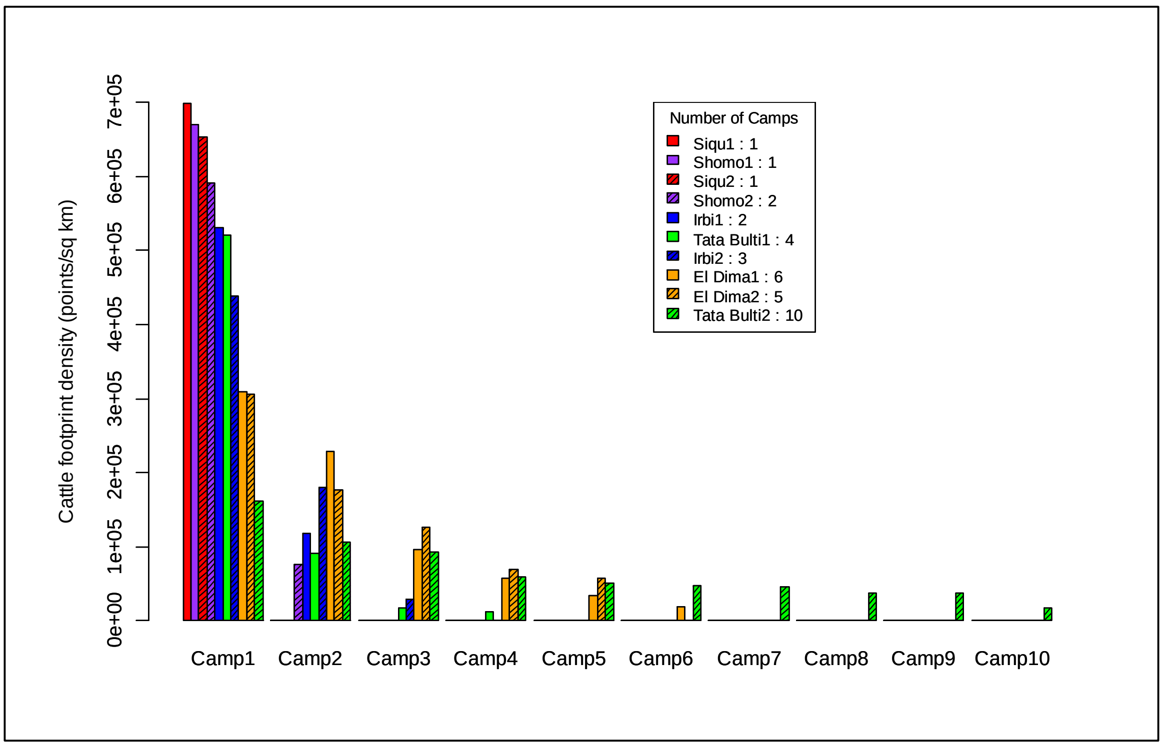

Figure 4. Density of utilization at each camp location of ten cows

Similar to Siqu, well-used travel corridors were evident in the utilization maps of the two Shomo households (Figures 3c and 3d). For most of the study period, the collared cattle walked each day to and from foraging areas in the southeast along fixed travel corridors which were nearly 3 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 major foraging areas. This pattern of travel corridors and minimal herding areas near the base camps (i.e. < 3 km) was largely due to the human settlement pattern in and around the community center. Village dwellings, livestock corrals, fenced crop fields and rangeland reserves (locally known as *kalo*) occurred as clusters around the community center, strongly confining the available area for livestock use to these narrow travel corridors between camps and southeastern foraging areas. The general direction of movement shifted under drier conditions of the warm dry-season. 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* was practiced in Shomo (Figure 4). Although Shomo2 household relocated their base camp location, the relocation was within the same village, thus was not considered practicing *forra* herding. However, average movement extent of Shomo pastoralists was almost twice as much as that of their Siqu counterparts, which resulted in less overall density of utilization (Table 1). In terms of utilization distribution within the extent of movement, Shomo pastoralists enjoyed less restricted grazing in their major herding area, compared to their Siqu counterparts whose major herding areas were highly restricted to a north-south pattern.

In contrast to Siqu and Shomo, pastoralists in Irbi practiced both *worra* and *forra* herding (Figures 3e and 3f, Figure 4). Since there were fewer fenced crop fields and rangeland reserves at this site, the herds did not have to follow fixed travel corridors starting from base camps. The collared cow from Irbi1 spent about one sixth of the entire study period at the only satellite camp, which was approximately 15 km from base camp (Figure 3e). The cow of Irbi2 spent almost a third of its time at two satellite camps, which were within 6 km from base camp (Figure 3f). The movement extents of cattle from both Irbi households appeared to be somewhat less and the overall density of utilization somewhat greater than those of Shomo (Table 1). This was because although Irbi pastoralists practiced *forra* herding, they only did so under extreme dry conditions. Instead, they spent most of their time around base camps, resulting in a concentrated resource-use pattern.

Cattle from the two households in Taka Bulti exhibited an extensive movement pattern (Figures 3g and 3h). However, the dry environmental conditions common to this area forced pastoralists to utilize rangelands far from their base camps. As a result, the Taka Bulti households practiced both *worra* and *forra* herding (Figure 4). Most satellite camps were set along seasonal migration routes leading towards their most distant grazing areas, which were as far as 35 km away from their base camps.

The utilization distributions of Taka Bulti households were distinct from the other study sites, as their extent of movement was larger, resulting in highly dispersed utilization patterns within the extents of movement. Such extensive movement was especially true for the case of Taka Bulti2 household, whose collared cattle spent over two thirds of the entire study period at nine different satellite camps (Figure 3h). This highly dispersed movement pattern exhibited by Taka Bulti2, consequently, resulted in the lowest overall density of utilization for any of 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 4). In contrast to Taka Bulti where satellite camps were set along the migration corridor, 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 conditions in the hills were much better than in the lowland plains surrounding the base camps. In addition, there were also no human settlements and associated *worra* herds to compete for resources, making this area ideal for *forra* herding.

Results from ANOVA indicated that utilization density among the five study sites were significantly different from each other ($F_{4, 585245} = 10242$, p-value < 0.001). The shapes of violins in Figure 5 showed that Taka Bulti had the widest tail, suggesting that cells of low utilization density accounted for a large proportion of their extents of movement. This was followed by El Dima. Despite a smaller extent of movement, it also showed a wide tail. The other three study sites were associated with much narrower tail. Although Irbi pastoralists practiced *forra* herding, most of livestock herding was conducted around base camp. The Shomo pastoralists had similar extent of movement to their counterparts in El Dima; however, distribution of density of utilization was different. The violin of Shomo had a wider neck and narrower tail than El Dima. This implies that despite pastoralists in Shomo having a relatively large extent of movement, the rangelands were still subject to recursive use as the households were largely sedentarized. The violin of Siqu had the narrowest tail and widest neck. In addition to being sedentarized, these households had smaller extent of movement compared to Shomo, which resulted in a clear recursive use pattern.

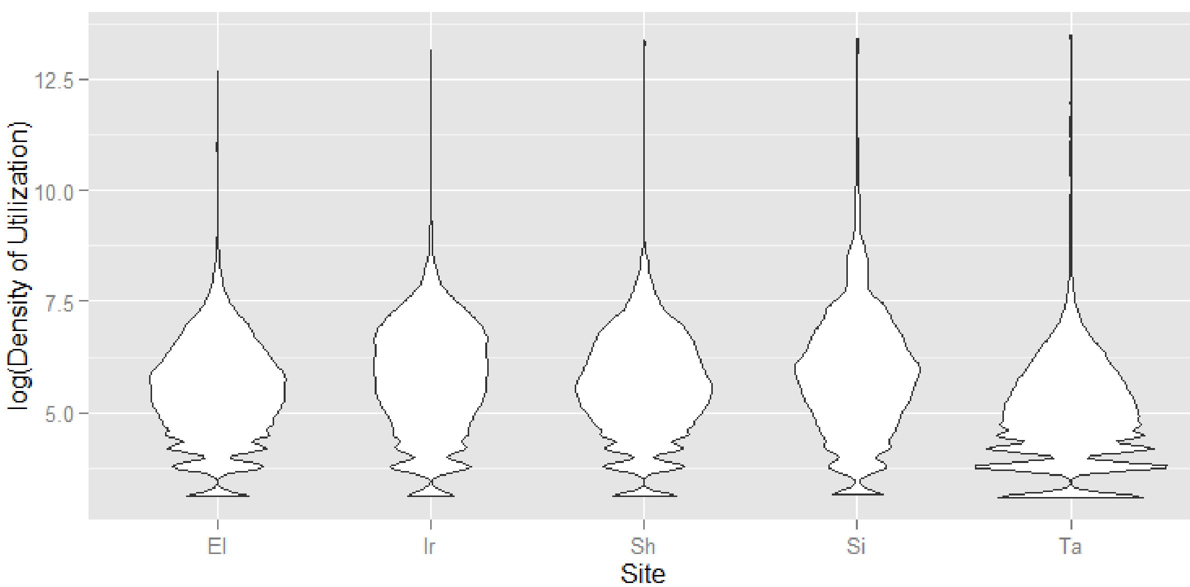

Figure 5. Violin plot of utilization density at five study sites.

There were also significant differences in the distance of each cell from base camp location according to ANOVA results ($F_{4, 585245} = 31799$, p-value < 0.001). El Dima pastoralists practiced herding in places up to 30 km from base camps (Figure 6). Similarly, Taka Bulti pastoralists also herded livestock in places up to 26 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-tailed violin. The cases of Shomo and Siqu were more similar to each other and different from the other three. Sedentarization confined their movements within 12 km from base camps. However, there were also differences between Shomo and Siqu. The peak of distance distribution of Siqu appeared at 2 km from base camp, while the peaks of Shomo ranged from 4 km to 8 km. Such comparison suggested that heavier grazing pressure occurred at more distant locations from base camps in Shomo.

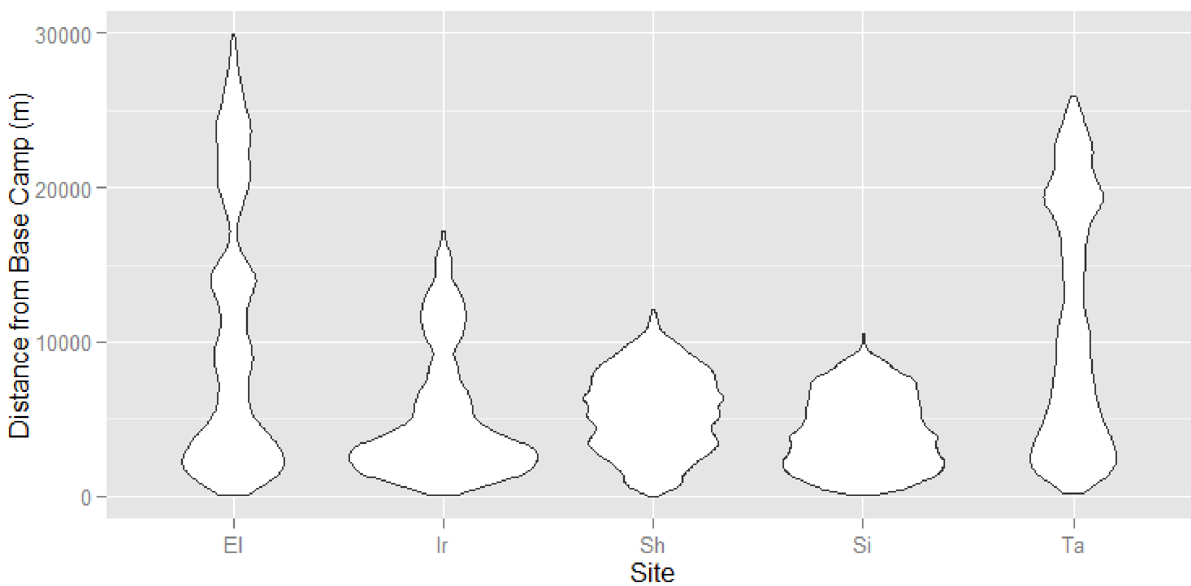

Figure 6. Distance from base camp locations of each utilized cell at five study sites.

3.2. Modeling density of utilization

Earlier models of pastoralists' spatial utilization of rangelands suggested that distance from camp locations could be used as an important predictor of utilization density. Starting from the base camp, the areas that are farther away from the base camp will be less likely to be used, indicating a piosphere utilization pattern (Lange, 1969; Sternberg, 2012). I first tested this model by investigating the relationship between density of utilization and distance from camp by running the OLS model. Site was used as a factor in this model. The result indicated a significant decreasing trend (slope = -3.729e-05, p-value < 0.001). However, the adjusted R-square was 0.09, showing poor capture of variations in the response variable.

In order to improve the prediction, I applied the GAM, which can effectively smooth the predictor. The results indicated that distance is a significant predictor of density of utilization (Table 2). The adjusted R-square is 0.15, which is 67% better than the simple linear model. In addition, the AIC value of GAM is 1827380, which is 39130 units lower than the linear model, indicating the GAM model is a much better fit than OLS.

Table 2. Estimation of density of utilization using GAM.

Variables	Estimate	Std. Error	t value
Intercept	5.483^{***}	0.003	1578.690
Irbi	0.156^{***}	0.005	29.970
Shomo	0.109^{***}	0.005	21.200
Siqu	0.174^{***}	0.006	28.620
TakaBulti	-0.371^{***}	0.004	-84.770
Smooth term	edf	Ref.df	F
Distance	8.999^{***}	9.000	9074.000

*** indicates significance at 0.001 level

Predictions from GAM modeling results suggested that density of utilization was not decreasing all the way as it got more distant from base camps (Figure 7). In the first 4 km from base camp, density of utilization decreases rapidly. However, when it got to 5 km, the utilization slightly went up until a distance at 7.5 km, representing the first grazing opportunity from base camp. This pattern was particularly true for Siqu and Shomo pastoralists. Since they only conducted *worra* herding, their utilization of rangelands rarely appeared beyond 10 km from base camps. Consequently, they mostly made use of rangelands at a shorter distance from their base camps. Pastoralists in other study sites also utilized the area around base camps more often, but camp relocation allowed them to access resources more distant from base camps.

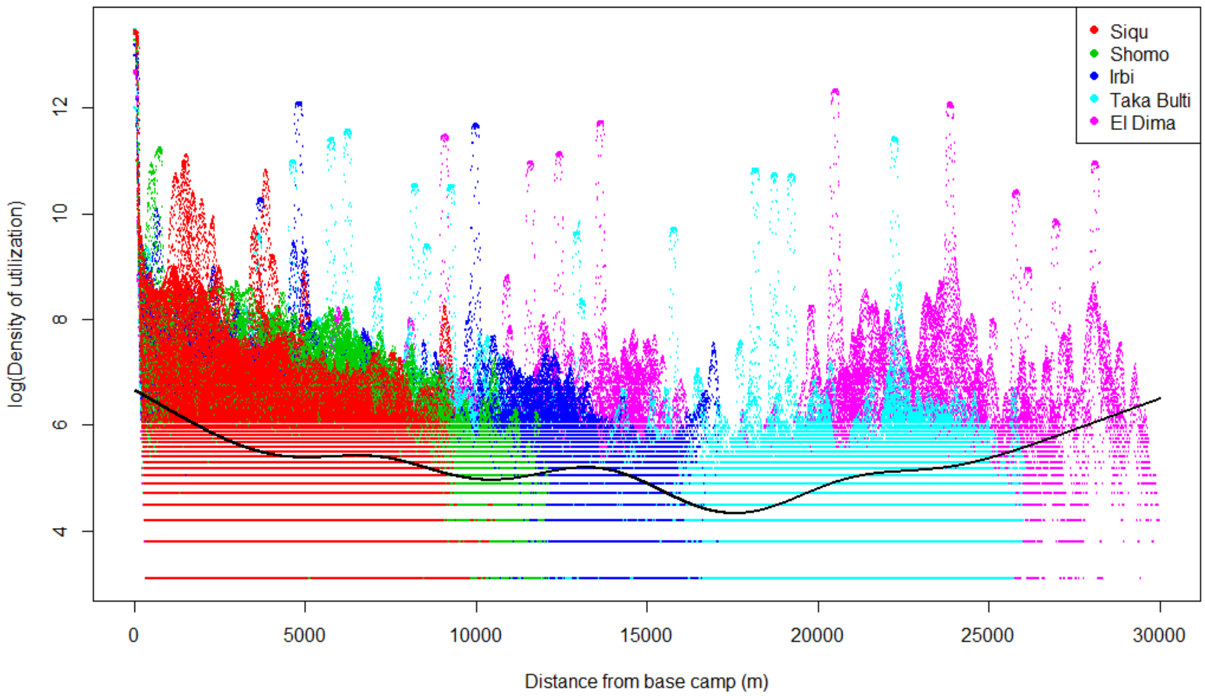

Figure 7. Density of utilization and distances from base camp locations. The black line represents predicted density.

The second grazing opportunity appeared at approximately 12 km from base camps, where the predicted density value peaked for the second time. This peak was largely contributed by the *forra* herding of Irbi pastoralists, who tended to set up satellite camps at an intermediate distance from home. In addition, Taka Bulti pastoralists also set up *forra* camps at similar distance from base camp, especially in late dry season. This was a compromised herding strategy, when *forra* grazing lands had forage but no surface water, while *worra* grazing lands had water in the permanent wells but little forage left.

After the second grazing opportunity, the predicted density value decreased until 19 km. Then there was an increasing trend until 30 km. Such upward trend was contributed by the extensive herding by pastoralists from Taka Bulti and El Dima. As shown in Figure 3, three out of four households spent more than half of the tracking period in their *forra* grazing lands. Such an upward trend reflected increasing foraging opportunity that was distant from base camp locations. In the less constrained study sites such as Taka Bulti and El Dima, rangelands at these locations were crucial for livestock grazing.

3.3. Recursive utilization of rangelands

Pastoralists in the five study sites indicated different degrees of recursive utilization of rangelands. Although the movement extent and average utilization density of El Dima and Shomo pastoralists were similar to each other (Table 1), they exhibited significantly different utilization distributions (pairwise t-test p-value < 0.01). This is because pastoralists in these two study sites employed different herding strategies: the former was engaged in extensive use of satellite camps in herding, while the latter only practiced *worra* herding. Such difference was manifested in the maps of utilization density (Figure 3). In El Dima, pastoralists used multiple small patches of rangelands, which were connected by less used migration corridors. In contrast, the Shomo pastoralists repeatedly used a few fixed migration corridors between base camps and major herding areas. They tried to make up for the disadvantages of giving up *forra* herding by dispersing their livestock in a bigger patch of rangeland distant from their base camps. In contrast to the nuanced difference between El Dima and Shomo, there were more evident distinctions among any other pairs of comparison between study sites.

In order to test the degree of recursive land use in the five study sites, I estimated the relationship between the duration of tracking and the cumulative extent of movement using GAM. The results indicated that: 1) there was a global trend that the extent of movement expanded as the tracking duration proceeded; and 2) the rate of increase slowed down as the tracking continued, suggesting recursive use (Table 3; Figure 8).

Table 3. Estimation of days of herding and study site as determinants of cumulative herding range using GAM.

Variables	Estimate	Std. Error	t value
Intercept	0.503***	0.003	150.670
Irbi	0.155***	0.005	32.510
Shomo	0.144***	0.005	30.510
Siqu	0.180***	0.005	38.050
TakaBulti	0.143***	0.005	30.440
Smooth term	Edf	Ref.df	F
Duration	5.711***	6.865	5134

*** indicates significance at 0.001 level

The regression results also indicated different recursive use among five study sites. Using El Dima as the benchmark site, all other study sites suggested significantly higher degree of recursive use. El Dima was the one with the least recursive use, as the cumulative curves were much closer to the 45° diagonal line (Figure 8). This indicated that these households had been constantly searching for new patches of pastures throughout the tracking period. Despite a greater movement extent, Taka Bulti pastoralists showed a higher degree of recursive use (the estimated coefficient was significantly positive). This was largely because they had to return to places closer to permanent water facilities at the end of dry season when surface water was all dried up in their *forra* grazing lands. Other sites showed much higher degree of recursive use. The highest was observed in Siqu, largely due to its constrained movement extent.

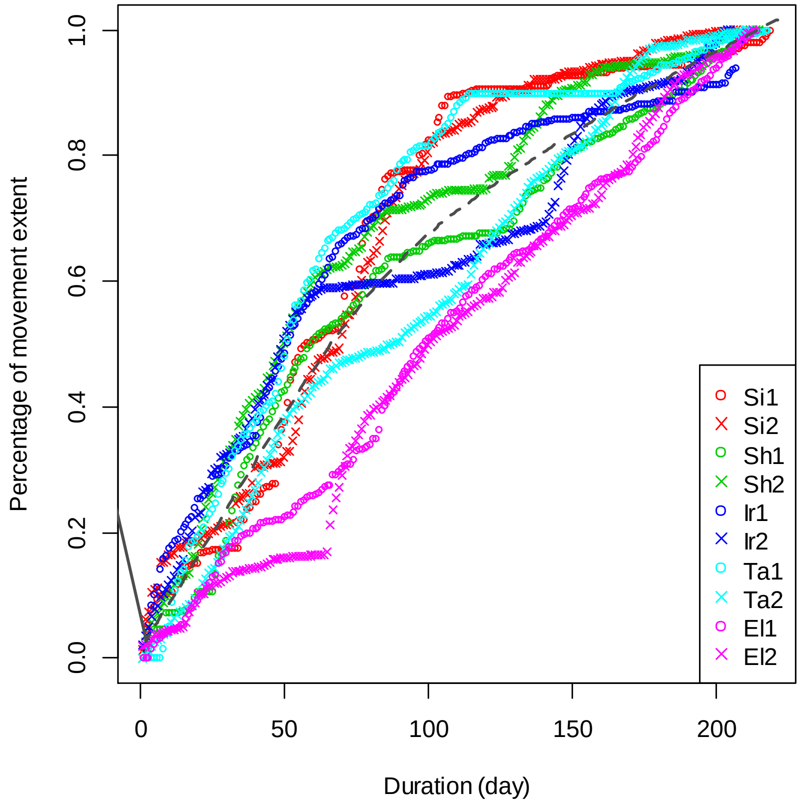

Figure 8. Movement extent and its relationship with duration of tracking. The grey dotted line represents the percentage of movement extent as the duration of tracking proceeds.

4. Discussion

The above results on spatial density of utilization and recursive use of rangelands suggested that pastoral mobility patterns in Borana are highly diverse. Three mobility models can be proposed to summarize the variations in the five study sites (Figure 9). The first type is a restricted herding model, which primarily involves linear movement between base camp and the major herding area (Figure 9a). Under this model, pastoralists do not utilize satellite camps and remain around a base camp year-round. The distance between base camp and major herding area is typically longer than that in the remaining two models. It is likely that repeated heavy use has either eliminated all forage resources or resulted in rapid consumption of available forage in areas near the base camp locations. This model would describe the mobility pattern observed in Siqu and Shomo. Due to relatively dense settlement, pastoralists usually had one area designated as their major herding area, and another area for dry season grazing. As a result, they developed several fixed travel corridors from base camp to the herding areas, and these corridors could be up to 3 km in length. Cattle typically traveled at a relatively fast pace as there was little forage available along the corridors.

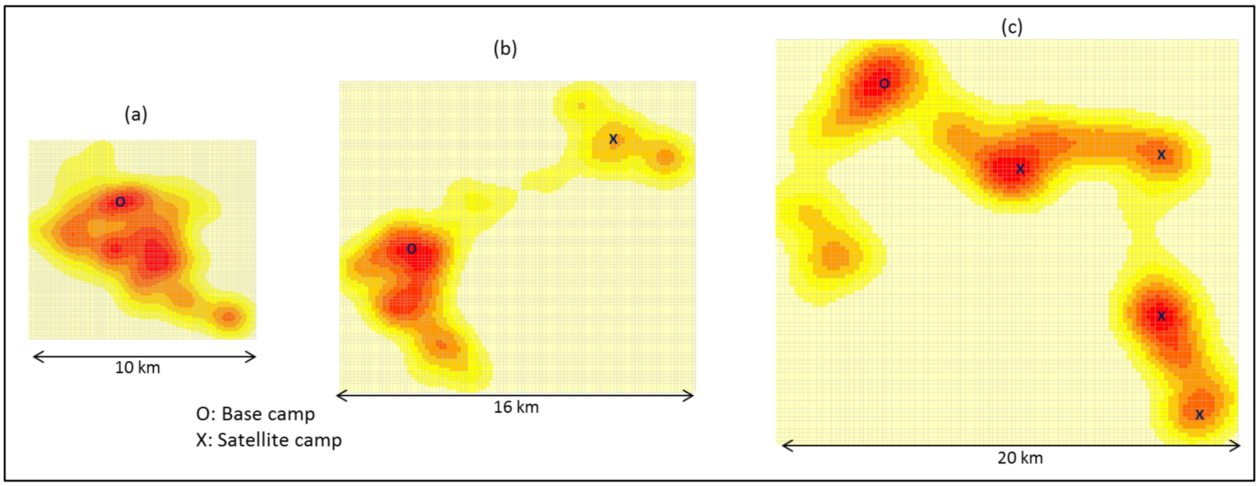

Figure 9. Three conceptual models of pastoral mobility patterns in Borana, Ethiopia. Red indicates high density while yellow represents low density of utilization.

The second type is semi-extensive herding model, which involves the use of both base and satellite camps (Figure 9b). 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 at the base camp. The mobility pattern observed at Irbi fits into this semi-extensive model. When herding around base camp, pastoralists did not use a fixed and repeated travel corridor such as those observed in Siqu and Shomo. Lower settlement density and high resource availability near the base camp allowed pastoralists to take different routes in daily travel to and from major herding areas. Under the semi-extensive model, satellite herding was practiced when resources around settlement eventually became exhausted in the dry season. The use of a satellite camp allowed forage around settlement area time for regrowth and thus would be available for use when the base camp was revisited between satellite camp moves.

The third type is extensive herding model, which is associated with extensive use of satellite camps (Figure 9c). This model would best describe the mobility patterns observed in Taka Bulti and El Dima. Similar to the semi-extensive model, pastoralists under the extensive herding model do not use fixed travel routes while herding around base camps. However, in contrast to the semi-extensive model, pastoralists directly move from one satellite camp to the next without returning to their base camps under the extensive model. Pastoralists generally keep their herds (i.e. immature stock, non-lactating cows and bulls) at their satellite camps for most of the year, while leaving lactating cows and calves in the base camp year-round. In the most extensive case, the range of movement was more than 115 km^2 during the study period, which was almost six times of the range in the restricted herding model.

5. Conclusion

This chapter investigated the spatial rangeland utilization patterns by pastoralists in the open grazing system in the Borana Zone of southern Ethiopia. The quantification of pastoral mobility was based on over 0.6 million geo-referenced points collected from continuous monitoring of 10 cows' movements over 7 months, as well as direct input from pastoralists through participatory mapping and interviews. The collection of such data itself was a crucial contribution to the study of pastoral mobility. Using extent of movement, density of utilization and recursive use of rangelands as indicators of pastoral mobility, I demonstrated that pastoralists have developed complex movement patterns given their unique herding contexts.

Spatial rangeland utilization pattern is largely determined by the herding context. In the sedentarized study sites such as Siqu and Shomo, settlement density was relatively high. Accordingly, pastoralists were obliged to use a limited number of narrow travel corridors extending from their base camps, through the settled area, to their major herding areas. *Forra* herding was not observed in Siqu or Shomo throughout the study period. In addition, these two sites also showed much higher degrees of recursive use of rangelands. In the relatively less sedentarized and wetter study site of Irbi, both *worra* herding and *forra* herding were observed. Cattle had more choices in terms of direction of travel from base camps due to abundant resource endowment and sparser settlement density. In the drier and more sparsely populated study sites of Taka Bulti and El Dima, the GPS tracking data revealed that more complicated mobility strategies were employed. Pastoralists at these sites commonly used multiple satellite camps, and most of their cattle herds spent over half their time at satellite camps throughout the study period, resulting in effective redistribution of grazing pressure within their herding range. Due to such differences in resource-use patterns, the degree of recursive use of rangelands were significantly different between El Dima and Shomo, despite exhibiting similar extent of movement.

Based on the empirical findings, I proposed three types of conceptual models to summarize pastoral mobility strategies in Borana. The first type is a restricted herding model, characterizing the daily long, linear movement between the base camp and major herding area throughout the year. The second type is a semi-extensive herding model, which depicts the case in which pastoralists are based in their base camps for most of the year, but move to one or more satellite camps under times of stress. The third type is an extensive herding model, which represents the most extensive movement strategy. Pastoralists have a base camp, but spend more than half a year herding around multiple satellite camps. This extensive mobility strategy is likely to have lower environmental impact than strategies involving recursive use over long-term stays at individual camp sites.

The research findings suggested that sedentarization and population growth led to increased settlement density, which constrained pastoral mobility to a single-camp strategy that could be more environmentally impactful than more extensive strategies. The recursive use of rangelands around settlements and along corridors indicated that the adoption of a *worra*-only grazing strategy has high potential for resource degradation. Village dwellings, livestock corrals, fenced crop fields and pasture reserves occurred as clusters around base camps, strongly limiting the available area for livestock to these narrow travel corridors between camps and foraging areas.

Given a projected warmer and drier climate (Funk et al., 2008) and a surge in human population in Borana (Coppock, 2010), the future of resource-use patterns is further complicated. On one hand, drier climate necessitates extensive movement as a coping strategy. On the other hand, population increase results in less grazing lands per capita, which constrains livestock movement. Therefore, future pastoral policy-making should carefully balance the demand for grazing lands and the increasing human and livestock population. Ultimately, the key to successful herd management in ASAL environment is the freedom of movement, which results in a continuous redistribution of livestock grazing pressure while reducing the chance of overgrazing and rangeland degradation.

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CHAPTER 5 MODELING PASTORALISTS' CAMP RELOCATION STRATEGIES IN BORANA, ETHIOPIA: AN INTEGRATED APPROACH

1. Introduction

It has been contended whether pastoralism is causing environmental degradation (Hardin, 1968) or is responsible for rangeland sustainability (Roe et al., 1998). In Hardin's argument on the tragedy of the commons, the pastoral system was used as a classic example of how resources could be depleted, with the assumption that each individual aims to maximize his/her own benefits in the common-pool. However, later scholars investigated the unique feature of pastoralism – mobility, and found evidence that being mobile is crucial to achieve synergy in the pastoral system, which not only ensures adequate forage intake for livestock, but also maintains rangeland ecosystem sustainability (Brown, 1971; Coughenour et al., 1985; Coughenour, 1991; Homewood, 2008; Smith, 1992). This is particularly true in the arid and semi-arid lands (ASAL), where forage quality and productivity within a single patch of pasture vary substantially within the year, primarily in response to changes in precipitation (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 needs of their livestock. In addition, extensive movement also results in a continuous redistribution of livestock grazing pressure while reducing the chance of overgrazing and rangeland degradation (Marin, 2010; Upton, 2012).

Various socio-ecological facets of pastoralism make it extremely complex, thus difficult to fully understand. Empirical investigations indicated that movement decisions made by pastoralists are based on not only ecological factors such as forage and water availability (Adriansen, 2005; Coppock, 1994; Liao et al., 2014; Moritz et al., 2010), but also social and political concerns including group companionships, intra- and inter-community competition and conflicts, and rangeland management regimes (Agrawal, 1999; Bedunah & Harris, 2005; Little et al., 2001; McCabe, 2004). Both internal and external forces take their toll on traditional pastoralism and its mobility strategies. Human population and settlement densities in many pastoral areas have grown to historic high points and such growth continues to accelerate (Blench, 2001; Coppock et al., 2011; Little & McPeak, 2014). Government sedentarization policies have influenced pastoralists to stop practicing long-distance, seasonal migrations and instead herd their livestock around their permanent settlement year-round (Fratkin & Roth, 2005). Furthermore, international development interventions promoting livelihood diversification, crop cultivation and water facility construction have also strongly affected pastoralists' movement decisions (McPeak et al., 2012). Adding further complexity to such decision making, interacting environmental disturbances like fire and fire suppression (Angassa & Oba, 2008), bush encroachment (Angassa & Baars, 2000; Gemedo-Dalle et al., 2006) and climate change (Funk et al., 2008) continue to reshape the playing field of modern pastoralism.

The Borana Zone in southern Ethiopia is such an example, where mobile pastoralism is inherently complex but increasingly challenged by a series of persistent and emerging socio-ecological factors (Solomon et al., 2007; Tache & Oba, 2010). However, current understanding of the complicated pastoral mobility pattern, especially camp relocation strategy, is still poor. Although broad migration routes have been mapped (Homann, 2005), it is largely unknown to what extent and under what circumstances will pastoralists choose to move beyond their range of settlement and set up satellite camps elsewhere. Such a knowledge gap is likely to make outsiders believe that pastoralists tend to overgraze specific patches of pastures, thus leading to the tragedy of the commons.

However, unraveling such complexity and elucidating the factors which determine the mobility strategies of pastoralists requires a considerable effort in mobility model development and evaluation. Given harsh environments, spatial remoteness, and frequent movements that are typical of pastoral communities in open grazing systems, it is challenging to collect continuous quantitative evidence of pastoral mobility in a consistent approach across multiple seasons. Research findings have clearly been hindered by limited availability of spatio-temporal data (e.g. GPS tracking datasets) needed to rigorously research mobile pastoralism. Therefore, existing research on pastoral mobility rarely revealed camp relocation strategies being employed in the open grazing system in ASAL. There is a clear knowledge gap on how camp relocation varies among different pastoral households and/or areas within the Borana Zone, and why such variation exists.

With the emergence of quantitative methods such as GPS tracking technology and associated analytical tools, tremendous progress has been made in the study of pastoral mobility. These technologies were first applied to investigate the spatiality of human-managed livestock movement contained within finite spaces such as paddocks (Bailey et al., 2006; Clark et al., 2014; Ganskopp & Bohnert, 2009). Efforts were also made to incorporate the use of GPS/GIS technologies to study livestock movements under the free-ranging situations typical of the African and Asian rangelands (Table 1). Portable GPS instruments were installed on livestock to track their movement in China (Kawamura et al., 2005), Senegal (Adriansen & Nielsen, 2002), Tanzania (Coppolillo, 2001), and Niger (Schlecht et al., 2004). Most recently, case studies have been conducted in Kenya (Butt, 2010; Butt et al., 2009) and Cameroon (Moritz et al., 2010) by integrating GPS technologies and ethnographic methods. Such integrated approach allows for better interpretation of GPS tracking data.

Table 1. Summary of previous GPS-tracking research projects

Research project	Country	Year	Duration	Frequency	Coordinates collected
Kawamura et al. (2005)	China	2002	5 days, 12 cows from 3 herding groups, 52 herding loops	Every 1 min	46800 (inferred)
Adriansen & Nielson (2002)	Senegal	1997-2000	3 years, one herd, no herding loops recorded	Once a week	1000 (inferred)
Coppolillo (2001)	Tanzania	1995-1996	73 days, 24 cows at one site, 73 herding loops	Every 12 min	5000 (inferred)
Schlecht et al. (2004)	Niger	1998	5 months, 14 cows, 180 herding loops	Every 10 s	777600 (inferred)
Butt et al (2009)	Kenya	2005-2006	1 year, 10 cows, 1118 daytime herding loops	Every 30 s	2760000
Moritz et al (2010)	Cameroon	2009	21 days, 20 units on 3 herds, 33 herding loops	Every 5 s	180000

However, most of the above GPS-tracking efforts either had low temporal resolution or spanned a short time period. Although Butt et al (2009) collected 2.76 million points forming 1118 herding loops, they were obtained mostly during the daytime. Due to limited battery lifespan, GPS collars deployed on livestock usually requires refitting on a daily basis. Consequently, the practice of camp relocation, which is common in the open grazing system, was rarely captured quantitatively. So far, there is an absence of frequent, continuous and cross-season movement data from which evidence of camp relocation can be derived. Another shortcoming in previous pastoral mobility study is that the tracking was conducted in a relatively homogeneous context. There was a lack of sufficient ecological and socioeconomic variation in the places where pastoralists herd animals. Therefore, it is difficult to infer how herding strategies would change given a different context.

In the Borana Zone of southern Ethiopia, previous research on pastoral mobility was largely based on qualitative observation and confined to areas closer to the administrative center (Coppock 1994), yet the zone is characterized by diverse socioeconomic and ecological conditions. As a result, pastoral herding strategies, especially camp relocation, are expected to be highly diverse as well. Empirical evidence of livestock movement, however, is yet to be collected to quantify camp relocation and predict how pastoralists will change camp sites in response to varying socioeconomic and ecological conditions at multiple scales.

In order to address the above knowledge gaps in terms of monitoring livestock movement and modeling camp relocation, this chapter aimed to investigate and predict the herding strategies of pastoralists in Borana. The data analysis was based on continuous and high-frequency GPS-tracking of livestock movement in five study sites with sufficient ecological and socioeconomic variations. Other methods such as remote sensing, household survey, participatory mapping and interviews were also applied to obtain data as predictors of camp relocation. Specifically, this chapter was dedicated to answering the following questions: 1) what are the different herding strategies in Borana, and how do they differ from each other in terms of travel distance across the study sites; 2) what are characteristics of resource conditions, resource users, and external environments in the five study sites; and 3) how do socio-economic and ecological factors affect pastoralists' camp relocation strategy.

The rest of the chapter proceeds as follows. The second section describes research methods. The third section investigates three herding strategies across five study sites. In the fourth section, I articulate the characteristics of resource conditions, resource users and external environment that could potentially affect pastoralists' camp relocation strategies. In the fifth section, I examine the relationship between pastoralists' camp relocation and their herding contexts by using generalized linear mixed-effects model at the daily level and linear mixed-effects model at the seasonal level. Implications of camp relocation are discussed at the end.

2. Methods

2.1. Study area

The Borana Zone is located in southern Ethiopia north of the Kenyan border. With about 43,000 km^2 in size, this region is home to over 350,000 people with a livestock population fluctuating around a million head (Coppock, 2010). Elevation in Borana ranges from 500 m to 2500 m above sea level with terrain varying from steep highland slopes to flat, dry river and lake beds in the lowlands. The climate is largely semi-arid with relatively cool annual temperatures (19-24°C) and a mean annual rainfall ranging from 300 mm in the lowlands to 1000 mm in the highlands. The annual precipitation distribution is bimodal, with 60% occurring during the long-rain season (April to May) and 30% during the short-rain season (October to November) (Coppock, 1994; Desta & Coppock, 2002). The vegetation is mainly mixed savanna, which is increasingly encroached by *Acacia* and *Commiphora* species (Angassa & Oba, 2008).

Pastoralism is the major livelihood strategy for the people in Borana. Cattle herding is generally practiced in two forms. One form is home-based herding, known as *worra* in the Boran local language, which involves the herding of lactating cows, calves and small stock close to settlements. The other form is satellite herding, referred to as *forra* in the local language, where temporary camps are used to graze bulls, non-lactating cows and immature stock at substantial distances away from base camps. *Forra* herding allows livestock to range more widely and have access to better forage than what might be available near base camps (Homewood, 2008). These two forms of herding are not mutually exclusive, as one household can practice both simultaneously through herd splitting.

Rangeland resource utilization patterns of Boran pastoralists are generally determined by seasonal movement cycles between the wet- and dry-season grazing areas. Typically, rangelands that had ponds or deep wells were used during the dry seasons, whereas pastures without permanent water facilities were used only during the wet seasons (Angassa, 2012). Historically, access to grazing resources on communal rangelands was more strictly limited by water availability (Helland, 1980). In recent years, however, the communal grazing patterns have changed as water facilities were constructed throughout the landscape as part of the efforts to sedentarize pastoralists and regulate their movement. As a result, water availability is not the overarching factor as it once was in terms of driving broad-scale seasonal migration activities. As pastoralists settle, they also claim patches of rangelands as private crop fields or grazing reserves, leaving the communal grazing system more and more fragmented (Angassa & Oba, 2008).

2.2. Sample selection

Reera[5] was used as the sampling frame for selecting study sites and households by the IBLI team. The selection process accounted for factors such as representativeness of the local pastoral system, accessibility by four-wheel-drive vehicles, and the size of cattle herds. In addition, it is ensured that the study sites had at least 50 households in order to draw household samples from sufficient populations. Based on these criteria, five *reera*, namely Siqu, Shomo, Irbi, Taka Bulti, and El Dima, were selected as study sites, which contained sufficient ecological and socioeconomic variations across the Borana Zone (Figure 1).

[5] Administrative units in Ethiopia occur in the following descending order of extent: nation, region, zone, district (*woreda*), and sub-district (*kebele*). *Kebele* is further sub-divided into sub-*kebele* to ease execution of daily administrative and extension activities. In Borana Zone, a sub-*kebele* is called *reera*. A *kebele* typically comprises three to five *reera*s. *Reera* is made of geographically adjacent villages called *olla*. *Olla* is group of households settled in a location that consists of as small as three to five households to as large as 20 to 30 households.

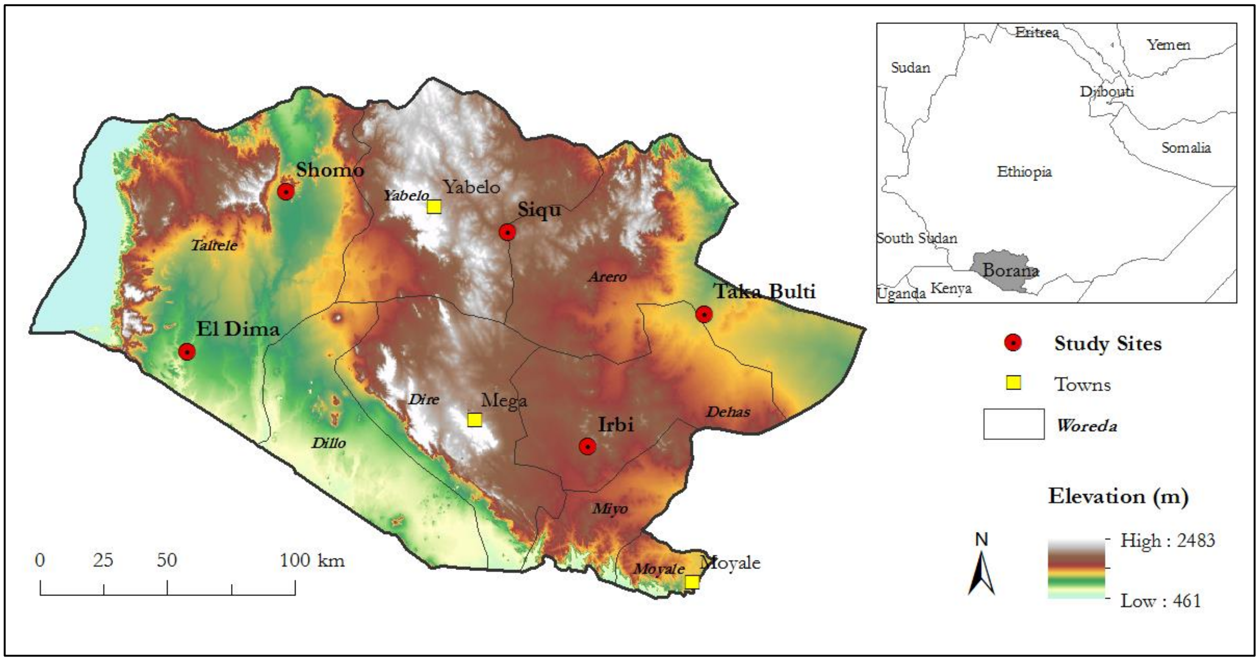

Figure 1. The five selected study sites in the Borana Zone of southern Ethiopia

Siqu is located in northcentral Borana within a relatively flat area near the border between Yabello and Arero *woreda*. Herds in Siqu are the least mobile of among the five study sites and typically migrate only under extremely harsh drought conditions. Shomo is located in Taltele *woreda* of northwestern Borana and is characterized as an area of flat and dry lake beds adjacent to steep hills. When pasture conditions are poor in neighboring areas, these pastoralists tend to migrate to Shomo. Consequently, livestock concentration in Shomo could become very high occasionally. Irbi is situated in southwestern Borana within the Dehas *woreda*. Irbi occurs at relatively high elevation and, during years of normal foraging conditions, commonly receives an influx of pastoralist herds from surrounding lower-lying area. When forage resources are substantially below the normal condition, Irbi households typically split their herds and take their animals to Yabello and Taltele. Taka Bulti is located in eastern Borana within Arero *woreda* and is characterized by dry river beds and flat to rolling adjacent terrain. Taka Bulti pastoralists are quite mobile but livestock movement patterns are affected by ethnic conflicts with neighboring Garri and Somali ethnic groups (Tache & Oba, 2009). El Dima is located in southwestern Borana within Tatele *woreda*. While the base camps of El Dima households are situated in the dry lowlands, *forra* herding opportunities mostly exist in the adjacent highlands to the west. El Dima grazing areas border northern Kenya and are periodically affected by ethnic tensions. Pastoralists in El Dima are highly mobile and occasionally migrate into Kenya in search for forage when adequate security prevails.

Selection of participant households from each study site was based on herd size. Ethiopian development agencies and extension staff provided assistance in compiling the number of households and associated livestock herd sizes in the five study sites. Within each site, households were stratified according to the number of cattle they owned. In order to constrain the sample to households that relied primarily on livestock herding as a livelihood, households whose cattle herd sizes fell within the bottom 35% of the *reera* population were excluded. In addition, households within the top 5% of cattle ownership were also excluded to avoid including commercial producers. The remaining households from each *reera* were divided into four herd-size categories: 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 of these categories for each *reera* (N = 20 households). The IBLI research team also conducted household survey and herd migration survey in these five study sites, which provided detailed profiles of resource users at both household and community levels.

2.3. GPS-tracking

In August 2011, three mature cows from each of the 20 selected households were fitted with custom-built, research-grade tracking collars by the IBLI team. These collars were capable of recording GPS location data every five minutes for six months or more without service or battery refit (Clark et al., 2006). Of the 60 collars deployed, 58 collars successfully collected viable data, with an average tracking duration being 135 days (N = 58). In total, over 2.25 million geo-referenced and time-tagged raw data points were collected, all of which were included in the data analysis.

2.4. Participatory mapping and interview

Although the practice of pastoral camp relocation can largely be inferred from the intensively-sampled GPS-tracking data described above, well-rounded interpretation of these patterns requires substantial input from the pastoralists themselves. In order to obtain in-depth understanding of camp relocation in Borana, I conducted participatory mapping sessions using base maps displaying topography and inferred camp locations. The mapping was conducted in July, 2013. Respondents included the four participant households and another two elder pastoralists. With the facilitation of a local translator, pastoralists were guided to draw their community perceived herding boundaries, community center locations, daily travel corridors, typical seasonal migration routes, and pathways to nearby roads.

In addition to mapping, I also interviewed pastoralists regarding the factors that affect their decision-making in camp relocation, including environmental conditions, conflicts within and among communities, crop cultivation practices, settlement patterns, access to roads and nearby towns, and development interventions by NGOs and government agencies. Follow-up validation interviews and mapping sessions were conducted in May 2014 in an effort to correct any misinterpretation of pastoral herding patterns. Findings from these qualitative investigations contributed to better interpretation of GPS-tracking data in terms of seasonality of resource use, decision-making regarding satellite camp location choice, and other socio-ecological factors that influence herd movement patterns.

2.5. Data processing

The geographic GPS-tracking points were projected to a Universal Transverse Mercator (UTM) grid for distance and area calculation. Location errors were identified and removed by using the rule of thumb that the distance traveled by a collared cow during a 5-min interval should be less than 1000 m (i.e. less than a sustained velocity of roughly 12 kph). The Boran cattle (*Bos indicus*) very rarely run at this velocity level for a sustained period of time. Consequently, data indicating this excessive rate of movement almost certainly contained substantial GPS location error and should be dropped from the dataset.

Then I determined camp locations from the tracking data. While at camp during the nighttime hours, 22:00-04:00 local time, cattle were typically enclosed within night corrals or circular bush fences with 20-50 m in diameter to reduce predation and losses from theft. Consequently, with cattle movement constrained to these small areas, it was a straightforward process to identify a potential camp location given its high density of utilization. Locations of satellite camps were determined by the rule of thumb that the tracked cow returned to the same place for over three days consecutively. Next, I 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 potential camp locations. These locations were further confirmed with participant households in my second round of fieldwork in May 2014.

Based on these confirmed camp locations, I quantified the daily travel distance of each collared cow. Lengths of these daily herding loops were calculated as the cumulative sum of straight line movements between each successive pair of GPS locations making up the movement path. Daily herding loops originating from base camp were classified as *worra* herding. Loops originating from satellite camps were classified as *forra* herding. Distance traveled during days when the cows moved to a new camp (i.e. camp-change days) was determined separately from days when the camp location was not changed, which was classified as transition herding. I conducted Analysis of Variance (ANOVA) to compare whether different herding strategies had a significant impact on the length of herding loops across the study sites.

I digitized the drawings of herding ranges from participatory mapping in ArcGIS 10.1, and estimated the size of perceived herding ranges from the polygons. According to the community center locations reported by pastoralists in the five study sites, I also calculated the distance of each study site to the nearby main road with regular bus service, as well as the distance to Yabello town, which is the administrative center of Borana Zone.

2.6. Seasonality and NDVI

Seasonality is an important factor that affects pastoral movement patterns (Coppock, 1994; Angassa, 2012). In order to distinguish wet season from dry season in the study period, I used Normalized Difference Vegetation Index (NDVI) data (spatial resolution = 250 m) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Terra satellites to assess temporal variations in vegetation greenness. Fifteen raster images that covered the study period between Aug 13, 2011 and Mar 21, 2012 were used in this operation. I extracted each raster pixel value within the zone, and calculated the average NDVI for each imagery date. These NVDI averages were plotted and smoothed to illustrate the relationship between NDVI and the study period (Figure 2).

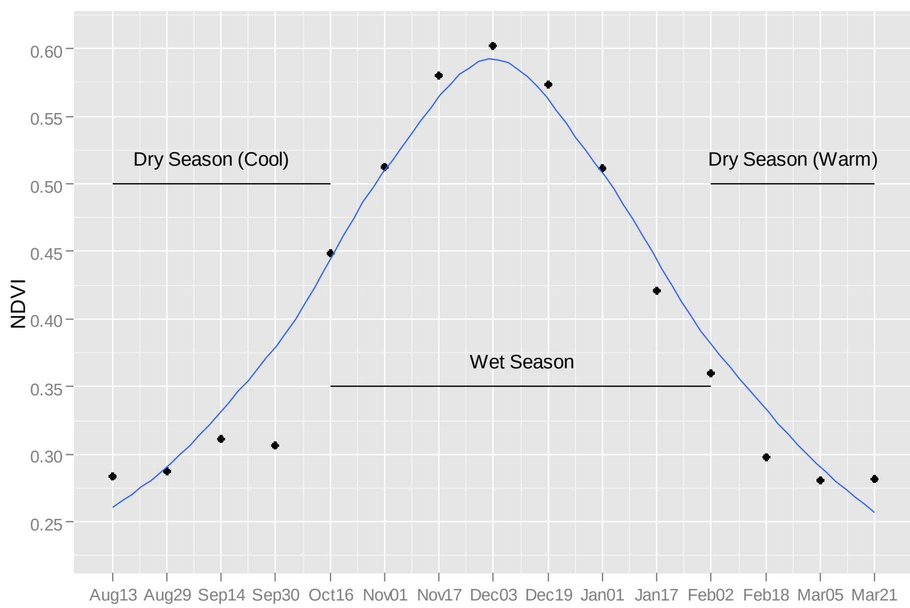

Figure 2. Changes in the slope rate of NDVI values derived from 15 MODIS image dates indicate breakpoints between three seasons during the study period: cool dry season, short-rain wet season, and warm dry season

Seasonality was inferred by identifying changes in the slope rate of the curve. The point on the curve with the greatest positive slope rate divided the first dry season period (i.e. the cool dry season) from the following wet season (i.e. short rains), while the point with the lowest negative slope rate split the wet season from the second dry season period (i.e. warm dry season). During the August 2011 to March 2012 study period, the cool dry season was represented by the period before 17 October 2011, the short-rain wet season between 17 October 2011 and 2 February 2012, and the warm dry season after 2 February 2012.

I also used NDVI as a predictor of camp relocation. At the seasonal level, I used the movement range polygon to extract NDVI values of all pixels, and calculated the mean NDVI for cool dry, wet, and warm dry seasons of each study site. At the daily level, I smoothed the 16-day NDVI data using general additive model (GAM) (Wood, 2013) over the study period for the five study sites. Then I used the site-specific model to derive the NDVI values for each day in the five study sites.

2.7. Prediction of camp relocation

I applied linear mixed-effects model and generalized linear mixed-effects model (Bates et al., 2014) to investigate how ecological and socioeconomic factors affected pastoralists' camp relocation strategy at multiple temporal scales. As herding strategy (*worra*/*forra*/transition) and NDVI vary at the daily level, I can test how daily variations in the environment can affect pastoralists' herding strategy. I excluded Siqu and Shomo because camp relocation was not observed in these two sites over the study period. Since the research question centers on the practice of camp relocation, I put *worra* herding as one category, and combined *forra* and transition as the other category because transition was ultimately related to camp relocation. Specifically, I investigated the probability of camp relocation given the synchronized NDVI values on a daily basis. I used cowID and Date as random effects in this model. The generalized linear mixed-effects logit model can be represented as:

$$Camp\ Relocation\ Probability = \beta_0 + \beta_1 NDVI + \beta_2 Site + b_1 \times 1|CowID + b_2 \times 1|Date\ +\ \varepsilon$$

where β_0 is the intercept; β_1 and β_2 are fixed-effect coefficients of NDVI and study site; b_1 and b_2 are random-effect coefficients of cow ID and Date; ε is the error and $\varepsilon \sim N(0, \sigma^2)$.

I further investigated how other community and household characteristics affect pastoralists' herding strategies. However, these factors varied very little over the study period, while NDVI and herding strategies changed on a daily basis. To balance the temporal differences among different factors, I conducted the analysis at the seasonal level. For cool dry, wet, and wet dry seasons, I estimated the proportion of days away from base camp and the mean NDVI value in these three seasons for each cow. All other factors stayed the same in the three seasonal periods. I also excluded the factors that were highly correlated with each other (Pearson correlation coefficient > 0.7).

I hypothesized that the proportion of days away from base camp (including *forra* herding and transition herding) was potentially subject to the influence of resource users, resource conditions and external environments (Agrawal, 2007). Consequently, I used NDVI and perceived community herding range as measurements of resource conditions, number of households in community, participant household herd size and community herd size as measurements of resource users, and distance to road with bus services as a measurement of external environment. All these predictors are considered fixed-effect at the community level except household herd size. I used cowID as a random-effect predictor.

In my modeling of camp relocation strategies using linear mixed-effects model, I took a step-wise approach to examine the impact of each group of factors. I added these groups of factors step by step to investigate their significance. I first built the null model, which only included intercept and random-effect predictor, namely CowID. Then I added resource condition variables, namely HerdingRange and NDVI. After that I added community resource user variables, including HHNumber and CommHerd. Next, I added external environment variable, which was DistRoad. Finally, I included HHHerd, the predictor at household level, into the model. The full linear mixed-effects model can be represented as:

$$Camp\ Relocation\ Proportion = \beta_0 + \beta_1 HerdingRange + \beta_2 NDVI + \beta_3 HHNumber + \beta_4 CommHerd + \beta_5 DistRoad + \beta_6 HHHerd + b_1 \times 1|CowID + \varepsilon$$

where β_0 is the intercept; β_1 to β_6 are coefficients of six independent variables; b_1 is random-effect coefficient of cowID; ε is the error and ε ~ N (0, σ^2). All data analysis in this chapter was conducted using R statistical software (R Development Core Team, 2014).

3. Herding Strategies

The Boran pastoralists generally use one base camp and potentially multiple satellite camps in their livestock herding practices. According to the type of camp used in herding, there are three strategies at the daily level. The first strategy is *worra* herding (Figure 3). This type of herding revolves around the base camp – pastoralists take their animals out of camp early in the morning, drive them to a piece of rangeland for grazing, and return to the base camp in the evening. Because most of the camps were set up in clusters, the surroundings of settlements are usually used as crop fields or community rangeland reserves. Therefore, the amount of forage resources around base camp locations is very limited. Consequently, pastoralists need to follow fixed corridors on their way to major herding areas. As shown in the example of Figure 3, pastoralists took their animals out early in the morning, and quickly herded them along a migration corridor to the rangelands with sufficient forage for the animals. After two hours' fast walking, the herd arrived at their feeding area, and spent the rest of day there until late afternoon. They largely followed the same path back to their base camp in the evening.

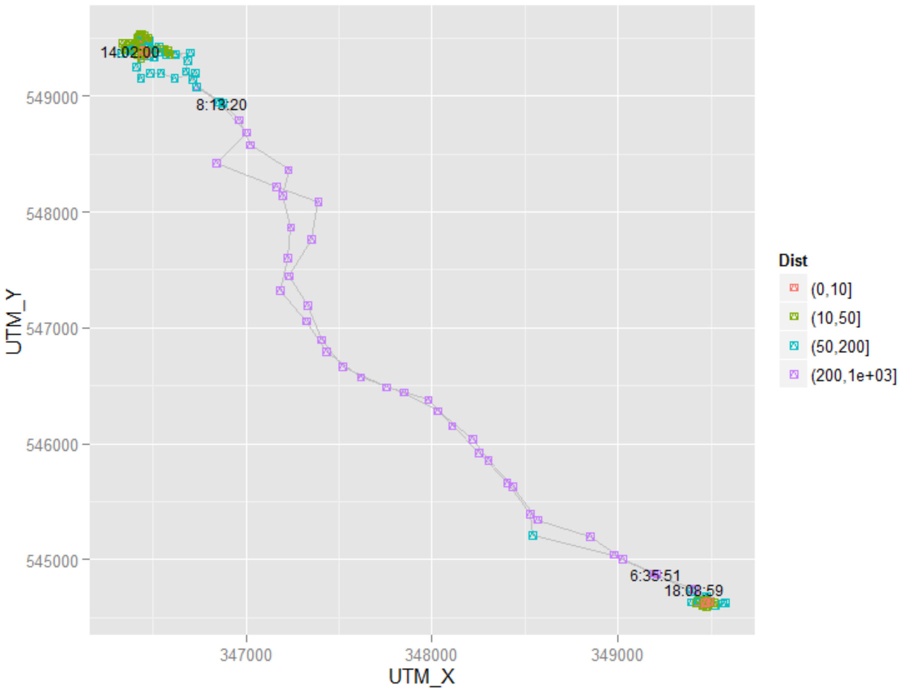

Figure 3. An example of *worra* herding. The legend shows the distance of movement (m) in a 5-minute interval.

In contrast, *forra* herding is a strategy for pastoralists to make use of underutilized forage resources that are distant from base camps (Figure 4). This herding strategy revolves around a satellite camp, which pastoralists make use temporarily in dry season. Due to less competition from neighbors and absence of settlements, pastoralists typically have better access to forage in close proximity of satellite camp locations. Therefore, they can start herding later in the day, and avoid long-distance walking to the herding area as they do in *worra* herding.

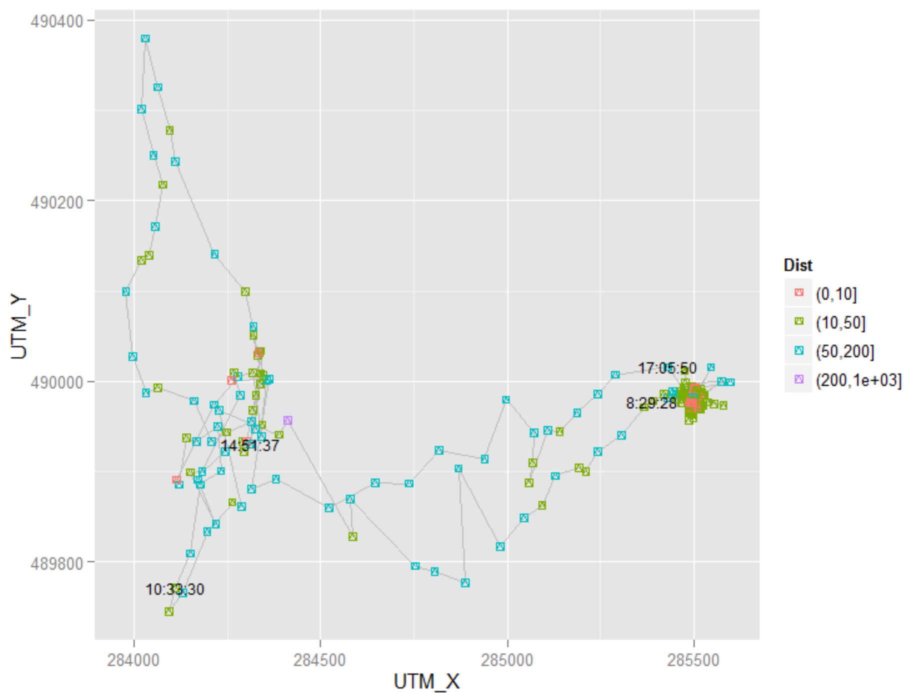

Figure 4. An example of *forra* herding. The legend shows the distance of movement (m) in a 5-minute interval.

The third type is transition herding, which is the case when pastoralists move from one camp to another (Figure 5). This type of herding is characterized by its movement toward one direction rather than returning to the same starting point as in the previous two types. Typically, pastoralists spend more time on traveling while conducting transition herding, as the distance between two camps can reach up to 30 km. Consequently, animals will only be able to graze periodically on these days. However, daily travel distance could be shorter in cases when pastoralists move from one *forra* camp to another nearby *forra* camp.

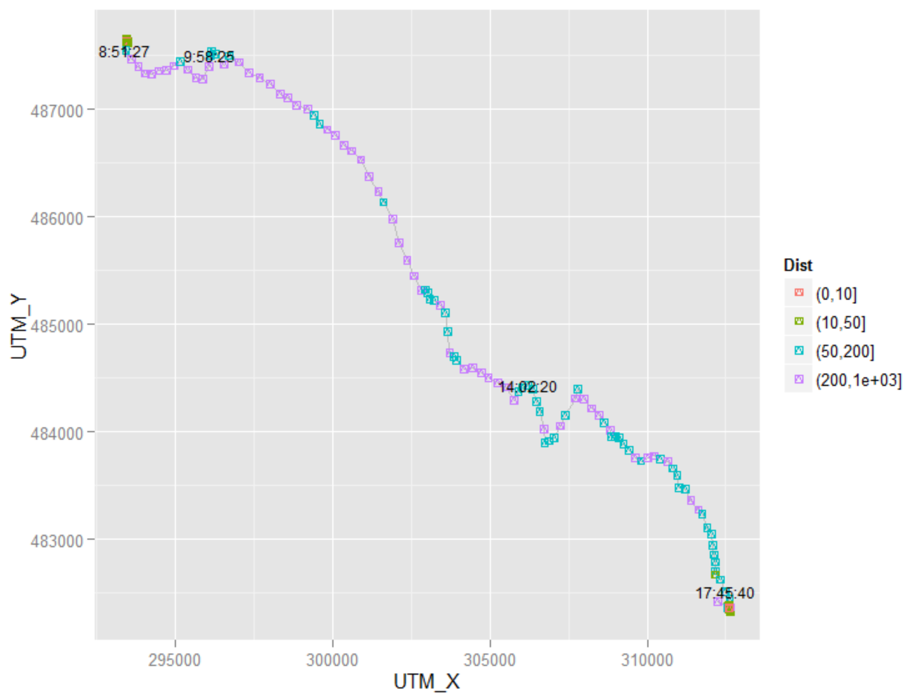

Figure 5. An example of transition herding. The legend shows the distance of movement (m) in a 5-minute interval.

The GPS-tracking recorded 7097 daily herding loops in the five study sites from August 2011 to March 2012 (Table 2). Nearly 80% of these loops were *worra* herding. Another 19% were *forra* herding. Transition herding only accounted 1.5% of these loops. The herding loop lengths differed according to study site and herding strategies.

Table 2. Summary of three herding strategies in five study sites

Site	*Worra* days	*Worra* distance (m)	*Forra* days	*Forra* distance (m)	Transition days	Transition distance (m)	Total days	Total mean (m)
El Dima	569	14750.03	822	12126.22	51	15852.76	1442	13293.35
Irbi	976	13979.01	266	16436.13	19	17865.34	1261	14555.88
Shomo	1335	20456.91	0	NA	0	NA	1335	20456.91
Siqu	1519	15823.65	0	NA	0	NA	1519	15823.65
Taka Bulti	1243	12173.43	264	18764.47	33	22612.55	1540	13527.02
Overall	5642	15688.40	1352	14270.40	103	18389.77	7097	15457.47

Table 3. Summary of Analysis of Variance of herding loop length

	Df	Sum Sq	Mean Sq	F value	p-value
Type	2	3.09E+09	1.55E+09	65.72	<0.01
Site	4	4.80E+10	1.20E+10	510.66	<0.01
Type*Site	4	1.23E+10	3.08E+09	131.08	<0.01
Residuals	7086	1.67E+11	2.35E+07		

I investigated the impact of herding strategy and study site on loop length using ANOVA. Specifically, I compared the daily travel distance of *worra*/*forra*/transition herding across five study sites. I hypothesized that daily herding loop length is identical under the three herding strategies and in the five study sites. Results from ANOVA rejected the hypothesis (Table 3). Herding loop distances varied significantly for different types of herding across the five study sites.

Pairwise comparison results from Tukey Honest Significant Difference (TukeyHSD) revealed more details in the variation of herding loop length. *Worra* herding is engaged in significantly longer loop length than *forra* herding, while transition herding is longer than both *worra* and *forra* (p-value < 0.001). In terms of study site, any pairwise comparison indicated significant difference (p-value < 0.001) except Taka Bulit and El Dima (p-value = 0.719), as the mean distances of travel in these two sites were similar. However, there was a significant interaction effect between herding strategy and study site (Table 3). Although pastoralists in Taka Bulti and El Dima exhibited similar average herding loop length, their *forra* herding loop lengths were significantly different from each other (p-value < 0.001). Taka Bulti pastoralists traveled longer distances while practicing *forra* herding, while El Dima pastoralists traveled shorter distances in their *forra* grazing lands. Such results suggested that it is the interaction of multiple factors that determine the actual herding strategies.

4. Socio-Ecological Contexts of Camp Relocation

The five study sites cover a wide range of socio-ecological variations. Siqu and Irbi are situated in the highland with wetter climate. Shomo and El Dima are at the bottom of Rift Valley. The elevation of Taka Builti is in-between these two groups (Figure 1). Community-perceived extent of herding ranges from 203 to 1544 km^2. These sites also have different numbers and types of water facilities. Quality of forage resources as reflected by NDVI also varies in these five study sites. Each community has different numbers of households and livestock that are dependent on the given amount of resources to survive and prosper.

4.1. Forage resource size and quality

Results from participatory mapping of herding range indicated that the community-perceived herding extent ranged from 203 km^2 in Siqu to 1544 km^2 in El Dima (Figure 6). It is worth pointing out that although pastoralists in all five study sites claimed a boundary of their *worra* herding range, only those in El Dima and Taka Bulti insisted they have their own *forra* grazing lands.

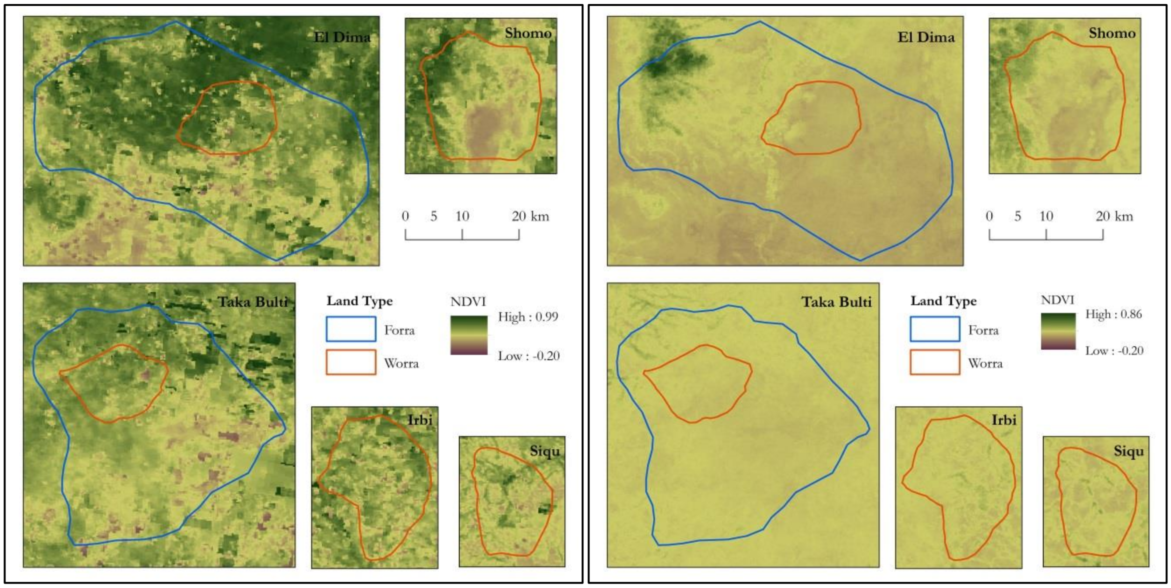

Figure 6. Herding ranges perceived by pastoralists and their NDVI values in the wet (2011-12-03) and dry (2012-03-05) seasons in five study sites

Pastoralists in El Dima claimed the largest boundary at 1544 km^2. Parts of their *forra* lands were located in Kenya, where they accessed water points in the dry season. However, El Dima pastoralists claimed the smallest size of *worra* land (168 km^2), which is 20% less than the most constrained study site. This result was consistent with their overall herding pattern that since they spent most of their time in *forra* grazing lands (see Chapter 4), it is unnecessary to claim a vast area for *worra* grazing. In addition, at the end of dry season, there was a greener area at the northwestern corner of their herding range that provided crucial forage resources to livestock.

The next largest herding boundary is claimed by pastoralists in Taka Bulti, with a size of 1237 km^2. They claimed an area of 161 km^2 for their *worra* animals. Such sizes were similar to those in El Dima. However, they had constrained access to *forra* grazing areas to the west of their *worra* lands due to competition with neighboring Boran communities. Most of their *forra* lands were to the south and east of their *worra* lands, which were sparsely populated but were exposed to potential risk of cattle rustling and other conflicts with their Somali neighbors.

In contrast to El Dima and Taka Bulti, pastoralists in other three study sites only claimed their *worra* grazing areas, and the sizes are larger than those in El Dima and Taka Bulti. In Siqu, a total of 203 km^2 land area was considered the community's *worra* grazing area. The number was 374 km^2 for Shomo and 311 km^2 for Irbi. However, it is worth noting that although pastoralists in Irbi occasionally practiced *forra* herding, they did not report any *forra* herding territory. This suggested that negotiation must be made with other communities when they moved beyond their *worra* grazing area.

Mean NDVI values in the five study sites followed an upside-down U shape curve in general (Figure 7). Minimum mean NDVI occurred at the beginning and end of the study period, with a value around 0.25. Maximum NDVI value showed up in the image of December 3, 2011, ranging from 0.55 to 0.62 in the five study sites.

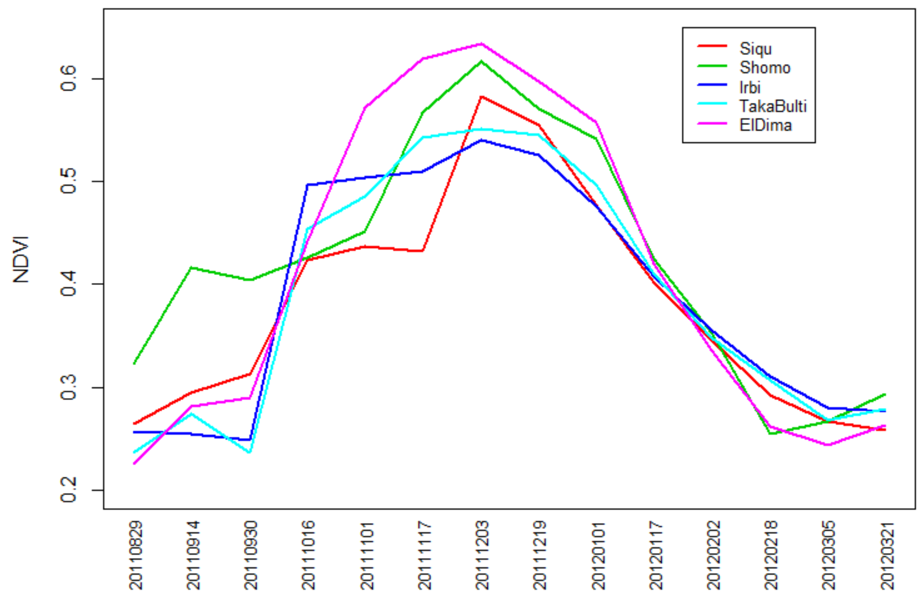

Figure 7. Variations in mean NDVI values of five study sites during the study period

I investigated the variation of NDVI across the study period using the general additive model. The results indicated that NDVI varied significantly over time, and the values were also significantly different in the five study sites (Table 4). Overall, highland areas such as Siqu (mean = 0.382), Irbi (mean = 0.389) and Taka Bulti (mean = 0.388) were associated with lower NDVI values. In contrast, Shomo (mean = 0.422) and El Dima (mean = 0.410), which are situated at a lower elevation, showed higher NDVI values. Phenological differences of distinct plant communities in the five study sites could presumably explain such differences in NDVI values (see Chapter 2).

Table 4. Estimation of determinants of NDVI variations using GAM

Parameters	Estimate	Std. Error
Intercept	4.10E-01***	1.62E-04
Irbi	-2.17E-02***	3.95E-04
Shomo	1.16E-02***	3.66E-04
Siqu	-2.87E-02***	4.75E-04
Taka Bulti	-2.23E-02***	2.43E-04
Smooth term	Edf	Ref.df
Date	8.999***	9

*** indicates significance at 0.001 level

In addition to temporal variation, NDVI values also varied in space. In the wet season, pastoralists in all five study sites enjoyed abundant high-quality forage, as over 90% of their grazing lands showed an NDVI value greater than the sample mean (0.398). However, in the dry season, although the average NDVI values were low for all sites, those in Shomo and El Dima were still left with 4 – 5% lands with NDVI value greater than the annual sample average. These greener pastures were key grazing sites for them in the dry season. In Siqu, pastoralists were not engaged in *forra* herding, and they relied on the few patches of community rangeland reserves (approximately 87.5 hectares) to survive the dry season. In Irbi, pastoralists generally moved beyond their perceived herding boundary and sought forage elsewhere, as no pixels in their grazing lands exhibited an NDVI value greater than 0.4. In Taka Bulti, pastoralists could forage in a bigger area than Siqu and Irbi because they had access to *forra* grazing lands. It is likely that extensive searching throughout the landscape allowed them to survive the dry season.

4.2. Household herd size

The 20 participant households kept a combination of cattle, sheep and goats (combined as shoat in IBLI household survey), and camels in their herds (Table 5). In terms of tropical livestock unit (TLU) owned by these households, the amount ranged from 5.5 to 145 units. Traditionally, cattle were the dominant livestock type in Borana. However, in recent decades, pastoralists have been reducing their dependence on cattle (see Chapter 7). As in 2012, cattle represented 83.8% of livestock unit. Meanwhile, pastoralists have been adding small ruminants and camels that are more adapted to the encroaching woody plant species (Angassa, 2012).

Table 5. Summary statistics of livestock owned by participant households

Livestock Type	Mean	Median	Min	Max
Cattle	30.9	19	4	140
Shoat	14.4	14.5	0	47
Camel	2.2	0	0	12
Livestock Unit	35.09	19.3	5.5	145.05

4.3. Community households and herd size

The number of resource users is a key factor that affects individuals' resource-use behaviors and the broader management outcomes in the common-pool (Ostrom, 1990). This is because pastoralists always need to consider grazing competition from neighbors and adjust their herding strategies accordingly. I obtained resource user data from two different sources. The number of households in each community (at the *reera* level) was obtained from a survey by the IBLI team and Ethiopian extension agencies in 2009. According to that survey, the number of households in the five study sites ranged from 137 in El Dima to 296 in Shomo (Table 6). The livestock unit number was obtained from IBLI household survey conducted in 2012. Since the research team asked more detailed questions regarding livestock ownership with a total of 140 households in the five study sites, the survey data are a better representation than other aggregate livestock data at the community level. I estimated the total TLU by multiplying the number of households by TLU mean. The least total TLU was observed in Taka Bulti, with 2166 units. The greatest total TLU occurred in Shomo, with 5298 units. However, if the size of resource were taken into consideration, then TLU/km^2 was estimated at nearly 20 for Siqu, and more than 14 for Shomo. TLU density in Irbi was only half of that in Shomo. In contrast to those three sites, the situation in Taka Bulti and El Dima was very different. Since they had vast *forra* grazing lands, the grazing pressure was spread-out in the landscape, resulting in sparse TLU density at 1.67 and 2.93 respectively.

Table 6. Number of households and livestock in the five study sites

Site	#HH	TLU Mean	TLU Total	TLU Density
Siqu	184	21.51	3958.12	19.53
Shomo	296	17.90	5298.06	14.16
Irbi	143	15.15	2165.88	6.97
Taka Bulti	188	10.99	2065.99	1.67
El Dima	137	33.02	4524.29	2.93

4.4. External environment

External environment is another important factor that determines resource-use behaviors (Agrawal, 2007). Specifically, access to markets, administrative centers and roads not only promotes livestock transactions and small business, but also allows external development agencies to reach the communities to implement intervention projects. I used access to roads with regular bus service and distance of travel path to Yabello town as indicators of pastoralists' connection with external world (Table 7). Pastoralists in Siqu exhibited good connection with external world – it is only 30 km from Yabello, with a road that runs through the community. Shomo and Irbi are situated in an intermediate distance from roads and from Yabello. A road with bus service also cuts through Taka Bulti, but travel distance to Yabello is nearly 190 km. El Dima is the most remote study site. Pastoralists must walk over 40 km to reach Dillo town that has bus service, and the distance to Yabello is more than 190 km.

Table 7. Distance to roads and administrative center in the five study sites

Site	Distance to Road (km)	Distance to Yabello (km)
Siqu	0	30.91
Shomo	20.89	65.89
Irbi	40.5	141.63
Taka Bulti	0	189.03
El Dima	45.03	198.92

5. Determinants of Camp Relocation

In the theory of resource-use behaviors in the common-pool, it has been proposed that resource conditions, number of resource users and external environment have fundamental impact on what resource-use strategy is adopted (Agrawal, 2007). The analysis in the above section suggested that there was sufficient variation in these three regards in the Borana rangeland system. Therefore, I hypothesized that these ecological and socioeconomic factors will contribute to different camp relocation strategies in the five study sites.

I first investigated how daily variation in NDVI affects pastoralists' camp relocation behaviors in Irbi, Taka Bulti, and El Dima. Results from the generalized linear mixed-effects model indicated that NDVI had a negative impact on camp relocation (Table 8). This meant that pastoralists were more likely to move beyond the extent of their *worra* grazing areas when NDVI value was low. In addition, pastoralists in these three sites showed significantly different responses to NDVI in their herding practices.

Table 8. Estimations of determinants of camp relocation at the daily level.

Independent variables	Parameters	SE
Intercept	8.22 ***	1.73
Fixed-effects		
NDVI	-14.09 ***	0.94
Irbi	-7.89 **	2.41
Taka Bulti	-10.47 **	2.64
Random-effects		
var (Date)	1.91	
var (CowID)	24.67	
AIC	2248.87	

Note: The sample size is 4243. SE means standard error; var (Date) is the variance component at the daily level; var (CowID) is the variance component at the individual animal level.

Significance code: ***: $p < 0.001$; **: $p<0.01$

According to the model prediction, El Dima is the site that is most likely to relocate their camp locations (Figure 8). When average NDVI drops below the average (0.4), the likelihood of camp relocation is 70%. In contrast, when NDVI is at the same level in Irbi and Taka Bulti, the probability of camp relocation is less than 20%. Only when mean NDVI is less than 0.1, the probability of Taka Bulti pastoralists to practice *forra* herding is more than 50%. At this point, Irbi is 80%, and El Dima is over 95%.

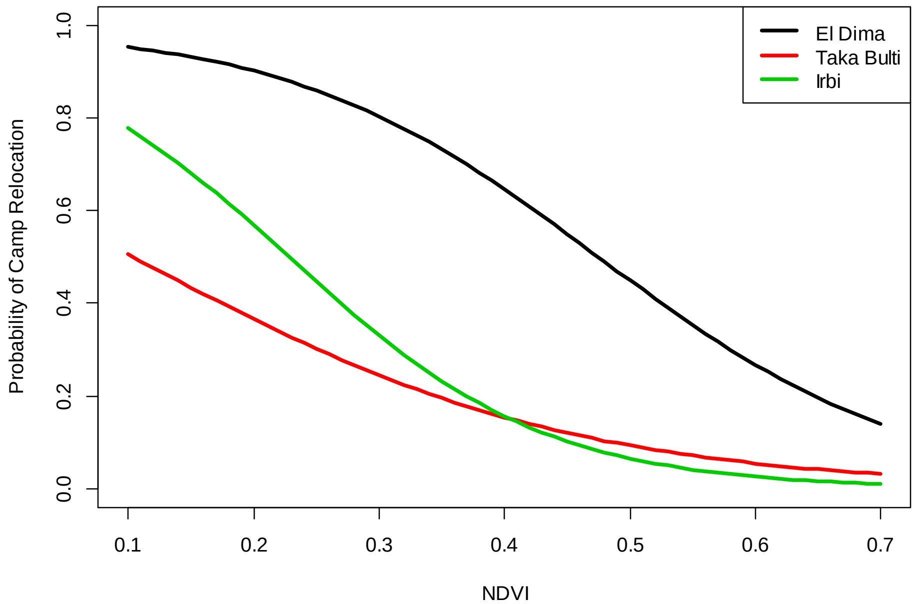

Figure 8. Prediction of probability of camp relocation in response to NDVI in Irbi, Taka Bulti, and El Dima

I further investigated the influence of socio-ecological factors on pastoralists' camp relocation behaviors at the seasonal level. Specifically, I took a step-wise approach to examine the impact of resource condition, resource user and external environment. In Model 1, I only included the random-effect predictor. The model estimation showed a variance of 0.08 for the random-effect (Table 9).

Table 9. Estimations of determinants of camp relocation at the seasonal level.

Independent variables	Model 1		Model 2		Model 3		Model 4		Model 5	
	Parameters	SE	Parameters	SE	Parameters	SE	Parameters	SE	Parameters	SE
Intercept	2.31E-01***	4.48E-02	3.13E-01**	1.05E-01	6.75E-01***	1.62E-01	4.72E-01**	1.61E-01	4.76E-01**	1.63E-01
Fixed-effects										
Site-level										
NDVI			-9.22E-01***	2.26E-01	-9.45E-01***	2.25E-01	-1.00E+00***	2.24E-01	-1.01E+00***	2.24E-01
Herding range			3.65E-04***	6.77E-05	2.64E-04***	6.26E-05	2.59E-04***	5.68E-05	2.53E-04***	6.15E-05
Number of HH					-3.27E-03***	7.24E-04	-1.88E-03*	7.61E-04	-1.89E-03*	7.68E-04
Comm herd					9.47E-05**	2.97E-05	4.81E-05	2.98E-05	4.64E-05	3.08E-05
Distance to road							6.39E-03***	1.79E-03	6.34E-03***	1.81E-03
Household-level										
HH herd size									3.01E-04	1.10E-03
Random-effects										
var (U_0)	0.0811		0.0497		0.0298		0.0204		0.0212	
ANOVA Chi-Sq			40.52***		19.17***		12.66***		0.09	

Notes: The sample size is 130. SE means standard error. var (U_0) is the variance component at the household level.

Significance code: ***: p < 0.001; **: p<0.01; *: p<0.05

When the two resource condition factors, namely NDVI and perceived herding range, were added into the model, the estimation improved significantly. The results showed that both factors are significant in affecting camp relocation (Table 9). Given higher NDVI, pastoralists were less likely to leave their home village and set up camps elsewhere. This was consistent with the findings at the daily level. In sites with a larger herding range, pastoralists were more likely to conduct *forra* herding. ANOVA indicated that Model 2 is significantly better than Model 1. The the variance of random-effect predictor is also 40% less than that in Model 1.

Next, I added resource user factors into Model 2. The results showed that the number of households had a significant negative impact on camp relocation. In communities with more households, pastoralists were less likely to practice *forra* herding. In contrast, the impact of community herd size had a significant positive impact, although less significant than the number of households. The sites with more livestock were more likely to migrate beyond their *worra* grazing lands to search for forage, probably due to intra-community competition. Overall, Model 3 is significantly better than Model 2 according to ANOVA results, and the random-effect variance is 40% lower.

After that, I put the external environment factor into Model 3, which is distance to road. The results showed that this factor had a significant impact on camp relocation as well. As distance to road increased, pastoralists practiced more *forra* herding. Adding this factor improved the model prediction, because the random-effect variance is 13% lower than Model 3.

Finally, I included the household level factor into Model 4. However, the results indicated this factor had no significant impact on camp relocation. ANOVA showed that adding this factor contributes little to better model prediction. In addition, random-effect variance increased slightly, suggesting that the variable of household characteristics did not explain camp relocation well. Therefore, the causal relationship between the household-level predictor and their camp relocation behaviors can hardly be established from the empirical data.

6. Discussion

Pastoralists residing in ASAL have developed complex mechanisms by which they can alleviate the threat of drought. They employ multiple adaptive strategies to facilitate mobility and minimize risk in the face of spatio-temporal variability of foraging resources (Behnke et al., 1993; Scoones, 1994). During dry periods, livestock herds may travel long distances to greener pastures (Butt, 2010; Sieff, 1997), expand their home range (Hoffmann, 2002), concentrate in key resource areas within their home range (Coughenour, 1991), rotate between camps (Goldstein et al., 1990; Liao et al., 2014), and forage more intensely around water points (Pickup & Bastin, 1997).

Among these coping strategies, the Boran pastoralists typically adopted camp relocation to deal with environmental stress. The results suggested resource availability, as reflected by NDVI, was an important driver of camp relocation at the daily level. However, pastoralists' responses to such seasonal variation were divergent. For the study sites where households were largely sedentarized, camp relocation was not adopted as a coping strategy for drought. Instead, community rangeland reserves were set up to meet dry season needs. In addition, they also claimed a larger *worra* herding area, and searched for forage that was more distant from their base camps. The constrained setting would not allow them to set up satellite camps within their *worra* grazing lands due to competition with neighbors.

For study sites where *forra* herding was still practiced, pastoralists generally moved beyond their *worra* herding extent when NDVI values dropped below certain thresholds. However, the proportion of days relocating beyond *worra* territory was also different. The reason that El Dima pastoralists spent most time in their *forra* grazing lands was largely due to the presence of good-quality forage on the hills in the northwest corner of their herding extent (Figure 6). In contrast, NDVI values within the herding range of Taka Bulti pastoralists were consistently low in the dry seasons. In addition, there were permanent water facilities near the community center. Arguably, these two factors made Taka Bulti pastoralists less likely to move beyond their *worra* grazing lands than El Dima. The case of Irbi was different from El Dima and Taka Bulti. Since they only had a small *worra* grazing area, they needed to move elsewhere to search for forage when the resource was not enough to support their livestock. However, they had to negotiate with other pastoralists and made compromises in their access to forage and water resources on other people's lands.

The estimated results of the two resource user factors, namely number of households and community livestock unit, suggested distinct mechanisms of impact on camp relocation. In general, pastoralists were more likely to practice camp relocation when the number of households in that community was smaller. This was more important than the absolute amount of livestock in the community. In communities with more livestock and fewer households, pastoralists could still organize themselves to practice *forra* herding to reduce grazing pressure around their base camps. Such findings were consistent with previous research that a smaller group of resource users is more likely to manage the common-pool resources in a sustainable approach (Ostrom, 1990).

In terms of external environment, pastoralists with better road access were more likely to engage in livelihood strategies other than livestock herding. Their livestock and crops could reach the markets more easily, which encouraged pastoralists to engage in more trading and small business. They could also sell their dairy products in the market, and quite often pastoralists produced charcoals and sold them to passers-by on these roads. Thus, engagement in these non-pastoral livelihoods reduced their likelihood to move extensively throughout the landscape.

However, the modeling results suggested that household-level predictor was not as important as community-level conditions in affecting pastoralists' practice of camp relocation. The context of herding largely affected what pastoralists could possibly do with their herds. No matter how many livestock owned by a household, if they were situated in a constrained herding environment with substantial competition from their neighbors, they were much more likely to relocate their herds beyond their *worra* herding range. In addition, better access to roads and bus services also served as a pull factor to discourage the maintenance of traditional extensive herding. Therefore, the overall context largely predetermined pastoralists' herding strategy.

The future of camp relocation is likely to be compounded by increasing human population associated with higher levels of cultivation, increasing livestock numbers on communal rangelands, and policies to restrict movement of pastoralists (Coppock, 2010). As a result of these factors, the practice of camp relocation will weaken, exacerbating vulnerability to environmental change and imposing a negative impact on the sustainability of pastoralism as a traditional livelihood system in ASAL. However, the projected trend of climate suggests that East Africa will witness greater variability in precipitation and temperature both within and between seasons (Funk et al., 2008), which made camp relocation more important as a coping strategy for environmental stresses. Therefore, future research needs to find an optimal balance to resolve the conflict between the necessity to practice camp relocation and the constraints on extensive movement, which will feed into policy design that could potentially ensure both livelihood security and rangeland sustainability.

7. Conclusion

This chapters investigated the camp relocation strategies in five study sites across the Borana Zone of southern Ethiopia. Using data from GPS-tracking, participatory mapping, interview and household survey, I revealed three distinct herding types at the daily level. *Worra* herding, which revolves around the base camp, accounted for nearly 80% herding loops in the monitoring of livestock movement. *Forra* herding is practiced beyond the *worra* grazing lands. It is performed as a drought coping strategy, which also reduces grazing pressure around settlement. A third type of herding is transition between camps, and its travel path does not form a closed loop. Distance of travel is significantly different for these three herding types across the five study sites according to ANOVA.

The five study sites are characterized with distinct socio-ecological endowments. Both resource quality, as measured by NDVI, and resource quantity, as measured by herding range mapped by pastoralists, are different in the five study sites. The extent of movement ranges from 204 to 1544 km^2. The number of resource users within the herding range are also different, ranging from 137 to 296 regarding the number of households, and 2166 to 5299 in terms of community livestock units. Access to roads is different as well. Sites like Siqu and Taka Bulti are right by the road, while pastoralists in El Dima have to walk nearly 45 km to reach road with bus service. At the household level, herd size ranges from 5.5 to 140 TLU for the 20 participant households.

The above variations in herding contexts resulted in a divergence of herding strategies. *Forra* herding was not observed in two of the study sites throughout the tracking period. For the other three sites, pastoralists were more likely to relocate beyond their *worra* grazing lands when the mean NDVI value in their perceived herding range was lower. This clearly suggested that camp relocation is a drought coping strategy. At the seasonal level, I tested the impact of resource conditions, resource users and external environment on camp relocation. For communities with a smaller range of movement, the proportion of days spent on *forra* herding was significantly less. For communities with a smaller group of households, they were more likely to conduct *forra* herding, and this factor was more important than the total number of community livestock units. In addition, better connection with external environment, as measured by the distance to roads with bus service, resulted in less *forra* herding behaviors. In contrast, household herd size had little impact on pastoralists' camp relocation behaviors.

Based my research findings, I conclude that the overall socio-ecological context largely predetermines whether camp relocation could be a feasible drought coping strategy. No matter how big the herd size of a certain household, as long as they were endowed with very constrained herding extent, camp relocation could be very challenging. Competition with neighboring communities limited the possibility of migrating beyond their *worra* grazing lands. Camp relocation was only possible if pastoralists made negotiation with other communities to access key resources such as forage and water. Even in cases where pastoralists have extensive herding area such as Taka Bulti, the presence of permanent water facilities at community center and the absence of ground water on *forra* grazing lands at the end of dry season also attracted certain pastoralists to stay around their settlement to water their animals. Only in the case of El Dima that extensive movement was commonly observed. This was largely due to resource heterogeneity within their large herding range. The presence of good forage in the far west corner of their herding range made it possible to herd their animals far from base camp in dry seasons.

Promoting camp relocation is certainly challenging given increasing human and livestock population. In fact, it is unrealistic to advocate for extensive herding when pastoralists are already sedentarized. With clusters of villages established in close proximity to each other, pastoralists easily run into conflicts in their pursuit of forage resources. However, clues could be drawn from the empirical findings to shed light on how to resolve this issue. For example, promoting resource heterogeneity can save resources for dry season consumption. At community level, this can be achieved through establishing specific rules in terms of at what time can forage resources at what locations can be accessed, where violations of these rules will incur gradual punishment. In addition, inter-community agreements can also be reached on the basis of negotiation and reciprocity to facilitate the sharing of rangelands under drought. In sum, coordinating collective herding behaviors at multiple scales could potentially minimize recursive use of rangelands and maximize rotational grazing. Such “mutually agreed-upon” solutions could be the fundamental principle in designing future community rangeland management policies.

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CHAPTER 6 SPATIO-TEMPORAL DYNAMICS OF CATTLE BEHAVIORS AND RESOURCE SELECTION PATTERNS IN THE OPEN GRAZING SYSTEM OF EAST AFRICA

1. Introduction

Pastoralism has long been considered the most important and sustainable livelihood strategy in the world's arid and semi-arid lands (ASAL) (Catley, et al., 2013; Dong et al., 2011; Sandford, 1983). In response to spatio-temporal variations of forage availability, pastoralists constantly adjust their herding strategies, which translates into changes in animal behaviors. In general, during wet seasons when resources are abundant, herders keep livestock in proximity to their settlements to reduce energy expenditure, increase forage intake and minimize the amount of labor required for herding (Coppolillo, 2000). Accordingly, a higher proportion of grazing and a lower proportion of walking behaviors is observed. Such a trend is reversed in dry seasons as forage declines in both quality and quantity. At those times, herders must direct their livestock to pastures farther from their settlements. The proportion of walking behavior is expected to be higher while grazing behavior becomes lower, resulting in higher energy expenditure and lower forage intake for the cattle (Samuels et al., 2007).

In addition to adjusting herding strategies revolving around their settlements, pastoralists also search extensively beyond base camp herding areas to pursue high-quality forage resources elsewhere. This strategy enables pastoralists to access unique ecological niches and take advantage of resource heterogeneity throughout the landscape (Liao et al., 2014). Typically, herders scout and track ecological variability, both spatially and temporally, by constantly adjusting the behavior of their animals (Niamir-Fuller, 1999). Therefore, livestock behavior can be used as a fine-scale indicator of how pastoralists cope with environmental variability by balancing forage intake and energy expenditure (Butt, 2010).

However, few empirical studies have sought to explain and predict the spatio-temporal manifestations of pastoral mobility at the behavioral level, and test the extent to which these behaviors change given different environmental characteristics and seasonal variations. Due to the lack of such fine-scale knowledge on cattle behaviors, broad-scale models on pastoral mobility generally assumed that 1) grazing intensity decreases as distance increases from hotspots such as water sources and settlement; and 2) the longer the spatial occupation of a specific location, the heavier the grazing pressure in that location (Coppolillo, 2001; Moritz et al., 2010; Sasaki et al., 2008; Spencer, 1973). Consequently, pastoralists' spatial resource utilization pattern is generally summarized as a piosphere (Andrew, 1988; Frank et al., 2012; Lange, 1969), which consists of a "sacrifice zone" that is subject to severe resource exploitation, followed by a "transition zone" that shifts into a nearly homogeneously grazed zone. This grazed zone gradually merges into undisturbed natural vegetation that is hardly influenced by grazing.

However, the above two assumptions are worthy of further scrutiny. First, empirical evidence has shown that when livestock density exceeds a certain threshold, the grazing intensity gradient radiating from settlement decreases very slightly, and forage cover on the rangelands is consistently low (Angassa, 2012). Second, longer presence of livestock at a specific location does not necessarily translate into heavier grazing pressure. High and low velocity behaviors such as traveling or resting have less impact on the rangelands than medium velocity behavior such as foraging.

In fact, it is the lack of long-term intensive monitoring of cattle movement that led to imprecise modeling of cumulative resource use patterns. Without cross-season evidence of cattle behaviors, it is likely to assume that grazing is highly concentrated around settlements, which may not necessarily reflect the actual herding strategies adopted by pastoralists. Such a knowledge gap usually results in finger-pointing at pastoralists, accusing them of "irrational" herding and being irresponsible for rangeland sustainability. However, without quantitative assessment of cattle behavior and resource selection patterns, any conclusions claiming that pastoralism translates into "the tragedy of the commons" may be rootless (Hardin, 1968).

With the advancement of GPS-tracking technologies, intensive animal movement data have been recorded, which provided promising perspectives for understanding how different animal behaviors translate into actual utilization of rangelands. To date, the GPS tracking technologies have been widely applied to study the movement behaviors of wildlife (Fryxell et al., 2008; van Moorter et al., 2013). Intensive tracking of domesticated animals is also emerging in the literature, and there are a few examples that made use of short lifespan GPS instruments to track cattle behaviors with a high temporal resolution (Butt et al., 2009; Moritz et al., 2013).

However, due to their limitation in data collection (short duration, limited ground-truth evidence, etc.), there was no prediction on the spatio-temporal dynamics of cattle behaviors within the extent of movement, and no comparison on how cattle behaviors vary across multiple study sites. Although animal behaviors such as foraging, traveling, or resting have been recorded (Butt, 2010), there were no solid linkages between these behaviors and statistical parameters of movement. In sum, the lack of intensive, continuous and quantitative evidence on how cattle move in the open grazing system across seasons hindered our understanding of resource-use behaviors of cattle, despite it being crucial to generate effective and sustainable rangeland management strategies.

The objective of this chapter is, therefore, to address the shortcomings in pastoral mobility research by establishing a solid relationship between cattle behaviors and statistical parameters of movement, and then from there, analyzing and predicting the spatio-temporal distribution of cattle behaviors. Specifically, this chapter aims to answer three research questions: 1) what behaviors are observed among cattle herded in open grazing system, and can they be characterized and distinguished statistically; 2) how do cattle behaviors vary within their herding range and within the time of day; and 3) what are the determinants of cattle's resource selection behaviors.

The Borana Zone in southern Ethiopia was selected as the study area. This region represents the typical rangelands in the Horn of Africa where extensive livestock herding is commonly practiced. The empirical data were obtained from multiple sources. Using custom-constructed GPS collars, cattle movement was monitored from August 2011 to March 2012, in which their locations were updated every five minutes. In addition, videography of cattle movement was collected concurrently with a handheld GPS instrument. Realizing that the movement of domesticated animals was largely driven and controlled by human beings, I also interviewed the herd managers regarding the characterization of cattle behaviors while shooting GPS-synchronized videos. Integrating empirical evidence from such multiple sources made it possible to further infer how pastoral livelihood systems and herding strategies are likely to be affected by potential climate change (Funk et al., 2008) and sedentarization of mobile pastoral communities (Fratkin & Roth, 2005) in the Horn of Africa.

2. Methods

2.1. Study area

The study was carried out in the Borana Zone located in southern Ethiopia bordering Kenya (Figure 1). Precipitation is bimodal, with 60% in the major rain season (April – May) and 30% in the minor rain season (October – November). Elevation ranges from 500 to 2500 m above sea level, with terrain varying from steep highland slopes to flat, dry river and lake beds in the lowlands. Small seasonal rivers and ponds are common throughout the zone. The landscape is a heterogeneous mixture of rangeland reserve enclosures, crop fields, clusters of fenced villages, and extensive tracts of savanna for open grazing. High-lying areas tend to be dominated by woody plants such as *Acacia tortilis*, *A. drepanolobium*, *Commiphora africana*, and herbaceous species such as *Chrysopogon auheri*, *Cenchrus ciliaris*, *Aspilia mossambicensis*, *Hibiscus boranensis*, *Vernonia cinerascens*. In contrast, drier lowlands are dominated by woody plants including *A. mellifera*, *A. reficiens*, *Solanum schimperianum*, *Justicia ornatopila*, and grass species such as *Digitaria naghellensis* and *Eustachys paspaloides*.

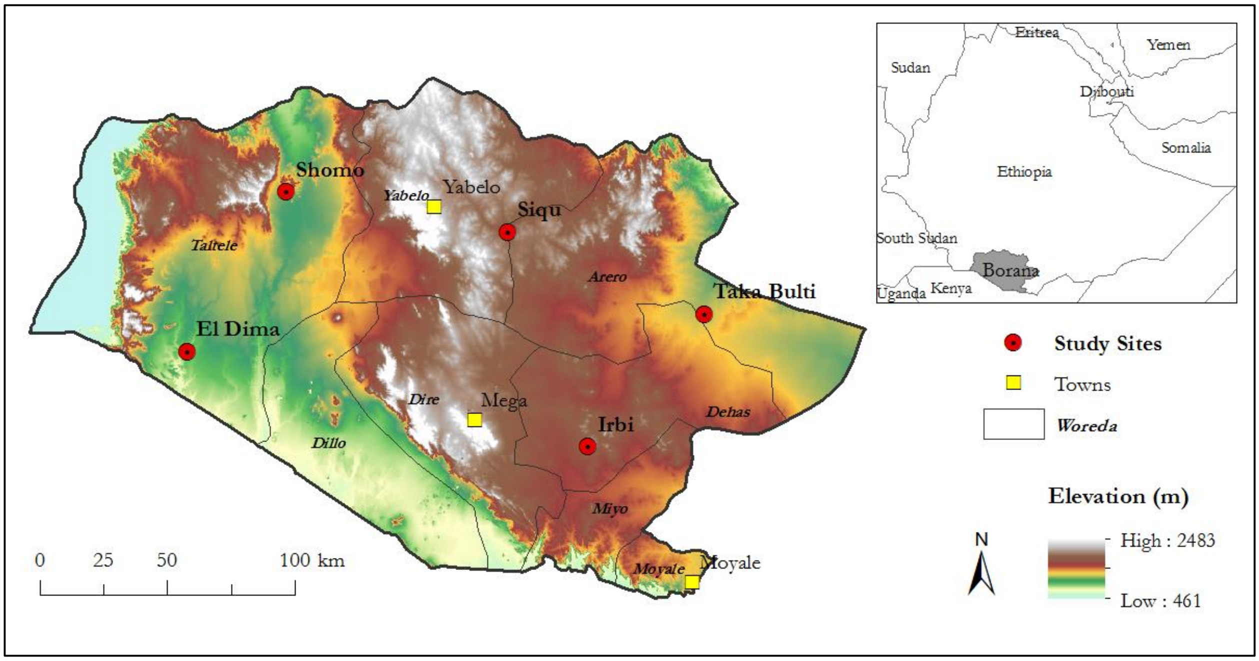

Figure 1. The five selected study sites in the Borana Zone of southern Ethiopia

Pastoralism is the major livelihood strategy in Borana given its arid and semi-arid environment. Cattle herding is generally practiced in two forms. One form is home-based herding, known as *worra* in the Boran local language, which involves the herding of lactating cows, calves and small stock close to home villages or base camps. The other form is satellite herding, referred to as *forra* in the local language, where temporary camps are used to graze bulls, non-lactating cows and immature stock at substantial distances away from base camps. *Forra* herding allows livestock to range more widely and have access to better forage than what might be available near base camps (Homewood, 2008). These two forms of herding are not mutually exclusive, as one household can practice both simultaneously through herd splitting.

Five study sites, namely Siqu, Shomo, Irbi, Taka Bulti and El Dima, were selected in this research. These sites contained sufficient socio-ecological variations throughout the Borana Zone (Figure 1). Siqu is located in northcentral Borana within a relatively flat area near the border between Yabello and Arero *woreda*. Herds in Siqu were the least mobile of among the five study sites and typically migrated only under extremely harsh drought conditions. Shomo is located in Taltele *woreda* of northwestern Borana and is characterized as an area of flat and dry lake beds adjacent to steep hills. When pasture conditions were bad in neighboring areas, they tend to migrate to Shomo. Consequently, livestock concentration in Shomo could become very high occasionally. Irbi is situated in southwestern Borana within the Dehas *woreda*. Irbi occurs at relatively high elevation and, during years of normal foraging conditions, commonly receives an influx of pastoralist herds from surrounding lower-lying area. When forage resources are substantially below the normal condition, Irbi households typically split their herds and take their animals to Yabello and Taltele. Taka Bulti is located in eastern Borana within Arero *woreda* and is characterized by dry river beds and flat to rolling adjacent terrain. Taka Bulti pastoralists are quite mobile but livestock movement patterns are affected by ethnic conflicts with neighboring Garri and Somali ethnic groups (Tache & Oba, 2009). El Dima is located in southwestern Borana within Tatele *woreda*. While the base camps of El Dima households are situated in the dry lowlands, *forra* herding opportunities mostly exist in the adjacent highlands to the west. El Dima grazing areas border northern Kenya and are periodically affected by ethnic tensions. Pastoralists in El Dima are highly mobile and occasionally migrate into Kenya in search for forage when adequate security prevails.

2.2. GPS tracking of cattle movement

From August 2011 to March 2012, three mature cows from each of the 20 selected households were fitted with custom-built, research-grade tracking collars by the IBLI team. These collars were capable of recording GPS location data every five minutes for six months or more without service or battery refit (Clark et al., 2006). Of the 60 collars deployed, 58 collars successfully collected viable data, with an average data set being 135 days in length. Twenty of these collars collected dataset over 200 days in length. A total of 2.25 million time-tagged and geo-referenced points were recorded during the tracking period. These data were all included in the analysis of cattle behaviors.

2.3. Videography of cattle behaviors

Robust inference of cattle behaviors from GPS-tracking rests on substantial ground-truth evidence. In May, 2014, I followed one household in each of the five villages to collect GPS-synchronized videography of cattle behaviors, with the assistance of one ILRI colleague and one research assistant. We walked with the herd managers and their cattle from their settlements (base camps) to their major herding areas where they typically slowed down their cattle for grazing. The time we left the settlement was 7:00 am in the earliest case and 8:30 am in the latest case. The time we arrived at the major herding areas also varied from 10:00 am to 12:00 am. In each herding pathway, I recorded segments of videos of cattle behaviors with an average duration of 5 min. Such duration is complementary to the temporal resolution of GPS-tracking. While I started recording videos, I turned on a handheld GPS to record the travel pathways. In total, I recorded 70 videos in the five study sites. In addition, I interviewed herd managers regarding cattle's behaviors observed in video shooting. The herd managers enumerated five general types of behaviors of their cattle, and elaborated the criteria that characterized each type of behavior.

2.4. Data analysis

I first determined camp locations from the tracking data. Base camps are situated at locations with the highest concentration of tracking points. Satellite camp locations were determined by the rule of thumb that the tracked cow returned to the same place for over three days consecutively. Accordingly, at the daily level, a herding loop that starting from and ending at the base camp is considered *worra* herding, a loop starting from and ending at the satellite camp is classified as *forra* herding, and all other loops are treated as transition herding. In addition, I also estimated the distance of each GPS-tracking point from its associated camps, namely the location where the herding began each day.

In order to establish the relationship between behavior and statistical parameters of movement, I estimated the travel velocity of each segment of cattle movement in the videography. This was done by calculating the travel path distance and start-to-end-point line distance of each tracked segment, which were then divided by the duration of each segment. Then I conducted linear discriminant analysis to classify cattle behaviors based on line velocity, because the GPS-tracking data had a temporal resolution of 5 min and did not show any further details at a finer scale. The supervised classification ended up with four split points in the range of velocity to distinguish the five behaviors enumerated by pastoralists. I also checked the accuracy of prediction by constructing a confusion matrix.

Once the linkage between velocity and behavior was established, I used the classification results to infer cattle behaviors using the GPS-tracking data. Specifically, I analyzed the spatio-temporal dynamics of all five identified cattle behaviors by visualizing the proportion of different behaviors within the time of day and along the distance from camp locations. Log transformation was conducted on the distance from camp to make it normally distributed. After that, I applied the general additive model (GAM) to investigate the determinants of spatio-temporal distribution of behaviors. The temporal models can be represented as:

$$Behavior\ Proportion = \beta_0 + f(Time) + Site + \varepsilon$$

where the response variable is the proportion of a specific behavior at a certain time of day; β_0 is the intercept; $f(Time)$ is non-linear and is subject to smoothing splines; ε is the error and $\varepsilon \sim N(0, s^2)$.

The spatial model can be represented as:

$$Behavior\ Proportion = \beta_0 + f(CampDistance) + Site + \varepsilon$$

where the response variable is the proportion of a specific behavior at certain location from camps; β_0 is the intercept; $f(CampDistance)$ is non-linear and is subject to smoothing splines; ε is the error and $\varepsilon \sim N(0, s^2)$. In both GAM models, I treated El Dima as the benchmark site because it exhibited the shortest herding time in the five study sites.

In addition, I examined the factors that determine cattle's resource selection behaviors. According to herders' descriptions and field observation, I considered the locations of heavy and medium grazing behaviors as the cattle's preferred space. Other behaviors were combined together to form another group of less preferred grazing space.

Elevation data, namely the 90-m resolution raster image, was obtained from the Shuttle Radar Topographic Mission (SRTM). A slope raster was derived from the elevation raster image. Then I used the location of all GPS-tracking points to extract topographic information from these two raster images.

I used NDVI as a measurement of forage availability, which was obtained from 15 MODIS satellite images (spatial resolution = 250 m) that covered the study period. Since the NDVI images have a temporal resolution of 16 days, I extracted the NDVI values by matching the date of animal locations with the time window of NDVI images. Season was determined from the mean NDVI curves at the zone level (see Chapter 5 for details). I considered the period before 17 October 2011 and after 2 February 2012 as dry season, and the period between 17 October 2011 and 2 February 2012 as wet season.

Specifically, I applied generalized linear mixed-effect model (Bates et al., 2014) to investigate the relationship between grazing behaviors and environmental conditions. The response variable was cattle behavior (1 = heavy or medium grazing, 0 = other behaviors). The independent variables included NDVI, elevation, slope, distance from camp, study site, herding type, and season. I used date and cowID as random-effect factors in the model. The logit model can be represented as:

$$GrazingBehavior = \beta_0 + \beta_1 NDVI + \beta_2 Elevation + \beta_3 Slope + \beta_4 CampDist + \beta_5 Site + \beta_6 HerdingType + \beta_7 Season + b_1 \times 1|Date + b_2 \times 1|CowID + \varepsilon$$

where β_0 is the intercept; β_1 to β_7 are coefficients of seven independent variables; b_1 and b_2 are random-effect coefficients of Date and cowID; ε is the error and ε ~ N (0, σ^2). All data analysis in this chapter was conducted using R statistical software (R Development Core Team, 2014).

3. Cattle Behaviors

Based on my interviews with herd owners, I identified five distinct cattle behaviors, namely watering/stationary, heavy grazing, medium grazing, light grazing, and traveling. Different combinations of these five behaviors generally resulted in two different manifestations of daily movement patterns in the five study sites (Figure 2). In Siqu and Shomo where pastoralists are largely sedentarized, the GPS-synchronized videos indicated that cattle walked for a long distance before they started to graze. In contrast, cattle in Irbi, Taka Bulti and El Dima encountered sufficient forage resources shortly after leaving their base camps, and thus could graze first before walking a long distance to reach their major herding areas.

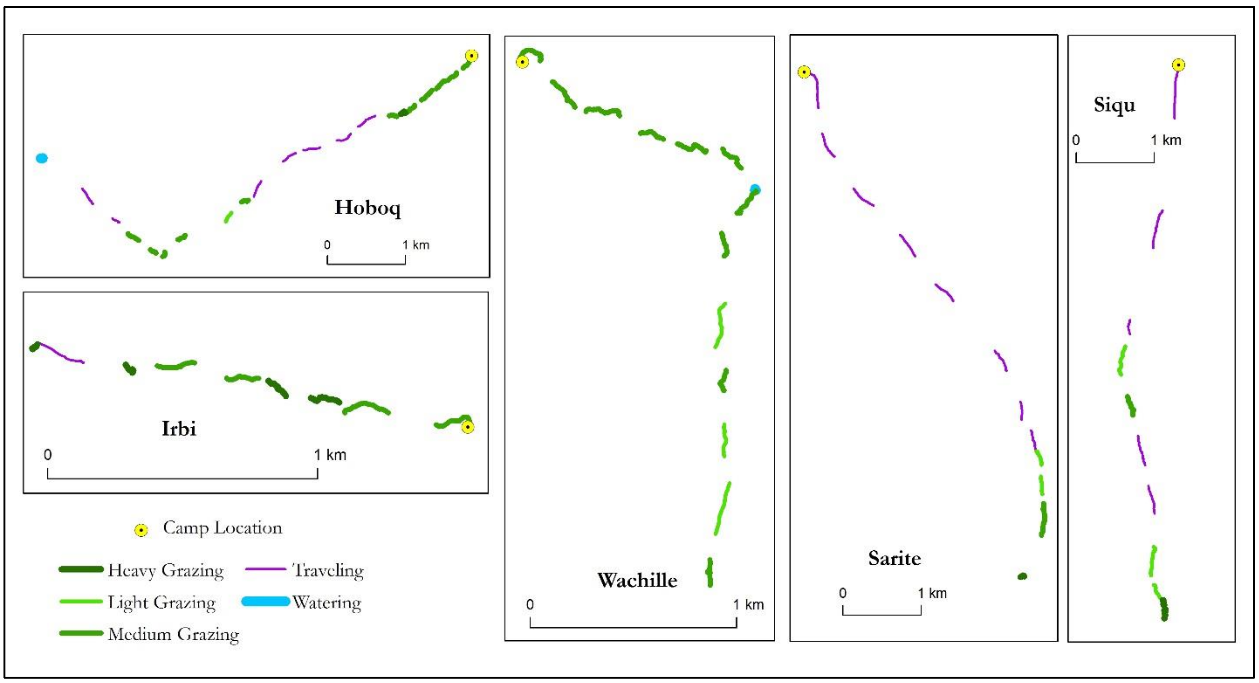

Figure 2. The spatial distribution of cattle behaviors observed in GPS-synchronized videography (n = 70)

Since each video is associated with a meandering travel path (mean temporal resolution = 10 s), I calculated both the actual velocity by following the path and the starting point to end point line velocity that matches with temporal resolution of GPS-tracking (Table 1). ANOVA indicates that the five behaviors were significantly different in terms of both path velocity ($F = 180.3$, p-value < 0.001) and line velocity ($F = 156.7$, p-value < 0.001).

Table 1. Five cattle behaviors and mean velocities

Cattle behavior	Sample size	Line velocity	Path velocity	Difference
Watering /Stationary	4	0.09	0.14	0.05
Heaving grazing	8	0.74	0.98	0.24
Medium grazing	28	1.44	1.68	0.23
Light grazing	9	2.39	2.56	0.16
Traveling	21	3.15	3.27	0.13

The first type of behavior was watering/stationary. In this behavior mode, cattle were relatively static, as it was associated with the lowest velocity among the five behaviors. This behavior was mostly observed when cattle stayed in corrals or rested after sufficient grazing, but they occasionally walked as well. Watering was also associated with low velocity rather than being completely static, and this was particularly true in the dry season. The entire watering process included waiting outside of a water facility, being herded into the facility, watering, and walking out of the facility. In addition, since the GPS collars had a location error up to 7 m, pure static behaviors in a 5-min interval were rarely observed in the GPS-tracking.

Heavy grazing occurred at a slightly higher velocity. This happened when cattle encountered abundant forage resources, and was also the type of behavior that was least driven by pastoralists. Cattle were usually left by themselves grazing after reaching their feeding area. At those times, cattle were more likely to meander rather than following a straight line; therefore, this behavior was associated with the greatest difference between line and path velocities.

When velocity got slightly faster, cattle behavior was characterized as medium grazing. This behavioral mode occurred when cattle were largely left to graze, but the forage resource was not abundant enough, so that cattle moved at a moderate velocity to forage. This behavior was also characterized by substantial difference between line and path velocity, as cattle meandered in their search for forage.

When cattle traveled at a line velocity around 2.4 km/h, such behavior was characterized as light grazing. Cattle occasionally foraged while moving at this velocity. Since forage resource was sparse, herders must keep driving the cattle to move forward under these conditions. In contrast to the above two behaviors, travel pathways of light grazing were more likely to result in straight lines. The difference between line and path velocity was 33% less than during heavy grazing.

Typically, when cattle moved at a line velocity near or above 3 km/h, their behavior was considered traveling. This behavior occurred mostly when moving from camp locations to a major herding area, and was almost entirely driven by herders. Consequently, cattle rarely grazed forage plants while walking at such a high velocity. The difference between line and path velocities was the least in this mode (other than being stationary), suggesting highly directional movement.

Since the temporal resolution of GPS-tracking was 5 min, which was similar to the duration of each video, I used the line speed for the classification of cattle behaviors using GPS-tracking data. Linear discriminant analysis was performed to determine whether there was a linkage between velocity and behaviors. The results indicated that the five behaviors and their associated velocity ranges were: watering/stationary (below 0.41 km/h), heavy grazing (0.41-1.06 km/h), medium grazing (1.06-1.94 km/h), light grazing (1.94-2.77 km/h), and traveling (above 2.77 km/h) (Figure 3).

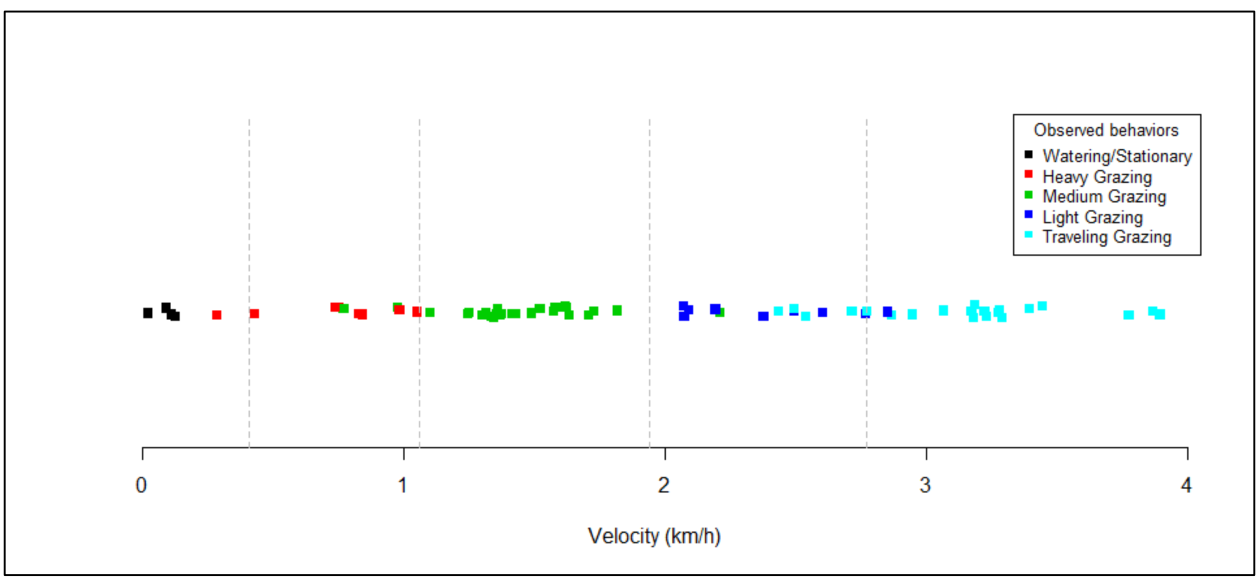

Figure 3. The relationship between observed cattle behaviors and velocity. Predicted velocity intervals for five cattle behaviors using linear discriminant analysis is also plotted.

I tested the accuracy of the classification by constructing a confusion matrix (Table 2). The overall accuracy was 87.1%, which indicated satisfactory prediction overall. Watering/stationary was predicted as 100% accurate. The three grazing behaviors showed accuracies between 85% and 90%. The lowest accuracy was for traveling (81%), in which 4 out 21 were classified as light grazing.

Table 2. Confusion matrix of predictions and observations.

Prediction/Observation	Watering	Heavy Grazing	Medium Grazing	Light Grazing	Traveling	Accuracy
Watering/Stationary	4	0	0	0	0	100.0%
Heavy Grazing	1	7	0	0	0	87.5%
Medium Grazing	0	2	25	1	0	89.3%
Light Grazing	0	0	0	8	1	88.9%
Traveling	0	0	0	4	17	81.0%

4. Temporal Distribution of Cattle Behaviors

4.1. Daily level

Temporal dynamics of cattle behaviors within the day largely reflected herders' decision-making in managing their herds on a daily basis. They needed to decide when to take their animals out of their fenced corrals, when to slow down their herd to graze, when to bring them back, and how to balance cattle energetics between traveling and foraging. Given their unique herding contexts, pastoralists in the five study sites followed different schedules in their herding, which were reflected in the variation of cattle behaviors (Table 3; Figure 4).

Table 3. Summary of average herding time, herding range and livestock density in five study sites

Site	Start Time	End Time	Duration	Herding Range (km^2)	TLU Density
Siqu	7:29:00	19:01:00	11h 32m	203	19.53
Shomo	7:19:00	19:31:00	12h 12m	374	14.16
Irbi	6:58:00	19:01:00	12h 03m	311	6.97
Taka Bulti	6:47:00	18:49:00	12h 02m	1237	1.67
El Dima	8:31:00	19:08:00	10h 37m	1544	2.93

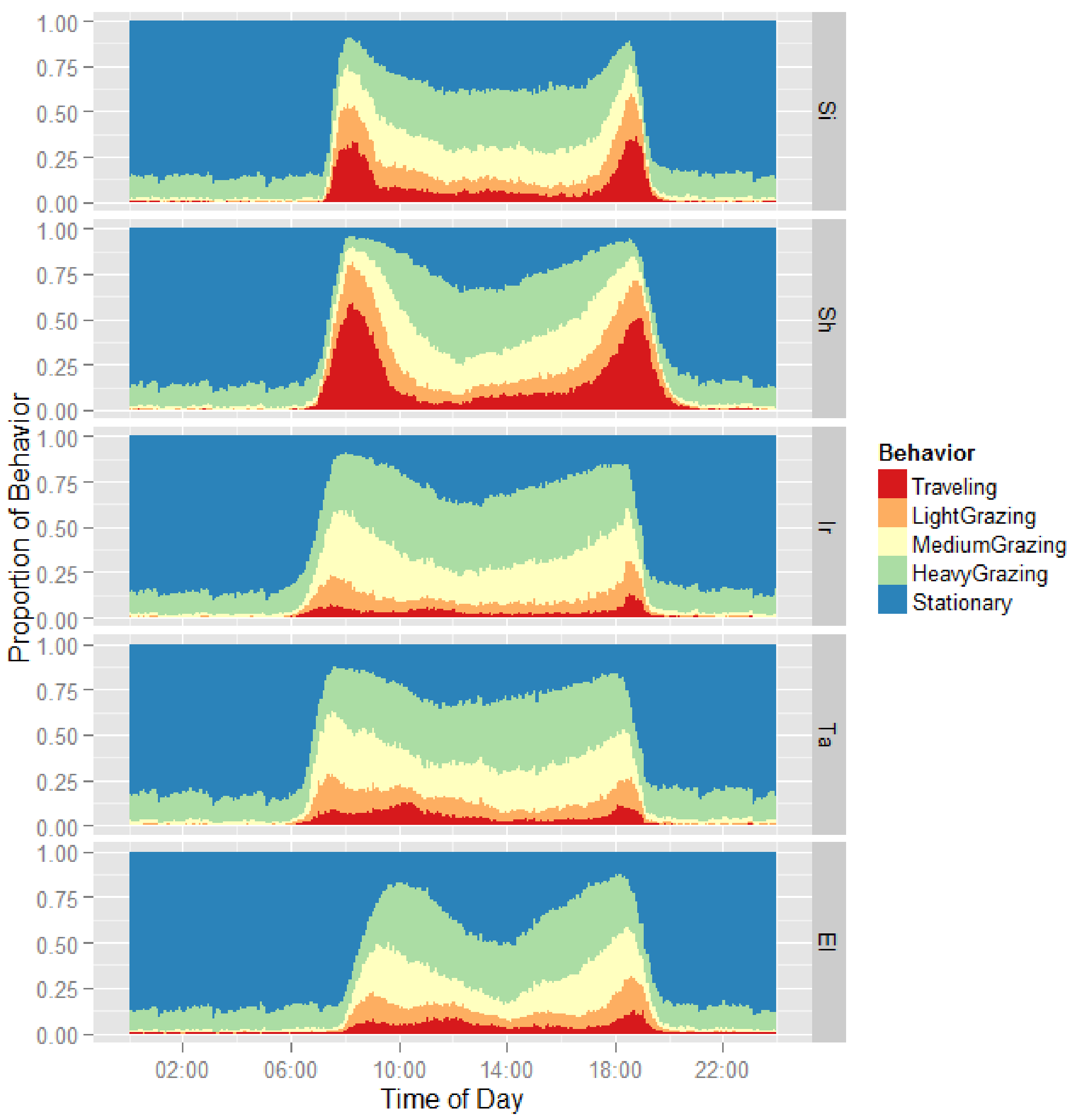

Figure 4. Distribution of cattle behaviors in different times of the day

Among the five sites, cattle in El Dima were engaged in the shortest amount of time herding. They spent less than 11 hours herding on average. They were the latest to leave their camps. Cattle in Siqu exhibited the second shortest herding time, which was approximately 11.5 hours/day. They were also the second latest to start herding in the day. Since Siqu pastoralists herded livestock in a more constrained extent, there was little incentive to start herding early in the morning because pastures were not distant from settlement. Cattle in other three sites were herded for over 12 hours/day. Among them, cattle in Shomo were associated with the longest time of herding. Since the area around the community center of Shomo was largely settled by clusters of villages and their crop fields, cattle had to move beyond these areas to reach forage resources that were distant from camp locations.

Estimation of determinants of temporal distribution of cattle behaviors indicated that all five behaviors varied significantly throughout the day, and the distribution of behaviors in the five study sites was also different (Table 4). Cattle in Shomo spent the most effort on traveling, which was significantly higher than El Dima. Traveling behavior lasted from 7:30 to 9:30 am, with the peak appearing around 8:30 am. At this time, traveling was the dominant behavior, which was over 50%. Another peak traveling behavior appeared at 7:30 pm, shortly before they went back to night corrals. The peak of heavy grazing behavior appeared around 12:30 pm. Compared to other sites, cattle in Shomo were the only group that spent less than 30% effort on heavy grazing. These cattle also spent more effort on light grazing. However, their heavy grazing and stationary behaviors were significantly less than El Dima.

Table 4. Estimation of determinants of temporal dynamics of cattle behaviors using GAM.

Behavior	Traveling		Light Grazing		Medium Grazing		Heavy Grazing		Stationary/Watering	
Parametric coefficients	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	36.27***	5.01	64.46***	2.50	135.55***	3.20	290.44***	2.92	825.84***	7.91
Irbi	-9.33	7.04	-9.48***	3.55	27.18***	4.52	12.32***	4.14	-178.58***	11.19
Shomo	97.61***	7.04	26.75***	3.56	6.99	4.52	-46.33***	4.14	-170.62***	11.19
Siqu	45.23***	7.05	15.39***	3.54	10.25**	4.52	-0.71	4.14	22.99**	11.19
TakaBulti	1.76	7.02	-2.77	3.54	18.83***	4.52	-7.74*	4.14	-217.18***	11.19
Smooth term	edf	F	edf	F	edf	F	edf	F	Edf	F
Time	8.97***	94.91	8.98***	369.90	8.97***	862.50	8.99***	1194	8.97***	1102

*** indicates significant at 0.01 level; ** indicates significant at 0.05 level; *indicate significant at 0.1 level

Cattle in Siqu were the next group that spent substantial amount of effort on traveling, which accounted for over 5% of all their behaviors. The traveling behavior peaks appeared at similar time as Shomo, although slightly later in the morning and earlier in the evening. Cattle in Siqu also had the second least effort spent on heavy grazing, which accounted for merely 30% of all behaviors. This value was only after the case in Shomo. These cattle also spent significantly more effort on light grazing than El Dima. However, heavy grazing of Siqu cattle was not significantly different from El Dima.

Cattle in Irbi and Taka Bulti exhibited much less effort on traveling than Shomo and Siqu, and their differences from El Dima were insignificant. With lower livestock density within their claimed extent of movement, they enjoyed much more freedom in movement. Traveling behaviors accounted for no more than 3.5% in Irbi, Taka Bulti and El Dima. They did not show two evident peaks of traveling behaviors. However, cattle in Irbi and Taka Bulti spent significantly less time on being stationary. Arguably, the longer duration of average daily herding made these cattle more active in movement than El Dima.

The above findings echoed my field observation of cattle movement pattern that in Siqu and Shomo, pastoralists had to drive their cattle fast into the feeding areas. In contrast, those in Irbi, Taka Bulti and El Dima could enjoy relatively abundant forage resources shorting after leaving camp locations. Consequently, traveling behavior rarely dominated in early morning and late evening in these three study sites.

5. Spatial Distribution of Cattle Behaviors

Spatial distribution of cattle behaviors reflected pastoralists' choices of grazing areas within their herding extents. Given their unique herding contexts, pastoralists adopted different strategies to herd their animals, resulting in substantial variation of cattle behavior distribution along the gradient from camp locations (Figure 5). Most recordings of behaviors occurred within a 50 m radius from the camps. These behaviors represented what cattle did in the night hours, which were mostly stationary. However, approximately 10% behaviors within this range were misclassified as heavy grazing. This was because during night hours, cattle sometimes could move very slowly within the corrals, which resembled the heavy grazing behavior during the day. Cattle could also be moving around while getting out of corral or being caught for milking. Consequently, any 5-min movement over 33 m was misclassified as heavy grazing around camp locations.

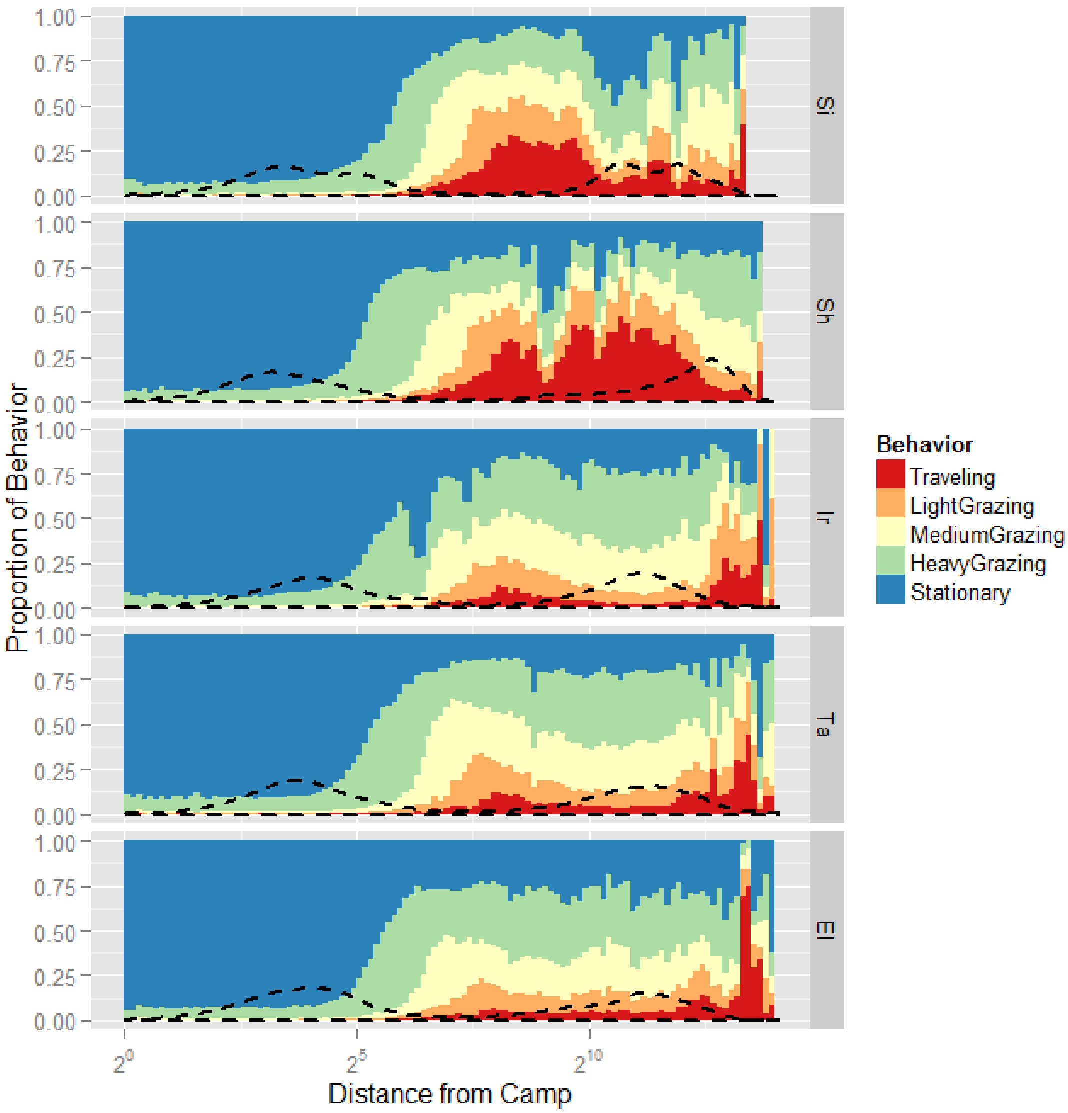

Figure 5. Distribution of cattle behaviors along the gradient from camp locations. Dotted lines indicate the density of behaviors along the distance gradient.

I investigated the distribution of five cattle behaviors relative to distance from camp locations using GAM. I excluded the behaviors within 50 m from camp locations because they were dominated by stationary behavior or false heavy grazing behaviors in all five study sites. Similar to the estimation of determinants of temporal behaviors, results of estimation of spatial behaviors also suggested that five behaviors were significantly different at different distances from camp locations, and the spatial distribution of behaviors in the five study sites was also different (Table 5).

Table 5. Estimation of determinants of spatial distribution of cattle behaviors.

Behavior	Traveling		Light Grazing		Medium Grazing		Heavy Grazing		Stationary	
Parametric coefficients	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	91.33***	17.22	168.50***	10.64	345.88***	30.83	745.77***	49.58	2124.59***	74.03
Irbi	-19.24	24.27	-25.56*	15.00	68.21	43.63	25.79	70.26	-456.56***	104.93
Shomo	236.53***	24.32	69.43***	15.32	14.53	44.34	-127.60*	71.31	-440.33***	106.02
Siqu	121.17***	25.54	42.86***	15.38	27.91	44.62	-1.15	71.77	84.32	106.67
Taka Bulti	1.09	24.63	-8.97	15.14	45.17	43.82	-22.56	70.30	-547.39***	104.58
Smooth term	edf	F	edf	F	edf	F	edf	F	edf	F
Distance	8.82***	84.13	8.96***	255.80	8.88***	131.10	8.81***	94.57	8.95***	422.80

*** indicates significant at 0.01 level; ** indicates significant at 0.05 level; *indicates significant at 0.1 level

Cattle in Shomo spent the most effort on traveling, which was significantly higher than El Dima. Traveling behavior was evident within a wide range from 500 m up to 8000 m in terms of distance from camp locations. Their second peak of behavior distribution (dotted line) appeared when the traveling behavior diminished along the distance gradient. Most of their behaviors at such locations were heavy grazing and medium grazing.

The traveling behavior distribution of Siqu cattle was also significantly different from El Dima. In general, these cattle exhibited a similar spatial distribution pattern as Shomo. Due to a much smaller herding range than Shomo, evident traveling behaviors only lasted until 1200 m from base camp locations. Beyond that point, cattle were able to enjoy more foraging, although they sometimes also walked fast.

The cases in Irbi and Taka Bulti were different from Shomo and Siqu but similar to El Dima. The second peak of behaviors (dotted lines) appeared much closer to camp locations than Shomo and Siqu, suggesting that cattle in these sites did not have to walk long distance to reach their foraging areas. In addition, traveling behavior hardly dominated the gradient from camp locations until the very end. Such a distribution pattern was largely due to their camp relocation activities. Longer distance walking typically appeared in days where pastoralists drove their animals from one camp to another. On these days, traveling behaviors would dominate until they reached a new camp site. Such dominance of traveling behaviors that were distant from the starting camp locations was not observed in the two sedentarized study sites. Arguably, camp relocation allowed them to access forage resources at a close to intermediate distance from satellite camps.

6. Determinants of Resource Selection

The above results suggested that the spatio-temporal dynamics of cattle behaviors varied significantly across the five study sites. Presumably, the unique herding contexts determined how pastoralists managed their herds, which was reflected in cattle behaviors. In this section, I tested how environmental covariates, herd management strategies and seasonality affected cattle's resource selection patterns. I combined the locations of heavy and medium grazing as cattle's preferred grazing areas, and locations of other three behaviors as non-preferred grazing areas. I also excluded the behaviors that fell within 50 m from camp locations, because they were more likely to be associated with errors. Behaviors that were greater than 50 m away from camps mostly represented the behaviors occurring in the daytime when the cattle were actually making a choice in resource selection.

I applied the generalized linear mixed-effects model to estimate the determinants of resource selection. The results suggested that multiple factors significantly affected cattle's resource selection (Table 6). First, environmental endowments largely determined how cattle selected resources. Forage availability, as represented by NDVI, had a significant impact on resource selection. Patches of pastures with higher NDVI values strongly attracted cattle to slow down their velocity and graze on these lands. Topological factors also influenced resource selection. In general, cattle preferred to graze on flatter areas, which were easier to access. They tended to pass the rugged areas with a higher velocity. In addition, grazing was more likely to occur at a higher elevation, which indicated that cattle usually walked upward from their camp locations to access better forage resources within the herding range.

Table 6. Estimation of determinants of resource selection by cattle using generalized linear mixed-effects model.

Independent variables	Parameters	SE
Intercept	-1.04E+00***	1.01E-01
Fixed-effects		
NDVI	4.88E-01***	4.38E-02
Slope	-2.03E-02***	1.64E-03
Elevation	8.01E-04***	7.66E-05
Distance to camp	4.43E-05***	1.87E-06
Site_Irbi	-5.29E-02	9.96E-02
Site_Shomo	-2.34E-01**	9.41E-02
Site_Siqu	-7.19E-01***	1.02E-01
Site_TakaBulti	3.97E-01***	9.44E-02
Type_Forra	5.92E-02***	1.76E-02
Type_Transition	-9.93E-01***	3.35E-02
Season_Wet	3.71E-01***	2.33E-02
Random-effects		
Var(Date)	0.02143	
Var(CowID)	0.04579	
AIC	321318.1	
Sample size	241004	

*** indicates significant at 0.01 level; ** indicates significant at 0.05 level

Distance to camp location was also a significant predictor of resource selection. In general, as it got farther away from camp, cattle were more likely to slow down their velocity to graze. In contrast, rangelands in proximity to settlement certainly had less grazing value. Consequently, cattle walked quickly to pass these areas that were settled with clusters of villages and cultivated lands. Such as pattern was particularly evident in Shomo, where cattle had to walk up to 8 km to reach their foraging areas.

Cattle's resource selection pattern also varied significantly in the five study sites. Using El Dima as the benchmark site, I found that cattle in Siqu and Shomo spent significantly less time on grazing but more on other behaviors. These two sites were more bounded in terms of herding range; therefore, they must spend more effort on walking in search for enough forage during the dry season. The case of Irbi was similar to El Dima. Although they did not have *forra* grazing lands, they occasionally migrated beyond their *worra* grazing extent by negotiating with neighboring communities. Cattle in Taka Bulti enjoyed an even higher proportion of time on grazing than El Dima. This was largely due to the fact that the duration of herding was longer than that in El Dima.

Herd management strategies also had significant impact on cattle's resource selection. In contrast to *worra* herding, cattle enjoyed more time on grazing while being herded on *forra* grazing lands. Pastoralists typically set up *forra* camps in places far from settlement, thus facing less competition from neighbors. Consequently, cattle did not have to walk a lot on a daily basis to reach forage resources, suggesting that relocating into *forra* grazing lands was an important strategy to reduce energy spent on daily walking while ensuring sufficient forage uptake. However, when cattle were in transition from one camp to another, they had less opportunity to graze. This was particularly true during long-distance migration, in which cattle were driven by pastoralists to move at a high velocity to reach the next camp before sunset.

Variation in cattle behavior distribution was also subject to seasonality. During wet season, cattle were able to spend significantly more time on grazing. In dry season, however, pastoralists strived to ensure forage uptake for their herds by increasing the amount of traveling and reducing the amount of resting to compensate for the forage gap. This was achieved through exploiting resources that were distant from base camp locations. According to the GPS-tracking data, cattle generally spent 3% more time traveling and 5% less time resting in the dry season.

However, the above seven predictors only explained 65% of the variation in cattle's resource selection behaviors revealed by GPS-tracking. In fact, cattle movement on the open rangelands was extremely complex, which was subject to the influence of multiple factors that usually interacted with each other. Although environmental covariates, herd management strategies and seasonality were considered in the model, cattle behaviors and their resource selection patterns were certainly under the influence of other factors.

Indigenous institution is crucial to determine how cattle move at a broad spatial scale. The *gadda* system has effectively regulated human population growth, settled disputes, interpreted and enforced resource-use policies for centuries in Borana (Legesse, 2000). It has been long noted that mobility sustains traditional pastoral livelihoods because of the freedom to move in pursuit of valuable forage resources at different times of year. Such movement is supported by free flow of information among different groups through herders, as well as an indigenous institution that promotes the use of social networks that rely on reciprocity to cope with environmental stresses (Butt, 2010; Moritz et al., 2013; Samuels et al., 2007).

At the community scale, pastoralists also set up their own rules to manage rangelands given their unique herding contexts. In my interviews with participant households, it was revealed that pastoralists in Borana typically set up community rangeland reserves for dry season use. Crop fields were also fenced by individual households in close proximity to settlements. Therefore, although these pixels appeared greener according to NDVI, cattle were more likely to move quickly through the narrow corridors in between these fenced lands.

Conflict with neighboring tribes could also affect cattle's resource selection behaviors. It has been widely reported that resources at conflict zones were usually better, but access to these resources were risky (Tache & Oba, 2009). Therefore, when pastoralists drove their animals into these areas, they needed to be very careful. Even when better forage existed in these areas, herders must keep their cattle moving constantly to avoid potential violence or cattle rustling (Kaimba et al., 2011).

In addition, access to resources among pastoralists in the same study site is also likely to vary. Households with a larger herd size usually have more power in the community, which indirectly translates into access to better forage resources in the seemingly open-access rangelands. Due to such privileges, they tend to dominate the limited grazing resources that are closer to camp locations. When conflicts arise with other less wealthy herders, they could use their power to drive them out of their herding areas. Consequently, the less wealthy pastoralists must herd their animals to places that are more distant from camp locations, resulting in a higher proportion of traveling behavior.

The projections of climatic change and government policy toward sedentarization will further complicate cattle's resource selection behaviors. On one hand, the projected trend of climate in East Africa suggested greater variability in precipitation and temperature both within and between seasons (Funk et al., 2008). This trend will make extensive herding and camp relocation even more important as coping strategies for environmental stresses. On the other hand, pastoralists are getting sedentarized, resulting in a process of land subdivision and tenure individualization (Angassa & Oba, 2008). Consequently, both cattle mobility (BurnSilver et al., 2004) and household mobility (Thornton et al., 2007) are likely to be compromised. This will have a negative impact on the sustainability of pastoralism as a traditional livelihood system in the Horn of Africa.

7. Conclusion

This chapter investigated cattle behaviors by integrating GPS-tracking and ground-truth evidence. It contributed to the broader literature on domesticated animal ecology by filling three gaps. First, the intensive monitoring of cattle movement provided quantitative evidence of behaviors in a consistent approach over multiple seasons. Second, a robust linkage was established between cattle behaviors and velocities derived from GPS-tracking data. Third, cattle behaviors were explained and predicted given different socio-ecological endowments in the herding contexts.

Specifically, I summarized five cattle behaviors that are associated with different ranges of velocity, namely: watering/stationary (below 0.41 km/h), heavy grazing (0.41-1.06 km/h), medium grazing (1.06-1.94 km/h), light grazing (1.94-2.77 km/h), and traveling (above 2.77 km/h). Distribution of five cattle behaviors varied significantly within the time of day and along the distance gradient from camp locations. Traveling and light grazing behavior were highly directional and occurred more frequently in closer proximity to camp locations, while medium and heavy grazing usually happened at a substantial distance from camps and movement pathways were more meandering. Two peaks of traveling behaviors were evident in the morning and evening for the sedentarized study sites, while such fast walking behaviors were far less dominant throughout the day in the mobile study sites.

The estimation of determinants of resource selection by cattle suggested that the environment endowment strongly affected how cattle move and behave. Cattle were more likely to graze on patches of rangelands with higher NDVI values, in areas that were flat and at a higher elevation. They typically spent more energy on traveling and less on grazing in dry season. The results also indicated that sedentarized study sites were significantly more resource-competitive than those where camp relocation is practiced. This was evidenced by the fact that cattle were engaged with more traveling in pursuit of sufficient forage in sedentarized sites. In addition, herd management strategies also influenced cattle behaviors. Cattle generally spent more effort on traveling when herded around base camp. If cattle were moved to *forra* grazing lands, they typically enjoyed more time on grazing and less time on traveling on a daily basis, although the transition between camps required more traveling. Such results clearly indicated that camp relocation is an important strategy to deal with stress in dry seasons.

However, despite environmental covariates, herd management strategies and seasonality largely explained the observed resource selection patterns by cattle, the complexity within the open grazing system still needs further examination. In fact, the Boran pastoralists have developed complex mechanisms by which they can alleviate the threat of drought. Therefore, future modeling of cattle's resource selection behaviors should take into consideration of not only the socio-ecological variations of herding context, but also household characteristics, indigenous rangeland management institutions and potential conflicts with neighboring tribes. Although it is difficult to obtain empirical data on these factors, these scenarios could be explored through agent-based models (Wang et al., 2013). Such simulation-based approach can potentially shed light on our understanding of the complex causal mechanisms of resource selection in the open grazing systems.

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CHAPTER 7 ADAPTATION TO BUSH ENCROACHMENT: INSIGHTS FROM ETHNOBOTANICAL KNOWLEDGE OF BORAN PASTORALISTS IN SOUTHERN ETHIOPIA

1. Introduction

It has been widely recognized by both pastoralists (Angassa & Oba, 2008) and ecologists (Gemedo-Dalle et al., 2006) that pastoral livelihoods can be seriously threatened by bush encroachment (Angassa & Oba, 2010; Kgosikoma et al., 2012; Solomon et al., 2007). Bush encroachment is the process in which woody plants (usually assumed as unpalatable to livestock) replace grasses and other herbs (mostly considered palatable to livestock) on rangelands. Once established, bush cover accelerates grass cover decline (February et al., 2013). With a significant reduction in the amount of palatable forage species, livestock will face a shortage of food to meet their nutritional demands, thus negatively affecting food production in pastoral systems.

Various approaches have been proposed to address the challenge of bush encroachment. The most commonly proposed solution is the use of fire to burn the bushes (Angassa & Oba, 2008). Fire is an important tool used traditionally by pastoralists to manage rangelands (Hudak, 1999). However, such a customary practice depends on the fuel loads in the understory layer of rangelands. In cases where fire has not been used for decades, intensification of grazing pressure reduces the fuel load required for fire to burn the bush cover. Another approach is bush clearing (Angassa, 2002; Gemedo-Dalle et al., 2006). However, counting on human labor to fight against bush encroachment is unrealistic because woody plants have established themselves and proliferated throughout the landscape. A third solution is to change pastoralists' livestock portfolios, namely replacing cattle with camels and small ruminants (Homann et al., 2008; Solomon et al., 2007). Based on the assumption that grazers prefer herbs, especially grasses, while browsers favor woody plants (Stuth, 1991), it seems rational to reduce cattle holdings and add more goats and camel into pastoralists’ herds given decreasing herbaceous plants and increasing woody plants.

However, the suggestion to replace cattle with goats and camels is yet to be validated with empirical and contextualized data of forage palatability to different livestock types (Heitschmidt & Stuth, 1991). Although it is generally true that cattle are grazers and goats are browsers, given the unique combination and availability of forage plant species in a specific context, how livestock forage selectively on the plants are yet to be explored. For instance, the woody species *Grewia* spp., are considered encroaching according to pastoralists, but these woody species are palatable to cattle as well (personal observation in Borana, Ethiopia). Therefore, only when we know exactly the palatability of each forage species to different types of livestock can we propose feasible and credible responses to the bush encroachment issue.

Pastoralists’ ethnobotanical knowledge, which is gained through daily interaction with the natural world, could shed light on how to address the challenge of bush encroachment. It has been widely recognized that indigenous ecological knowledge and their assessment of environmental change would effectively complement scientific research (Berkes, 1998; Fernandez-Gimenez, 2000). The knowledge of pastoralists could serve as the basis for decision making in the utilization and management of grazing lands. Considering that pastoralists are frequently observing and exploiting their rangelands, their contribution to rangeland management could be more reliable than policies designed by outsiders such as ecologists and development agencies (Knapp & Fernandez-Gimenez, 2008). Specifically, pastoralists hold a rich body of knowledge on forage plant species and perception of rangeland vegetation dynamics (Kaye-Zwiebel & King, 2014; Kgosikoma et al., 2012), which can be used as the basis to facilitate the generation of context-specific and empirically grounded responses to bush encroachment.

However, in the Borana Zone of Ethiopia where bush encroachment has been seriously affecting pastoral livelihoods in the past decades, previous research on pastoralists’ knowledge of forage plant species is too generalized in the ethnobotany literature. The first comprehensive study of ethnobotany in

Borana documented 327 plants (Gemedo-Dalle et al., 2005). Among these plants, 188 had certain foraging value. Other range literature also documented general palatability of plants (Angassa & Oba, 2010). In all these efforts, however, livestock types and their level of preference to specific plant species were not differentiated. One plant species was considered either useful or not useful to livestock in general. Lack of specific knowledge on forage palatability is a major barrier to the development of context-specific solutions to guide livestock production.

Another knowledge gap is the shortage of accurate and comprehensive assessment on bush encroachment on livestock production. On one hand, a substantial amount of literature focused on the issue of bush encroachment itself. These studies mostly focused on species that are encountered in plant surveys (Angassa & Oba, 2008; Tefera et al., 2007). On the other hand, dynamics of livestock holdings and livestock production are commonly investigated in development studies literature, which were found to be fluctuating throughout time and following a trend of shift from grazers towards browsers (Homann et al., 2008; Megersa et al., 2014). However, there is a disconnection between vegetation dynamics and livestock production. Without any context-specific knowledge on palatability of forage species and perception on vegetation dynamics, we can hardly assess the impact of bush encroachment of livestock production, except making general conclusions that bush encroachment negatively affects pastoral livelihoods.

The overall objective of this chapter is thus to investigate pastoralists' ethnobotanical knowledge on forage species and perception of bush encroachment, and the implication of their knowledge on livestock production in the pastoral system in the Borana Zone of southern Ethiopia. Specifically, I examined forage plant species and their palatability to cattle, sheep, goats and camels, the four major livestock types herded by pastoralists in the study area. By interviewing pastoralists in five study sites, I documented a list of 252 forage species and their palatability level to four livestock types. I collected voucher specimens of these plants, and identified the scientific names in the National Herbarium of Ethiopia. In addition to probing indigenous knowledge of forage plants, I examined pastoralists' perception of bush encroachment. Then I simulated the encroachment process given the palatability and dynamics of vegetation to explore how livestock production will be affected. I concluded that bush encroachment does not necessarily translate into hopeless situation for livestock herding in Borana. In contrast, pastoralists have been actively adapting to the ongoing bush encroachment process by shifting their livestock holding portfolio based on their ethnobotanical knowledge. Such adaption not only mitigates adverse impact of bush encroachment, but also enhances resilience of the pastoral system in Borana.

2. Study Area

The study was carried out in the Borana Zone, located in southern Ethiopia bordering Kenya (Figure 1). Elevation in Borana ranges from 500 m to 2500 m above sea level, with terrain varying from steep highland slopes to flat, dry river and lake beds in the lowlands. Small seasonal rivers and ponds are common throughout the region. The landscape is a heterogeneous mix of rangeland reserve enclosures, crop fields, clusters of fenced villages, nested within the dominant savanna rangelands. Moist high-lying areas tend to be dominated by woody plants such as *Acacia tortilis*, *A. drepanolobium*, *Commiphora africana*, and herbaceous species such as *Chrysopogon auheri*, *Cenchrus ciliaris, Aspilia mossambicensis, Hibiscus boranensis, Vernonia cinerascens*. In contrast, drier areas are dominated by woody plants including *A. mellifera, A. reficiens, Solanum schimperianum, Justicia ornatopila,* and grass species such as *Digitaria naghellensis* and *Eustachys paspaloides*.

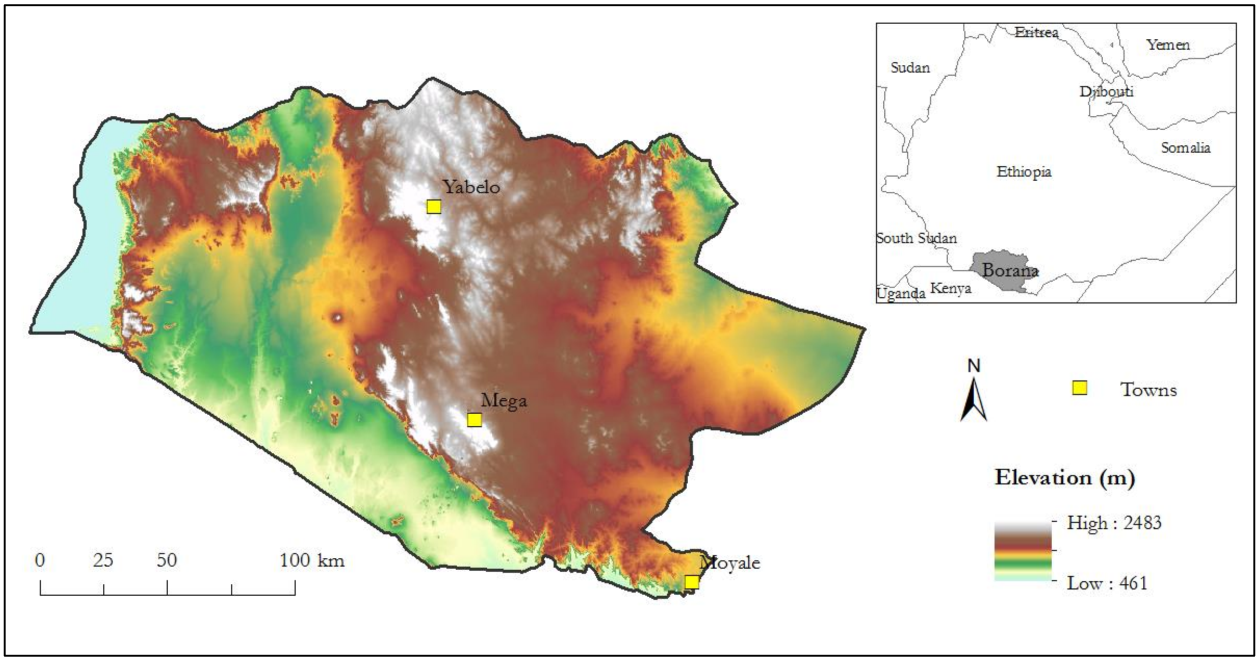

Figure 1. Location and elevation of the Borana Zone in southern Ethiopia.

Bush encroachment was first noticed in 1970s in the study area. By late 1990s, bush encroachment reached a climax stage that affected 24% of the rangelands at the regional scale (see Figure 2 as an illustrative example). In the bush encroachment climax areas, the woody cover exceeded 60%, with the density approaching 2000 trees/ha (Oba 1998). Major encroachers identified include *A. mellifera*, *A. reficience*, and *Commiphora spp* (Angassa & Oba, 2008). Despite ongoing bush encroachment, pastoralists continued to survive in a harsh environment with extreme and unpredictable weather conditions (Abule et al., 2005; Solomon, 2003), indicating a strong capacity to adapt to the changing environment. Therefore, any attempt at improving the living conditions of the Borana should first incorporate a thorough understanding of the pastoralists' ethnobotanical knowledge.

Figure 2. An example of bush encroachment in Borana, Ethiopia

3. Methods

3.1. Plant interview, voucher specimen collection, and plant identification

My empirical research of ethnobotanical knowledge started with a pilot fieldtrip to Borana in February, 2013 to interview pastoralists regarding their knowledge on forage species and general perception on bush encroachment. Preliminary input from pastoralists indicated that different livestock types have distinct preferences towards the same plant species. In addition, a specific livestock type holds different level of preferences to plants, which is subject to change over time. For example, cattle generally eat any grass species as long as they encounter them, but only consume certain woody plants in the middle and end of dry season. Therefore, it is important to not only distinguish the livestock types' palatability, but also the level of palatability to the livestock.

Based on preliminary input from pastoralists, I conducted fieldwork in the summer of 2013 and 2014 with the assistance of a local research assistant, who was born and raised as a pastoralist and fluent in both Afaan Oromo and English. Interviews and voucher specimen collection were conducted in five study sites including both lowlands and highlands of the Borana Zone. In each interview of forage plant palatability, there were at least three active herders and one elder pastoralist.

Ecological knowledge not only rests in people's minds, but also in their relations within their habitat (Kassam et al., 2010). Therefore, instead of conducting interviews in the village, I had pastoralists take me to the part of rangelands with the highest diversity of plants, which, in most cases, were the rangeland reserves saved for calf grazing in dry season. For each species I encountered, I asked the local name and palatability to cattle, sheep, goats and camels (Table 1). Quite often, pastoralists disagreed with each other regarding the palatability to livestock. Such differences in pastoralists' knowledge, as indicated by the lack of agreement on some aspects of palatability, is consistent with studies elsewhere (Kassam, 2009). When such cases occurred, I facilitated a discussion among pastoralists to come up with a consensus. Usually the elder pastoralists were consulted if the group could not decide.

Table 1. Example of field data collection sheet

Local Name	Cattle Palatability	Sheep Palatability	Goat Palatability	Camel Palatability
Saphansa	2 1 [0]	2 [1] 0	2 [1] 0	[2] 1 0

Note: 2 indicates highly palatable, consumed throughout the year if available; 1 indicates barely palatable, consumed only in the middle and end of dry season; 0 indicates unpalatable. Palatability of a specific plant is recorded based on input from pastoralists; however, being palatable does not necessarily translate into being nutritious.

After I probed the palatability information of a plant, a voucher specimen was collected. I also took a picture of the fresh specimen for subsequent identification. These plant specimens were transported to the National Herbarium of Ethiopia at Addis Ababa University for drying, freezing and identification. During the identification process, I determined scientific name and growth form of each specimen.

In addition, I conducted focus group discussions to examine pastoralists' perception of bush encroachment. In contrast to the plant interviews that probed details of palatability, in this exercise I focused on general desirability of plants as forage. I asked pastoralists to identify and rank the top five most common shrubs and trees, top five most desirable shrubs and trees, and top five most undesirable shrubs and trees. At last, I asked pastoralists to identify and rank the top ten encroaching species in their herding environment.

3.2. Quantification of palatability and ranking result

I quantified the palatability of each plant species by referring to its palatability and seasonal consumption. If one species is considered highly palatable, it is consumed at any time of the year. If one species is regarded as barely palatable, it is eaten only in the dry season. Although the length of dry season varies across years, pastoralists generally agreed that there are approximately four months in which livestock have to rely on the less preferred plants to survive the times of stress. If one species is unpalatable, it will not be eaten under any circumstances. Accordingly, I ended up with a proportion of 12:4:0 months, which equals 3:1:0 for the three levels of palatability. Therefore, I assigned a palatability value of 3 to highly palatable species, 1 to barely palatable species, and 0 to unpalatable species.

Perception and ranking of species desirability and level of encroachment are analogical to risk identification and ranking exercises. Therefore, I followed Smith, Barrett, & Box (2000) to quantify the ranking results, namely normalizing and converting the rankings into a rescaled interval between 0 and 1, where 0 represents lowest values and 1 indicates the greatest values to a specific species. The index, I, is then calculated as:

$$I_i = 1 - (r_i - 1)/n$$

where r_i represents the ordinal ranking of a species, and n is the number of plants ranked in each exercise. In the case of desirability ranking, n = 5. Therefore, the most common desirable plant is assigned a value of 1-(1-1)/5 = 1, the second 1-(2-1)/5 = 0.8, the third 0.6, the fourth 0.4, the fifth 0.2. The values of undesirable plants are determined by following the same rule, but are assigned with negative values. In the case of encroachment ranking, n = 10. Therefore, the most encroaching species is assigned 1-(1-1)/10 = 1, the second 1-(2-1)/10 = 0.9, and the last 1-(10-1)/10 = 0.1.

3.3. Livestock holdings

In order to investigate the impact of bush encroachment on livestock production, it is necessary to collect data on pastoralists' livestock holdings. This chapter made use of data from household survey conducted by the IBLI research team. More specifically, I analyzed livestock portfolio data from 515 households collected in 2014. I also compared the 2014 livestock holding data with that in 1982 (Coppock, 1994) to investigate changes in portfolios over the past three decades. According to the conversion rule of tropical livestock unit[6] (TLU), I converted livestock heads to livestock units to compare the two datasets in three decades.

3.4. Plant clustering

In empirical work, the use categories of plants are often identified via a series of rules that separate the sample into pre-defined groups. A variety of approaches exist, based on rules stemming from different theoretical foundations. Among these approaches, an iterative, data-driven approach based on cluster analysis is gaining popularity. This is a statistical data reduction method for classifying a large number of multivariate observations into smaller and tractable subgroups characterized by maximizing intra-group homogeneity and inter-group heterogeneity (Everitt et al., 2011). In this approach, some latent common

[6] 1 cattle = 0.8 camel = 10 sheep/goats

characteristics within the data allow one to put individual plant species into subgroups based on similarity along some specific parameters.

In order to identify different functional groups of plants in supporting livestock herding, I performed the k-means cluster analysis to assign each plant into a distinct group based on its palatability to cattle, sheep, goats and camels. The k-means method uses the local structure of the data to delineate clusters by iteratively minimizing the within-group sum of squared errors[7]. Since cluster analysis is a heuristic classification procedure rather than a statistical test, I used the Simple Structure Index, which is a good indicator of the best partitioning of the data (Borcard, 2011), as the criterion for selecting the optimal k value in addition to common sense check.

3.5. Simulation of bush encroachment

A key to assess the impact of bush encroachment on livestock production is to acquire measurement of forage abundance, such as the biomass of edible parts of plants on the rangelands. This is usually achieved through intensive plant survey and subsequent lab processing of collected samples. However, the objective of this chapter is to capture the diversity of forage plants as much as possible. Plant surveys cannot fulfil such an objective because it can only capture the diversity within the very limited sampled quadrats. Therefore, rather than focusing on direct measurement of forage abundance, I simulated the process of bush encroachment based on pastoralists' perception to approximate the dynamics of vegetation shifts, and infer the relative abundance of forage and their palatability to livestock.

Since my focus is on diversity rather than absolute abundance, my simulation treated all 252 plants as equal units. In each step of replacement, I randomly took two herbaceous plants out of the pool, and

[7] This is measured with respect to the Euclidean norm of the cluster means across the vector of variables used as defining characteristics. Since k-medians cluster analysis yielded qualitatively identical results in these data, I omitted those results.

add two woody plants. Since pastoralists agreed that the availability of grass species is decreasing more rapidly than other herbaceous plants, in each step of replacement I took one grass species out of the pool until they were depleted, and another one from the entire pool of herbaceous plants including grasses. On the encroaching side, each time I added two woody plants into the pool. One was from the list of top ten encroachers reported by pastoralists, while the other was randomly drawn from the pool of all woody plants. The simulation and all other data analysis in this chapter was conducted using R statistical software (R Development Core Team, 2014).

4. Results

4.1. Diversity and palatability of plants

I listed a total of 252 plant species distributed in 49 families and 158 genera. Borana pastoralists named more than 88% of these species in the field. The families with the greatest numbers of species were Poaceae (40 species), Fabaceae (30), Asteraceae (22), Malvaceae (19), Acathaceae (13), Amaranthaceae (12), and Lamiaceae (11). These seven families accounted for over 58% of all species I listed. Such findings are consistent with Gemedo-Dalle et al (2005), in which more than half of the forage species belong to Poaceae, Fabacaeae, Lamiaceae, and Asteraceae.

Out of 252 species, 233 have foraging value to at least one livestock type in Borana. Among the 233 species, 179, distributed in 114 genera and 33 families, are considered highly palatable to at least one of the four livestock types (Table 2). A total of 175 plant species distributed in 123 genera and 42 families (which largely overlap with the previous 179 highly palatable plants) are barely palatable to at least one livestock type. However, there are also 128 plant species in 89 genera and 41 families that at least one livestock type will not consume even in the dry season. Such a pattern indicates that there are both unique and overlapped niches in the foraging preference of cattle, sheep, goats and camels.

Table 2. Summary of taxonomic rank and palatability as reported by pastoralists in Borana

Taxonomic rank	Total	Highly palatable	Barely palatable	Unpalatable
Family	49	33	42	41
Genus	158	114	123	89
Species	252	179	175	128

Further investigation of palatability to specific livestock types indicated more overlapped niches than unique ones (Figure 3). Nineteen species have no foraging value to any livestock. Fifty-four species can only be consumed in dry season, showing low palatability to all four livestock types. Only 13 species, accounting for approximately 5% of the entire sample, are preferred only by one type of livestock, representing unique foraging niches. In contrast, over 65% of plants are competed for by more than one livestock type: 72 species are preferred by two livestock types, another 72 species are ideal for three livestock types, and 20 species are favored by all livestock types. Such a distribution indicated that the four livestock types are largely in competition with each other to forage on the highly palatable species.

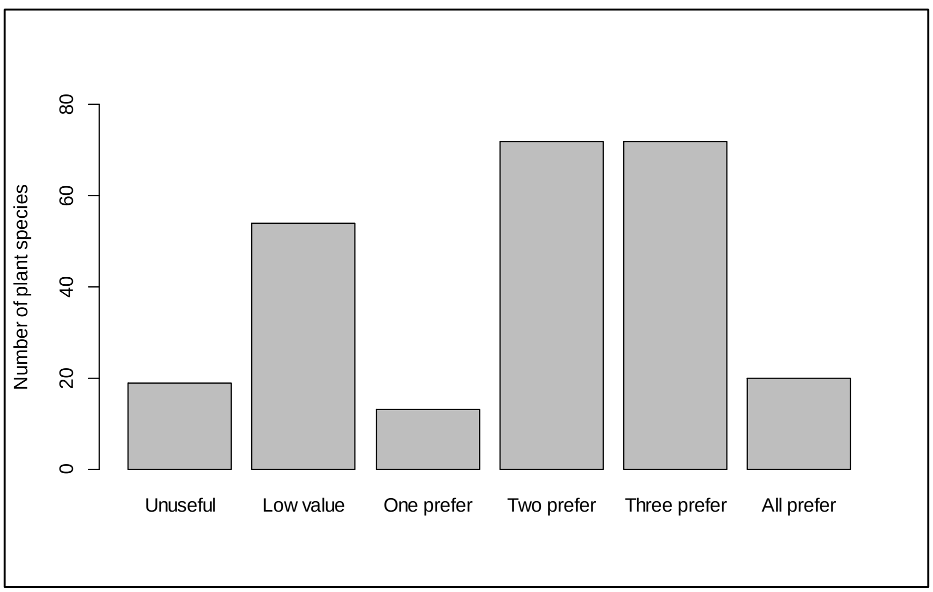

Figure 3. Degree of preference by four livestock types and their distributions

4.2. Livestock preference of forage plant species

Analysis of palatability at the individual livestock type level generated more nuanced results (Figure 4). Goats have the lowest number of unpalatable plants at 25 and the highest number of palatable species at 156. In contrast, cattle are more selective in their foraging behaviors. They refuse to eat 87 plant species even under extreme drought conditions. This is are nearly 3.5 times as many as that of goats. In addition, cattle only prefer 73 plant species, which is less than half of that of goats. The preference of sheep and camels lie between goats and cattle. Sheep consider 125 species as highly palatable and 57 species as barely palatable, while camels prefer 101 species and can consume 90 species under dry conditions, possibly indicating better adaptation to the arid and semi-arid environment.

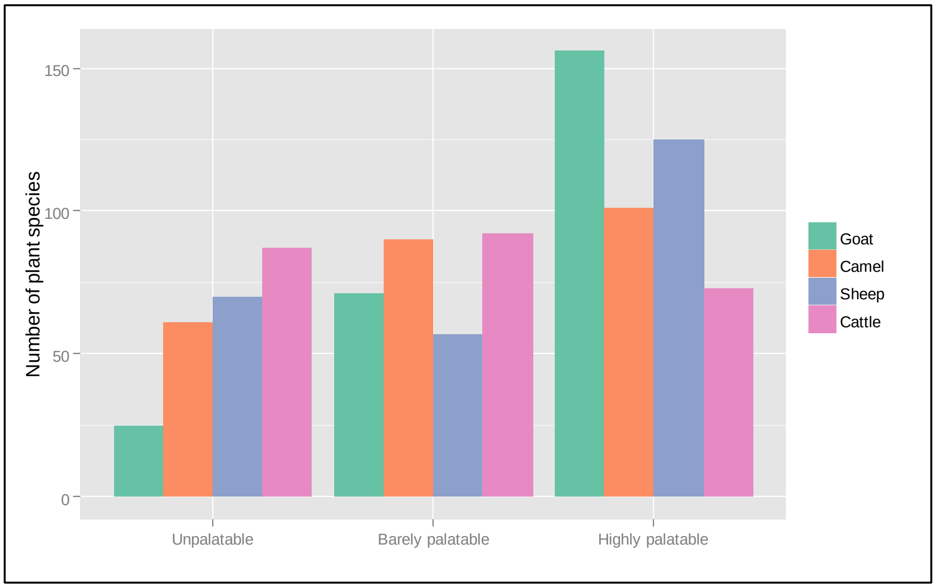

Figure 4. Plant palatability to goat, camel, sheep, and cattle reported by pastoralists in Borana

Based on growth forms, I identified 77 forbs, 40 grasses, 5 succulents, 8 climbers, 59 shrubs, 26 trees, and 37 shrub-trees[8]. Herbaceous plants, including forbs and grasses, accounted for 49% of species. Woody plants, including trees, shrubs, and shrub/trees, consisted over 51% of the total. Herbaceous and woody plants exhibited different palatability to the four livestock types (Figure 5). For goat, only 6

[8] Shrub/tree is a growth form between shrub and tree, which is common in the Borana drylands. Certain species can grow into a tree or shrub, depending on the site conditions.

herbaceous and 14 woody species are unpalatable, while 84 herbaceous and 68 woody species are highly palatable. Such a preference pattern indicated that goats are generalists rather than pure browsers. Camels are the only livestock type that strongly favor woody over herbaceous plants. They prefer 68 woody species, but only 30 herbaceous plants. In addition, 30 herbaceous plants are unpalatable to camels, which is the highest among all livestock types. Sheep also have a wide range of preference, but they like more herbaceous than woody plants. They prefer 87 herbaceous but only 36 woody plants. In addition, 46 woody species are unpalatable to sheep, which is twice that of camels and three times that of goats. Cattle, as highly specialized grazers, strongly prefer herbaceous plants and dislike woody species. On one hand, the herbaceous/woody plants ratio preferred by cattle is over six to one – only 10 woody species are palatable to cattle, but 63 herbaceous plants are preferred by cattle. On the other hand, there are 25 herbaceous plants unpalatable to cattle, but over 60 woody plants belong to this category.

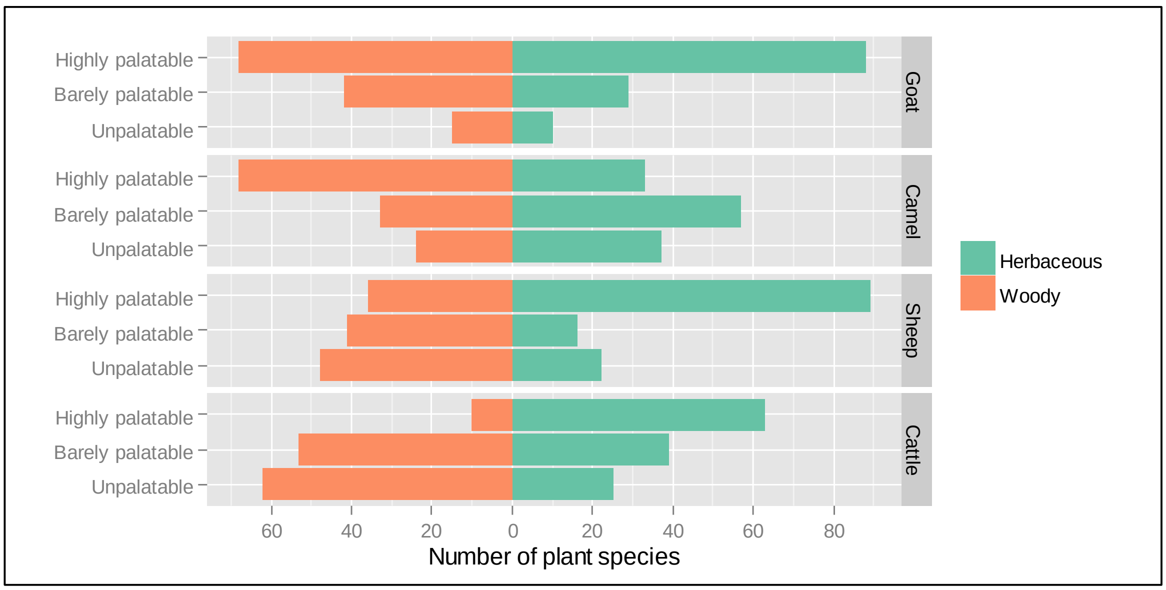

Figure 5. Palatability of herbaceous and woody plants to goat, camel, sheep, and cattle

4.3. Functional clusters of plants

Based on the Simple Structure Index and common sense check, I identified five distinct plant groups as the optimal fit from the cluster analysis. The summary statistics of the identified clusters are shown in Table 3.

Table 3. Plant clusters estimated via k-means clustering

Palatability	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Whole sample
Cattle	1.34	3.00	0.85	0.38	0.16	1.23
Sheep	2.06	2.76	3.00	0.54	0.14	1.71
Goat	2.94	2.50	2.77	1.25	0.35	2.14
Camel	3.00	0.61	0.73	1.21	0.08	1.56
Mean	2.33	2.22	1.84	0.84	0.18	1.66
No. of plants	95	46	26	48	37	252
Percent of plants	37.7%	18.3%	10.3%	19.0%	14.7%	100%

Cluster 1 is the largest group with the highest mean palatability to all four types of livestock in general, representing nearly 38% of the entire sample. This group is featured by its high palatability to camels and goats. Sheep show intermediate preference to this group. While for cattle, the average palatability is barely palatable in most cases. Over two thirds of plants in this cluster are woody plants. Typical plants in this group include *Grewia spp.* and *Hibiscus spp.* in the family of Malvaceae, all seven *Commiphora spp.*, and some desirable *Acacia* species such as *A. tortilis, A. bussei*, and *A. nilotica*.

The second plant group is characterized by their highest palatability to cattle. This cluster has the second highest average palatability, and it is also the third largest group, representing about 18% of the whole sample. In addition to being palatable to cattle, this cluster of plants is also favored by sheep and goats. Camels, in contrast, do not count on these plants as their major source of food. All plants in this group are herbaceous, and 37 out of the 46 plants are in the family of Poaceae.

The distinguishing feature of Cluster 3, representing 10% of the sample, is their high palatability to small ruminants, but low palatability to pure grazers and browsers. This cluster represents a unique niche for goats and sheep. Average palatability of this group is 1.84, which is the third highest. Twenty-three out of 26 plants in this group are herbaceous. They are mostly forbs in the families of Acanthaceae (7), Asteraceae (4), and Fabaceae (3).

Plants in Cluster 4 show an average palatability of 0.84, indicating that most species in this group are only consumed under pressure. This is the second largest group, accounting for 19% of the entire sample. This group mainly serves as the forage for goats and camels in dry season, and has minimal value for cattle and sheep. Nearly 73% of plants in this group are woody. Typical plants include less desirable *Acacia* species such as *A. mellifera*, *A. reficiens*, *A. horrida*, and some succulent plants in the family of Euphorbiaceae.

The plants classified as Cluster 5 have the lowest palatability compared to all other clusters: only 10% as valuable as the sample average. The preference by all four livestock types is low, although goats show slightly higher tolerance to this group than cattle, sheep, and camels. Nearly 15% of plants belong to this low-value group. About 38% of plants are herbaceous and 62% are woody. These 37 plants are widely distributed in 19 families.

4.4. Which part of diversity supports livestock production

Different plant families play different roles in supporting pastoral livelihoods in Borana (Table 4). The average palatability of 252 species is 1.81. Poaceae as the most common family is highly preferred by livestock. All 40 grass species are favored by at least two types of livestock. The family of Burseraceae is also highly preferred. Despite the fact that species in the family of Burseraceae, mostly *Commiphora spp.*, are considered encroaching, they provide valuable forage for sheep, goats, and camels. Fabaceae, as the second largest family, is also valuable as forage, although 7 out of 30 species are consumed by livestock only in dry season. A similar pattern is observed for Asteraceae, which mostly consists of herbs and small shrubs. Malvaceae, Amarathaceae, and Lamiaceae have a wide range of distribution in terms of its preference by livestock. In contrast, the family of Solanaceae is preferred by none of the livestock. Euphorbiaceae, Asparagaceae, Boraginaceae have slightly more pursued than Solanaceae, but their palatability value are less than 1. The rest families have an average value of 1.36, which is lower than the sample average at 1.81. However, they are some small families that are highly palatable, such as Polygonaceae (1), Cyperaceae (3), Commelinaceae (2), Loranthaceae (2), Apiaceae (1), Resedaceae (1), and Santalaceae (1), which are preferred by at least three livestock types.

Table 4. The common families and their degree of preference by livestock

Family	Total	No Value	Low Value	One Prefer	Two Prefer	Three Prefer	All Prefer	Palatability Mean
Poaceae	40	0	0	0	14	23	3	2.73
Fabaceae	30	0	7	0	14	6	3	1.93
Asteraceae	22	0	6	0	7	4	5	2.09
Malvaceae	19	1	2	2	6	5	3	2.16
Acanthaceae	13	0	0	3	7	2	1	2.08
Amaranthaceae	12	1	2	1	3	4	1	1.92
Lamiaceae	11	0	3	2	1	3	2	1.91
Euphorbiaceae	9	3	2	2	1	1	0	0.78
Burseraceae	8	0	0	0	2	6	0	2.75
Solanaceae	7	3	4	0	0	0	0	0.00
Asparagaceae	5	0	4	1	0	0	0	0.20
Boraginaceae	5	1	3	0	1	0	0	0.40
Convolvulaceae	5	2	0	0	1	2	0	1.60
Other families	66	8	21	4	15	16	2	1.36
Total	252	19	54	15	72	72	20	1.81

There are eight families that make up the majority of highly palatable species to the four livestock types (Figure 6). For cattle, the family of Poaceae accounts for over 54% of their palatable species. It is also the largest family in the preference lists of sheep and goats. However, these small ruminants have more other choices, as grasses only account for 19% and 30% for goats' and sheep's highly palatable plant pools respectively. In contrast, camels rarely consider grasses as palatable. Fabaceae contributes to a large number of highly palatable species to camels and goats. Following that are the families of

Asteraceae, Malvaceae, Lamiaceae, Acanthaceae, Burseraceae, and Amaranthaceae, which are all important to camels, sheep, and goats, but are less palatable to cattle.

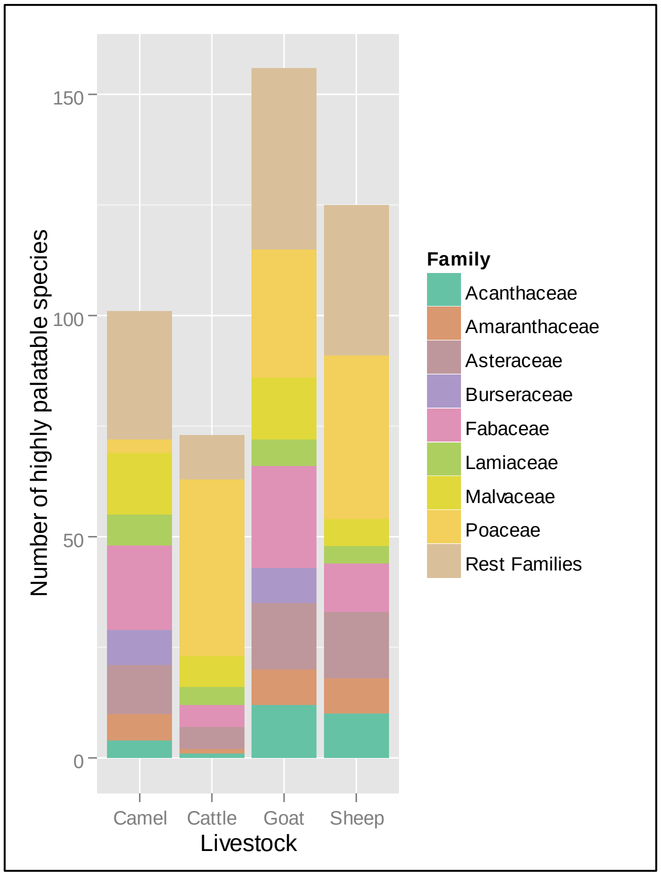

Figure 6. The part of plant diversity that supports pastoral livelihoods in Borana

4.5. Livestock holding portfolios

According to the IBLI survey with 515 households, the average livestock holdings include 12.8 cattle, 4.8 sheep, 11.2 goats, and 1.2 camels in 2014 (Table 5). Of the surveyed households, nearly 95 % were involved in rearing cattle. Cattle is the dominant livestock type, accounting for over 80% of TLU among the surveyed households. According to Cossins & Upton (1987), the Borana rangelands before 1980s were very suited for cattle grazing. Consequently, livestock herding largely revolves around cattle husbandry (Homewood, 2008), which are also culturally important to the Boran pastoralists (Legesse, 2000).

Table 5. Livestock holdings at the household level in 2014

Livestock	Min	Median	Mean	Max	Raised by % of HH	% in TLU
Cattle	0	7	12.8	250	94.8	80.5
Sheep	0	2	4.8	180	67.4	3.0
Goats	0	8	11.2	120	87.2	7.1
Camels	0	0	1.2	20	33.0	9.4
TLU	0	8.9	15.9	265.6	99.0	100

Disease used to be a pervasive constraint for the production of small ruminants and camels before 1980s. This may be a consequence of the relatively moist conditions in places with a semi-arid or sub-humid climate (Coppock, 1994). However, as the climate gets drier (Funk et al., 2008), more and more households have been adding ruminants and camels to their herds. By 2014, 87.2% of households reared goats, contributing to 7.1% of TLU; 67.4% of households raised sheep, which made up 3 % of TLU; and 33% of households reared camels, accounting for 9.4 % of TLU.

Further analysis of livestock portfolio at the household level indicated that pure cattle-herding households only account for only 7% of the entire sample (Table 6), despite that cattle are the most important livestock. Nearly a quarter of households kept all four types of livestock, and another 38% of households reared a combination of cattle, sheep, and goats. Another common livestock portfolio is the combination of cattle and goats, accounting for 16% of sample. An additional 5% of households added camels to the cattle/goat combination. In total, these combinations make up over 83% of households, indicating the majority have been diversifying their livestock portfolios in response to changing climate and ongoing bush encroachment process.

Table 6. Types of livestock kept by pastoralists (n = 515)

Cattle	Sheep	Goat	Camel	Proportion of households
X	X	X	–	38.4%
X	X	X	X	24.1%
X	–	X	–	15.7%
X	–	–	–	7.0%
X	–	X	X	5.2%
–	–	X	–	1.7%
X	X	–	–	1.7%
X	X	–	X	1.6%
–	X	X	–	1.2%
–	–	–	–	1.0%
X	–	–	X	1.0%
–	–	X	X	0.8%
–	X	–	–	0.2%
–	–	–	X	0.2%
–	X	–	X	0.2%
–	X	X	X	0.0%

Note: X indicates household has this type of livestock; – indicates household does not have this type of livestock.

I compared the livestock portfolio data with that of 1982, which were collected in eight major livestock markets in Borana (Coppock, 1994). I used such data for comparison because it covered both the highland and lowland areas within the Borana Zone. Household level livestock holdings data collected in early 1980s were confined to specific areas of Borana, thus unrepresentative of the broader picture. I converted the number of livestock into TLU. The comparison showed the change in proportions of each livestock type. Over the past three decades, pastoralists have been replacing cattle with the other three types of livestock (Table 7). Chi-sq test suggested the portfolio change is significant (χ^2 = 7.22, p-value = 0.065). The greatest increase happened to camels, which grew from less than 2% to nearly 10% in pastoralists' herds in terms of TLU. The second important increase is from goats, rising from 4.7% to 7.1%. The proportion of sheep also grew, although to a lesser extent. This might be because sheep share similar preference to forage plants with cattle in Borana. Increase in camels, goats, and sheep, consequently, led to a decrease in the proportion of cattle holdings from 92.3% to 80.5%.

Table 7. Livestock portfolios by TLU in 1982 and 2014

Year	Cattle	Sheep	Goat	Camel
1982	92.3%	1.2%	4.7%	1.8%
2014	80.5%	3.0%	7.1%	9.4%

1982 data source: Coppock (1994, p.113)

4.6. Desirability of woody forage plant species

Woody plants are generally considered less useful in livestock production. However, the results suggested that certain woody species are crucial to livestock. In the focus group discussions with pastoralists regarding overall desirability of woody forage plants, I ended up with a list of 56 species. The most common desirable plants are *Grewia villosa*, *G. tembensis*, *A. tortilis*, *G. lilacina*, *Aspilia mossambicensis*. The most common undesirable plants are *A. mellifera*, *A. senegal*, *Alternanthera sessilis*, *Solanum somalense*, *A. oerfota*, and *A. reficiens*. It is worth pointing out that pastoralists suggested that species that were undesirable in some localities might be useful forage in other areas. Thus, the same species could be categorized as either desirable or undesirable. For example, *Commiphora africana* was considered undesirable in the highlands such as Siqu, but desirable in the lowland area such as Taka Bulti.

I conducted a linear regression to investigate how palatability to each livestock type contributes to its overall perception of desirability by pastoralists. The results showed that usefulness to cattle is the strongest factor that determines pastoralists' overall rating of plant palatability (Table 8). Whether a plant is useful for cattle grazing positively affects pastoralists' perception on the plants. Camel also determines the overall perception, although to a less significant extent. Such results matched pastoralists' livestock portfolio, in which camels make up the second largest proportion of TLU. Whether a plant is palatable to sheep or goats played insignificant role in pastoralists' perception. The overall regression results echoed with the significance of cattle in supporting livelihoods of Boran pastoralists as shown above.

Table 8. Estimation between perceived overall desirability and palatability to livestock types

Livestock	Estimate	Std. Error
Intercept	-0.773**	0.363
Cattle	0.415**	0.165
Sheep	-0.0002	0.146
Goat	-0.227	0.247
Camel	0.417*	0.217

** indicates significant at 0.05 level; * indicates significant at 0.1 level

4.7. Bush encroachment perceived by pastoralists

I collected a list of 29 species from five focus group discussions on bush encroachment, in which each group reported the top ten encroaching species. Six out of the top ten encroachers were in the same genus of *Acacia* (Table 9). Pastoralists unanimously agreed that *A. mellifera* is the top encroacher, which showed high encroachment index and was mentioned in all five focus group discussions. *A. oerfota* had the second highest index and times of mention. *A. reficiens*, *C. africana*, and *S. somalense* were mentioned three times, but pastoralists tended to assign a higher encroachment index to *A. reficiens* than the other two, due to its strong suppression to the growth of herbaceous plants and low value to support cattle grazing.

Table 9. The top encroaching species identified by pastoralists

Species	Encroachment Index	Times Mentioned
Acacia mellifera	4.7	5
Acacia oerfota	3	4
Acacia reficiens	2.5	3
Acacia senegal	1.7	2
Commiphora africana	1.6	3
Osyris quadripartita	1.4	2
Acacia horrida	1.2	2
Acacia seyal	1	2
Sansevieria ehrenbergii	0.8	2
Solanum somalense	0.8	3

Given the above pattern, I hypothesized that encroachment index is correlated with pastoralists subjective perception of plant's overall desirability. Specifically, plants with low desirability tended to be associated with a high encroachment index. I conducted simple linear regression to test the hypothesis. The result showed a significant negative correlation between desirability and encroachment index (Figure 7). Despite the fact that certain amount of encroaching species are somehow palatable to livestock, pastoralists' perception of these encroaching species were quite negative. This is because the establishment and proliferation of these species strongly suppress the growth of herbs in the understory, which are more important to support a herding system dominated by cattle.

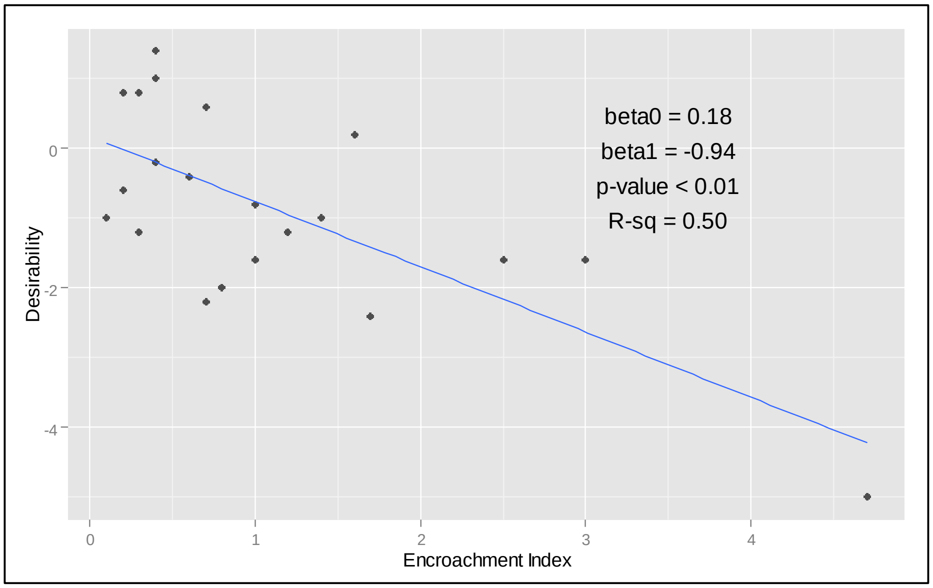

Figure 7. The relationship between encroaching index and usefulness as a forage species

5. Discussion

5.1. Dynamics of bush encroachment and implications on livestock production

Given the differences in preference to forage species as revealed above, the ongoing bush encroachment process has different implications on the production of cattle, sheep, goats and camels (Figure 8). For cattle, 17 out of the 29 encroaching species are entirely inconsumable, and 9 are only eaten in the dry season, which make the violin plot highly skewed toward the lower end of palatability. However, the bush encroachment process does not necessarily translate into hopeless situation for the entire livestock herding sector in Borana. This is because among the encroaching 29 species, there are 10 highly palatable and 9 barely palatable species for sheep. Goats can even get better adapted to the ongoing bush encroachment process. There are 17 species that are highly palatable to them, making the violin plot skewed toward the higher end of preference. For camels, there are also 13 encroaching palatable species, and another 12 barely palatable species for dry season consumption, which can potentially allow them to adapt to the bush encroachment process smoothly. Therefore, I hypothesized that the consequence of bush encroachment is significant reduction in cattle's palatability overall, but its impact on the production of sheep, goats and camels is insignificant.

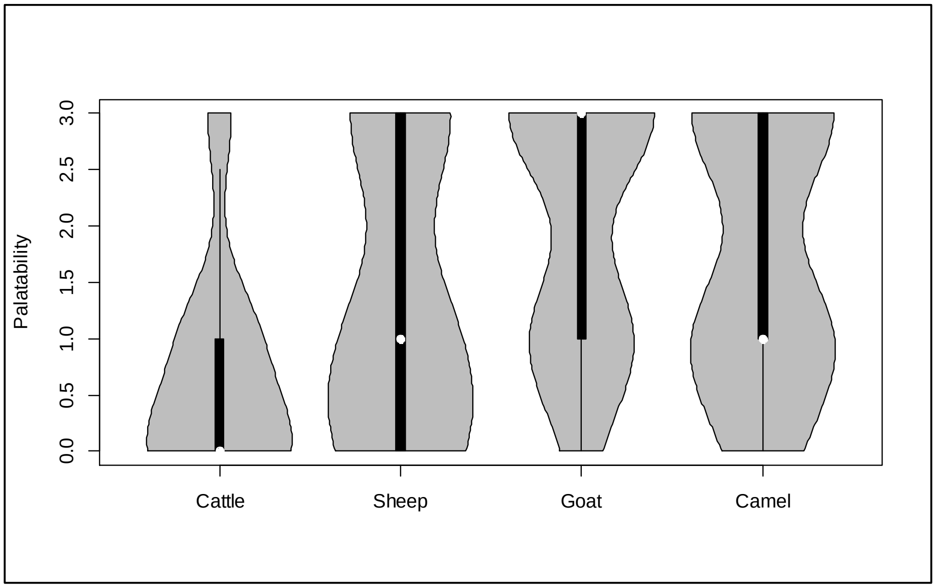

Figure 8. The palatability of encroaching species to livestock

I tested the above hypothesis through a simulation approach. Bush encroachment is a dynamic process in which woody plants replace the herbaceous. It is challenging to collect empirical data to capture the changes in vegetation composition on the Borana rangelands. However, simulation can potentially address this challenge, if pastoralists' perception of vegetation shifts and forage plant diversity on the rangelands can be sufficiently incorporated.

The simulation results supported the hypothesis that plants' overall palatability decreases as a result of bush encroachment (Figure 9). Simple linear regression between average palatability to cattle and percentage of encroachment indicated that the slope rate is significantly negative for all 100 simulations. In addition, under any of the current and projected scenarios of bush encroachment, cattle exhibit the lowest average palatability compared to all other three livestock types. In fact, cattle will be the most negatively affected livestock when woody plants replace herbs, as their average palatability reduction is 0.58 (Figure 10), almost a 50% decrease from the current state at 1.23.

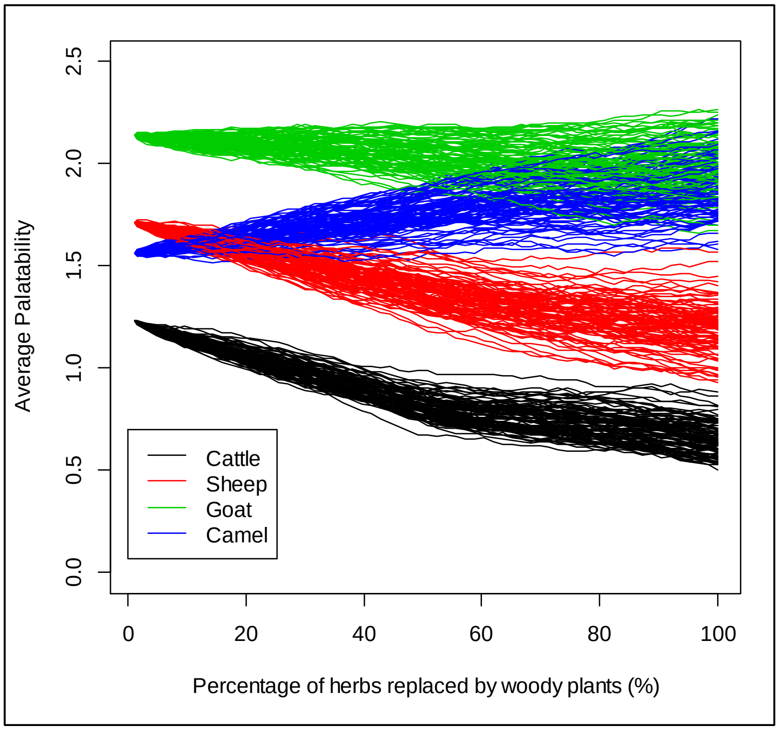

Figure 9. Simulated bush encroachment process and corresponding average palatability of plants to cattle, sheep, goats, and camels

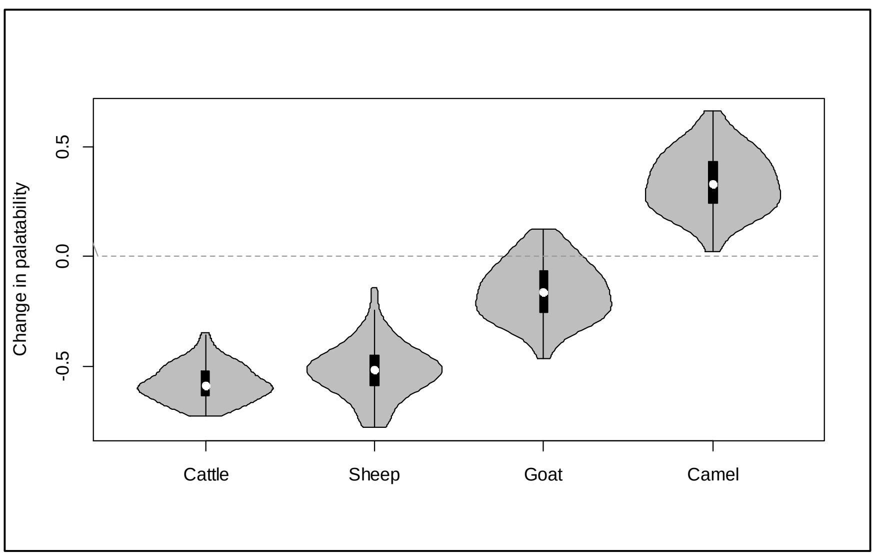

Figure 10. Change in palatability when all herbs are replaced by woody plants

However, the second half of hypothesis was not supported by the simulation results. Similar to cattle, sheep will also be negatively affected (Figure 9 and 10). Although sheep can consume a large proportion of the encroaching species identified by pastoralists, increase in woody species availability cannot compensate the loss of the highly palatable herbs. However, sheep's tolerance to certain woody plant species makes them less vulnerable compared to cattle. Average change in palatability for sheep is 0.5, which is a 30% reduction.

The impact of bush encroachment on goats depends on the scenario (Figure 9 and 10). On average, palatability for goats decreases from 2.14 to 1.98, which is a 7% reduction. Under most scenarios, goats will also be negatively affected, but in 15% of cases goats can be better-off. Such result further confirmed that goats are generalists rather than pure browsers. Although goats are well-adapted to woody plants, the ultimate impact of bush encroachment on goat production depends on which woody plants will dominate the rangelands. Despite the uncertainty for goats, they still enjoy the highest average palatability compared to all other three types of livestock, when herbs are all replaced by woody plants.

Camels are the only livestock type that will be better-off as rangelands get more encroached with woody plants. Plants' average palatability will grow from 1.56 to 1.9 as the bushes encroach, which is a 22% increase (Figure 9 and 10). Although camels' starting point palatability is 26% less than goats, as the woody plants proliferate throughout the rangelands and replace the herbs, camels gradually close the gap to 4%. Under 14 simulated scenarios, camels end up with even greater palatability than goats. As a pure browser, reduction in herbaceous plants has minimal impact on them, while the increasing woody species will certainly contributes to their diet.

5.2. Livestock portfolio change as adaptation to bush encroachment

As shown in the results section, pastoralists have been actively adapting to the process of bush encroachment by changing their livestock holding portfolio. Pastoralists have been reducing their reliance on cattle by adding more camels, goats and sheep to their herds since 1982. Pastoralists' choice of a certain livestock holding portfolio is the key to ensure their food security and pastoral system resilience.

As a unique group of people whose livelihoods depend on forage plants, pastoralists are always the first to perceive any changes in vegetation shifts. Through long-time observation and practice, they have accumulated a rich body of knowledge on forage plants. As they perceive the feedback from environment that woody plants are replacing herbaceous plants, transition into a less cattle-dominated livestock portfolio is an active adaptation to such vegetation shifts.

In order to examine how change in livestock holding portfolio contributes to pastoralists' overall utilization of forage resources, I estimated the change in palatability according to three different combinations of livestock types given the simulated bush encroachment process. The first combination is the scenario in 1982, in which the TLU proportion of cattle/sheep/goats/camels is 92.3: 1.2: 4.7: 1.8. The second combination is the scenario in 2014, with a TLU proportion of 80.5: 3.0: 7.1: 9.4. The third combination includes equal amount of TLU distributed in the four livestock types. As most pastoralists have been adding more small ruminants and camels to their herds, the third scenario could represent one potential livestock portfolio in the future.

The results indicated that bush encroachment has negative impact on all three scenarios (Figure 11), but the degrees of impact are significantly different from each other (three pairwise t-tests p-value < 0.01). If pastoralists collectively maintain a livestock portfolio as they did in 1982, the negative impact of bush encroachment will be 0.55 on average, when herbs are replaced by woody plants. However, shifting the portfolio into the state of 2014 significantly reduced the negative impact. Given the current portfolio, the reduction in palatability is 0.47, which is 15% less than that of 1982. If pastoralists choose to put an equal amount of cattle, sheep, goats, and camels in their herds in the future, the impact of bush encroachment will be 0.23, which is 59% less than the scenario in 1982 and 51% less than the scenario in 2014.

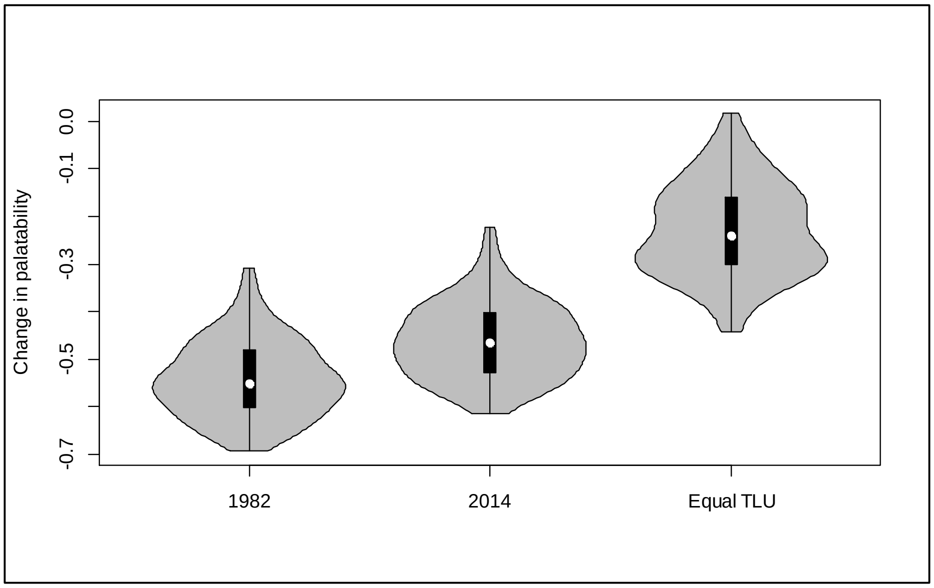

Figure 11. Three scenarios livestock holding portfolios and their implication on overall forage plant utilization

Through changing livestock portfolio, pastoralists can get better adapted to the bush encroachment process. Such flexibility to choose what livestock to put in their herds represents a unique way for pastoralists to exercise their food sovereignty (Kassam et al., 2010). In the pastoral context, food sovereignty is based on ethnobotanical knowledge of palatability of plants, as well as the ability to perceive the change in the availability of foraging plants. At the core of food sovereignty is the capacity to adapt to such changes in order to meet the nutritious demands of livestock and consequently ensure food security. Although the overall impact of bush encroachment on livestock production is still negative, the adverse impact could be mitigated by changing livestock portfolio. As shown above, over the past three decades, a shift in livestock portfolio resulted in 6% increase of overall palatability to livestock, given the current forage plant availability. As the bush encroachment process proceeds, the shifted livestock portfolio can make a greater difference to mitigate palatability loss, from 6% to 15%.

The broader resilience literature has also pointed out that resilience does not mean absence of change (Davies et al., 2015). Instead, the coupled socio-ecological pastoral system, if resilient, constantly readapts itself to retain their basic functions. In fact, resilience is generally considered an attribute of the self-adapting socio-ecological system. The conventional definition of resilience emphasizes two capacities of the system, which are to 1) absorb disturbance and maintain the state of the system, and 2) build and increase adaptation through self-organization (Carpenter et al., 2001; Folke, 2006; Holling, 1973).

The research findings in this chapter provided unique insight in terms of how resilience can be operationalized in a pastoral setting. Despite of holding a deeply-rooted cultural preference to cattle, the Boran pastoralists have been reducing reliance on them, exhibiting a clear capacity to create a fundamentally new system when underlying ecological structures make the existing herding practices untenable. The capacity to adapt to encroaching woody species through changing livestock portfolio could be an important surrogate and a quantifiable proxy of resilience (Bennett et al., 2005). The research findings echo with a broader call to operationalize resilience as stochastic dynamics of individual and collective human well-being in front of myriad stressors and shocks (Barrett & Constas, 2014).

6. Conclusions

Pastoralists in Borana, Ethiopia hold a rich body of ethnobotanical knowledge on forage plant species. In my study of 252 plant species, pastoralists were able to name over 85% of them, and articulated their degree of palatability to cattle, sheep, goats, and camels. These plants play different roles in livestock production. In general, cattle, as pure grazers, are more selective in foraging, and strongly prefer herbaceous plants. Sheep also prefer herbs, but are more tolerant to woody plants than cattle. Goats are better considered generalists than pure browsers in the Borana context, because only 8% of species are unpalatable to them. Camels are browsers, showing strong preference to woody than herbaceous plants. Based on palatability to livestock, the plants are classified into five clusters with distinct functions in livestock production.

Pastoralists' ethnobotanical knowledge serves as the basis for adaptation to the ongoing bush encroachment process. Based on pastoralists' knowledge on forage species, the simulation of the bush encroachment process indicated that it will have most negative impact on cattle, and sheep to a less extent. Camel will be better off as woody plants replace the herbs. Goats are the only species that is less sensitive to vegetation shifts as they are generalists rather than pure browsers. Although encroaching woody plant species are not preferred as much as herbaceous, especially grass species, they could play a crucial role in supporting pastoral livelihoods due to their palatability to camels and goats.

Pastoralists have been changing their livestock portfolio in the past three decades. Although cattle is still the dominant livestock type, they are adding camels and small ruminants in their herds. Pure cattle-herding households only account for only 7% of the entire sample. Such active adaptation is a clear indicator of resilience in the pastoral system. Resilience does not mean absence of change. In fact, absorbing disturbance such as bush encroachment and maintaining stable livestock production through self-organization is the key to resilience. Despite of holding a deeply-rooted cultural preference to cattle, the Boran pastoralists have been reducing reliance on them to pursue other livestock types that are better adapted to current rangeland conditions.

Future research efforts need to focus on the relative abundance of the identified 252 forage species. Intensive plant surveys should be conducted to derive an estimation of edible biomass of forage plants. With such information, we can better quantify the palatability to different livestock portfolios, and identify an ideal combination of livestock that can efficiently make use of the given forage resources throughout the landscape. Of equal importance is the spatio-temporal distribution of forage species, which is crucial to design rangeland management and utilization strategies across the heterogeneous tropical rangelands.

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CHAPTER 8 CONCLUSION: OPERATIONALIZATION OF PASTORAL RESILIENCE IN BORANA, ETHIOPIA AND XINJIANG, CHINA

1. Introduction

My graduate research, including MS and PhD, is dedicated to the study of pastoralism. Five years is a very short period to fully understand the complexity within open grazing systems; however, I was fortunate enough to work in the two most extensive rangeland systems in the world – the East African savanna and the Central Asian steppe. Eight months in southern Ethiopia with Boran pastoralists and two months in northwestern China with Kazak pastoralists allowed me to directly observe how pastoralists make their livelihoods in those regions, and discuss with them in terms of how to maintain sustainability and resilience at both household and ecosystem levels given persistent and emerging socio-ecological challenges.

Built on my empirical findings in East Africa and Central Asia, I aim to explore the general implications on pastoral resilience in the conclusion chapter. Pastoralists' unique resource-use strategies demonstrated clues about how resilience can be operationalized in places where resource distribution is highly variable in space and time. Despite tremendous socio-ecological challenges, pastoralism remains to be a viable livelihood strategy in the twenty-first century. Comparisons between these two pastoral systems suggested that the inherent characteristics of pastoralism contributes to resilience at both household and system levels. In this chapter, I first compare the similarities and differences between the East African and Central Asian pastoral systems. Then I investigate pastoralists' subjective interpretation of resilience. Building on their definition, I discuss the surrogate indicators of resilience in both contexts, which included mobility, land use pattern, and livelihood diversification. At the end, I point out my future research directions on pastoralism.

2. Socio-Ecological Settings

The empirical research in my graduate studies was conducted in the Borana Plateau in southern Ethiopia and the Altay Mountains in Xinjiang, China, which were representative of open grazing systems in the savanna of East Africa and the steppe of Central Asia respectively (Figure 1). The similarities and differences of these two sites allowed me to compare and contrast how resilience was manifested and operationalized in pastoral contexts. Extensive herding was practiced in both sites to make use of patches of rangelands situated in different locations. In particular, both Boran and Kazak pastoralists adopted camp relocation as a key strategy to ensure forage intake and rangeland sustainability.

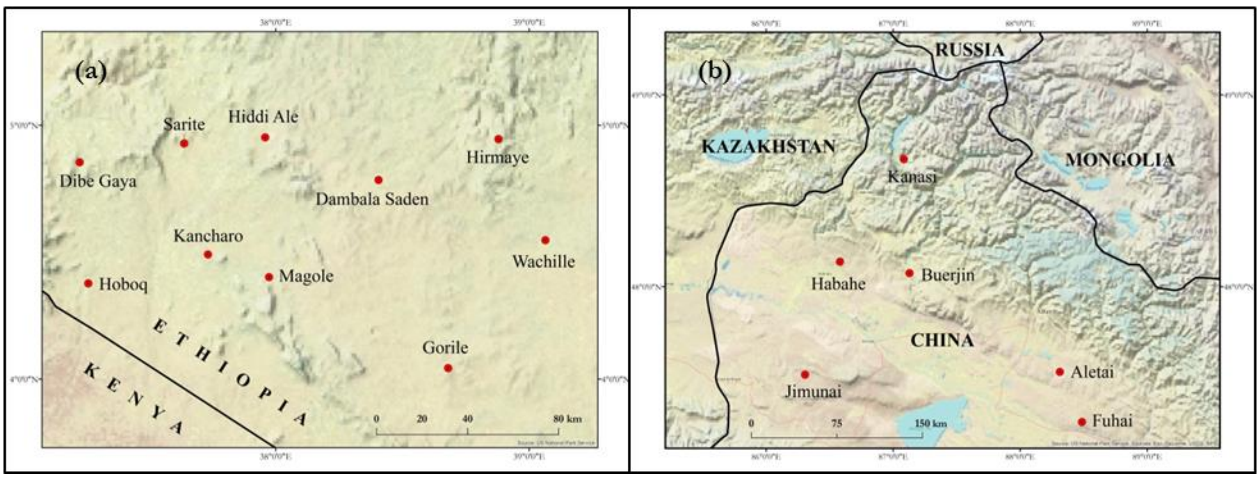

Figure 1. Study sites in Borana, Ethiopia and Altay, Xinjiang, China. Red circles indicate the pastoral communities engaged in my research.

Pastoralists in Borana and Altay were both perceived as ethnic minority groups who made their livelihoods in the most remote regions of their countries. Consequently, these pastoral communities have been subject to substantial external interventions over the past decades. In Ethiopia, the government and NGOs pushed for the sedentarization of Boran pastoralists by implementing development projects such as crop cultivation, water facility construction, rangeland fencing, and cash for labor (Helland, 1994; Homann et al., 2008). Similarly, Kazak pastoralists were also subject to government intervention as they went through the era of communes (1960-1980) and subsequent decollectivization (mid-1980). Convinced by the destructive impacts of mobile pastoralism to rangeland ecosystem (Harris, 2010), the central government has recently decided to transform the “backward” livelihoods by implementing a new series of sedentarization and development projects (Xinhua, 2011).

At the same time, tremendous differences exist between these two pastoral systems. Although both sites are characterized as being arid or semi-arid, the Borana Zone (3.5-5.5° N) is located in a tropical setting in the southernmost of Ethiopia, while the Altay District (46-49° N) is situated in the cold temperate zone of the Earth. The steppe rangeland in Altay is dominated by short grass (Zhang, 1992), while the savanna in Borana is increasingly encroached by woody plants that suppress the growth of herbaceous species (Angassa, 2012). Given the climate and forage characteristics, the Kazak pastoralists in Altay practiced long-distance seasonal migration between the Gobi desert and mountain meadows, while the Boran pastoralists herded livestock in relatively smaller area and relocated between different patches of rangelands within the community herding extent.

3. Pastoralists’ Definition of Resilience

Both Boran and Kazak pastoralists defined resilience as the maintenance of decent living standards throughout time. Pastoralists generally believed that decent livelihoods were largely achieved through keeping a viable number of livestock at the household level. Meanwhile, being mobile made it possible to cope with temporary environmental stresses and disturbances in certain geographic locations, and seek forage and water elsewhere. Accordingly, both pastoral societies have developed complex land use patterns, which allowed for sufficient forage intake for livestock on one hand, and ensured rangeland sustainability on the other hand. Furthermore, both Boran and Kazak pastoralists referred to the diversification of their livelihood portfolio as a crucial approach to smooth household income given the changing socio-ecological context. However, it is worth pointing out that although herd size was not mentioned by pastoralists, it is indeed the basis of pastoralism. It is assumed that the operationalization of pastoral resilience is based on a viable number of livestock owned by individual households.

Difference in subjective definition of resilience in these two pastoral societies largely stemmed from their unique ecological settings. In Borana, the interpretation of resilience was built on the heterogeneity of spatio-temporal resource distribution on the rangelands. For one, the mosaics of different rangeland types at a fine spatial scale necessitated micro-mobility to make use of these resources effectively. For another, bimodal distribution of precipitation resulted in two rain and two dry seasons within a year, which made Boran pastoralists adopt macro-mobility (seasonal migration at a broader scale) as a response to uneven rainfall distribution. A combination of micro- and macro-scales mobility strategies allowed pastoralists to keep track of greener pastures, and they were thus able to keep a viable number of livestock in a rangeland ecosystem constantly in disequilibrium (Behnke, Scoones, & Kerven, 1993).

In addition, Boran pastoralists also emphasized the importance of effective rangeland zoning and management to achieve resilience. Rangelands were traditionally divided into *worra* lands (close to settlement) for wet season grazing and *forra* lands (distant from settlement) for dry season grazing (Homewood, 2008). However, as pastoralists were getting more sedentarized, such a divide became less common. Since pastoralists in certain communities stopped practicing *forra* herding, they simply divided their *worra* lands into different patches for wet and dry season grazing separately. In addition, after the extreme drought that struck the entire Borana Zone in 2011, the pastoral communities started to design new strategies for managing rangelands. The most common approach was to fence certain parts of rangelands as reserves, and set up specific rules regarding when these reserves can be accessed throughout the year.

In contrast, the Kazak pastoralists' definition of resilience focused on following the plant phenology and climate pattern along the gradient from Gobi desert to alpine meadow. The abundant forage in alpine meadows attracted pastoralists to move up into the Altay Mountains in the summer, while heavy snowstorms drove them down to the Gobi desert in winter. Therefore, the Kazak pastoralists' operationalization of resilience was manifested in the directional and vertical movement along a corridor up to 300 km. In addition, the rangelands in Altay were largely assigned to individual households during decollectivization in the 1980s, although fences were not set up to delineate the boundaries. Consequently, each household had their own summer pasture, mid-pasture, lambing pasture and winter grazing lands, which served different ecological functions for livestock herding. However, the boundaries of these pastures were fuzzy, and sharing of grazing lands was common among Kazak pastoralists, especially under drought or snowstorm.

As these two study sites were challenged by harsh environmental conditions and faced with external development interventions, both Boran and Kazak pastoralists started to engage in non-pastoral strategies to complement household income in case of poor livestock production. In fact, non-pastoral livelihoods have become a significant part of household income in Kazak. As in 2011, over 31% of household income was from crop cultivation, wage labor, hired herding, government subsidy and small business (Liao et al., 2015). Pastoralists in Borana also emphasized the importance of non-pastoral livelihoods to smooth household income, and their practice of diversification was commonly reported in literature (Tache & Oba, 2010; Tache & Sjaastad, 2010).

Overall, pastoralists' definition of resilience largely focused on how to maintain household welfare given the socio-environmental stresses in ASAL. Although resilience in both pastoral contexts was manifested in maintaining a viable number of livestock through flexible access to pastures at multiple locations, pastoralists also highlighted the importance of diverse livelihood portfolios. Such a definition echoed with the broader theory of resilience. On one hand, mobility and a well-designed land use pattern allowed pastoralists to absorb the impact of disturbances such as drought and snowstorm and maintain their herd size. On the other hand, flexibility in rangeland management and freedom to diversify into non-pastoral livelihoods reflected the pastoralists' capacity to build and increase adaptation through self-organization.

4. Surrogate Indicators of Pastoral Resilience

Various factors have been proposed as indictors of resilience, which included governance, civic capacity, natural resources, economic resources, and knowledge sharing (Walsh-Dilley et al., 2013). Specific to the pastoral system, indicators such as mobility, communal pooling, diversification, storage, and reciprocity have been applied to analyze resilience (Fernández-Giménez et al., 2015; Upton, 2012). This study chose three key factors – mobility, land use pattern and livelihood diversification – as indicators of pastoral resilience, which were the most frequently mentioned surrogates of resilience by Boran and Kazak pastoralists. These three indicators not only characterized resilience in the study areas, but also contained the essence of other factors. For instance, mobility and land use patterns could suggest whether reciprocity and communal pooling was practiced, because pastoralists commonly sought help from neighbors who were willing to share pastures during drought. Land use pattern also indicated the concept of storage, as hayfields were designated for winter use in Altay, and community fenced rangeland reserves were set aside for grazing in dry season in Borana. Due to the above reasons, it is considered that mobility, land use pattern and livelihood diversification were reasonable surrogate indicators of pastoral resilience in both Borana and Altay.

4.1. Mobility

Mobility is the most important indicator of pastoral resilience because it allowed pastoralists to chase greener pastures and mitigate environmental stresses. The role of mobility has long been recognized in terms of its contribution to pastoral resilience (Fratkin, 1997). Pastoralists generally moved their livestock to temporary camps that were closer to areas of underutilized pastures during times of stress (Moritz et al., 2013). Both Boran and Kazak pastoralists believed that greater mobility translated into greater resilience, as a viable number of livestock stock could only be maintained by a household if they were allowed to be mobile.

The mobility in Borana was manifested in two scales. At a broader scale, seasonal migration was practiced between wet and dry season grazing areas. Wet season grazing was organized around their settlement village. Pastoralists took their animals out for grazing during the day, and brought them back to the corral in the evening. Dry season grazing involved the use of multiple satellite camps, which were set up in places that were dozens of kilometers away from the settlements. Pastoralists herded animals at each satellite camp for several weeks. As the forage and surface water started to diminish, they moved to a satellite camp location to herd their animals. Such camp relocations could last for months until the next rain season came, when they took animals back to settlements. This strategy was practiced in 6 out of 10 pastoral communities in Borana, including Hoboq, Wachille, Gorile, Kancharo, Magole, and Dibe Gaya. Among these six communities, pastoralists in Wachille and Hoboq were especially mobile, and heavily relied on satellite camp-based herding. Their livestock spent up to eight months out of a year at multiple satellite camps.

Given increasing human population and government sedentarization policies, the traditional extensive herding pattern has been gradually replaced by restricted grazing around settlements where herding started and ended on a daily basis. In such cases, pastoralists practiced another form of rotational grazing within their constrained herding extent. In the wet season, animals were herded on rangelands close to villages, in which the herding loop length was generally less than 12 km. As the dry season came and nearby forage was diminished, pastoralists took their animals to more distant locations for grazing, and their daily herding loop length could reach up to 30 km. Such a herding strategy was observed in Dambala Saden, Sarite, Hirmaye and Hiddi Ale, which were closer to Yabello, the administrative center of the Borana Zone. In these sites, pastoralists have established dense settlements and fenced crop fields in clusters around the villages, resulting in limited migration corridors towards the major grazing sites.

In contrast to Boran pastoralists whose mobility patterns were either nomadic or restricted, the spatial migration pattern of Kazak pastoralists was transhumant featured by directional and vertical movement. This mobility pattern was a unique adaptation to their ecological endowments. Pastoralists generally moved along a southwest-northeast corridor after snowmelt, and followed the same path back to their overwintering villages on an annual basis. Their seasonal migration distance covered hundreds of kilometers. Although rigorous, conducting such long-distance migration redistributed grazing pressure.

Absence of grazing in winter and spring pastures during the summertime allowed forage plants to regrow, which could support animal consumption when they returned to these locations for a second time in the year. Summer pastures were also only used in a seasonal window between late June and early September. Resting these alpine meadows in both early and late growing seasons enabled vegetation to recover.

There was less variability in the overall migration pattern of Kazak pastoralists than that of the Boran. The Kazaks generally followed fixed migration routes each year, because their pastures were assigned to individual households in multiple locations. Consequently, the Kazak mobility pattern was more seasonally predictable. In winter, most households stayed in the lowland along the Ertix River valley, with an average elevation around 500 m. In spring, pastoralists started to migrate towards the mountains in the northeast. Along the migration route towards the mountains, they usually traveled a few days, and then camped in one location for several weeks in their designated herding areas. In summer, they arrived in the mountains to enjoy fresh alpine meadows. In fall, pastoralists followed the same route back to overwintering villages, but with fewer stops along the way (Liao et al., 2014). Even when drought hit the system, pastoralists still followed such a broad migration schedule. However, they could increase camp relocation frequency and negotiate with their neighbors to access their grazing lands. Most participants in my discussion indicated they were willing to accept visitors herding on their lands, knowing that they might need to rely on such reciprocity to survive the next drought or snowstorm.

4.2. Land use pattern

In order to facilitate rotational grazing and ensure rangeland system sustainability, pastoralists have developed complex land use patterns. To them, a major concern is flexible access to different pastures at times of need, rather than fixed control of a specific piece of land with varying forage productivity. Both Boran and Kazak pastoralists set specific rules on land use according to their unique ecological contexts.

Boran pastoralists' land use pattern largely followed the bimodal distribution of annual precipitation for efficient utilization of diverse rangelands (Figure 2). Traditionally, pastoralists practiced *worra* herding around their base camps during the wet seasons, which were from March to May and from October to December. As the dry season approached, pastoralists took their animals to graze the under-utilized forages away from home. This was known as *forra* herding, which usually took place from January to February and from June to September. In communal rangelands, access to grazing lands was largely controlled by the availability of surface water. The lack of water facilities in *worra* pasture in the dry season forced pastoralists to take their animals far away from settlements.

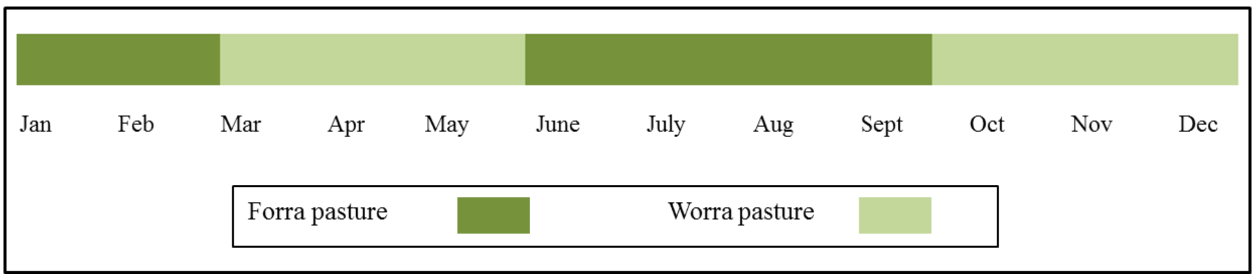

Figure 2. Rangeland types and rotational use patterns in Borana, Ethiopia

Worra pasture could be further divided into *qaye*, *kalo*, and *mata tika* to achieve greater degree of rotational grazing. *Qaye* was the area close to villages, usually within a 1 km radius. Due to high density of livestock presence in this area, forage was depleted soon after the rain. *Kalo* was the rangeland with fences, which served as a reserve for livestock consumption in the dry season. In certain communities, *kalo* was only reserved for calves in the dry season. *Mata tika* was the major herding area; however, the exact distance from settlements largely depends on the settlement pattern. In the densely settle study sites such as Dambala Saden and Sarite, *mata tika* could be up to 5 km from base camps. This was because the lands around the settlements were claimed for other uses such as crop cultivation and rangeland reserves. Therefore, pastoralists had to travel a longer distance to reach *mata tika* on a daily basis. In contrast, *mata tika* for pastoralists in the less sedentarized communities, such as Gorile and Wachille, was typically within 1 km from settlements.

However, broad-scale seasonal migration was changing, as pastoralists got sedentarized and claimed patches of rangelands as private crop fields or grazing reserves, leaving the grazing system more fragmented. As a result, some pastoralists gave up *forra* herding, and stayed around their base camp throughout the year. This translated to highly restricted movement between base camp and major herding areas. Even though, certain areas of *mata tika* were designated as wet season herding area, while the rest were typically used in the dry season. Such rangeland zoning practices reflected a unique adaptation to resolve the conflict between dense settlement and livestock herding.

In contrast to Boran pastoralists' zoning of rangelands for different purposes of use at a finer scale, Kazak pastoralists' herding extents were spread-out along a corridor extending up to 300 km. These rangelands, including winter pasture, lambing pasture, mid-pasture, and summer pasture, served different functions in pastoralists' annual herding activities, moving from Gobi desert to alpine meadow (Figure 3). By matching the zoning of rangelands with their associated plant phenology, pastoralists enhanced the resilience of both livestock herding and rangeland ecosystem.

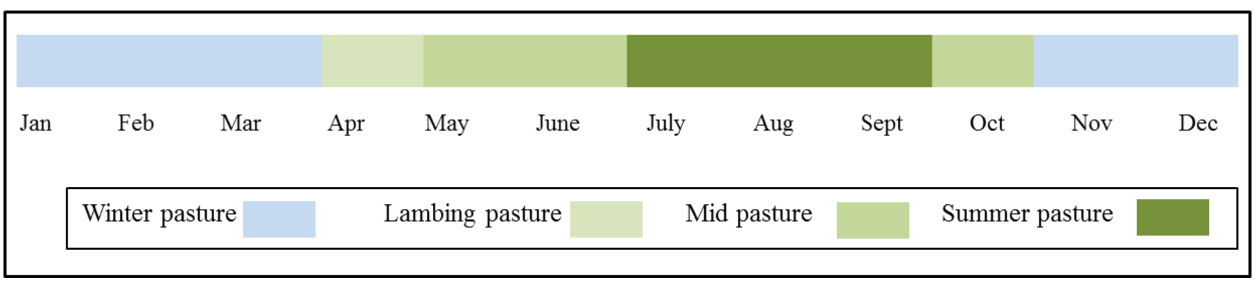

Figure 3. Temporal pasture land use patterns in Altay, Xinjiang, China

In Altay, winter pasture was generally situated in a transitional area between the Gobi desert and the Altay Mountain Range, with an average elevation of 500 m. The landscape was mainly desert fodder land. This place was less threatened by snowstorms in winter compared to the mountains in the north, and provided minimal water and fodder that was scarce farther south in the desert. There were two kinds of transitional pastures. One was called lambing-pasture, which was used for lambing and calving after snowmelt. The other was called mid-pasture, which served as the second transitional zone before they finally reached summer pasture. Vegetation in this area was mainly short and sparse grasses. In fall, pastoralists returned to mid-pastures after leaving their summer pastures. After a whole growing season, the vegetation could support another two months' consumption there before they returned to winter villages. The vegetation type in the summer pastures was mainly alpine meadows, which are the most productive pasture lands of all. This was the major site for pastoralists to fatten their herds before heading them back to overwintering villages.

4.3. Livelihood diversification

The practice of non-pastoral livelihoods was often brought up in my discussion with pastoralists. Both Boran and Kazak herders believed that engaging in non-pastoral income-generating activities provided more options given increasing difficulty of livestock herding. In pastoral contexts where human population increased too fast to allow each household to maintain a viable number of livestock, diversification into other livelihoods seemed inevitable. Under certain circumstances, diversification is crucial to smooth household consumption and income flow (Ellis, 2000). However, the Boran and Kazak pastoralists debated among themselves regarding the contribution of livelihood diversification to household welfare and beyond. In fact, livelihood diversification in the pastoral contexts has always been controversial. This was not only because the ecological endowments made non-pastoral livelihoods unsuitable, but also because pastoralists held less advantage in practicing non-pastoral livelihoods than their sedentary neighbors.

In Borana, the most commonly practiced non-pastoral livelihood was crop cultivation. Nine out of ten communities were growing teff, maize, and sorghum in their fenced crop fields. In reality, none of the households used the whole fenced area as a crop field. Only half of fenced land was used to grow crops. The rest was left as reserved rangeland for individual households. Without livestock grazing inside the fenced lands, the forage plants could grow very well, thus providing valuable support in the dry season. However, lands outside of fences were almost barren. Such difference in land cover made some pastoralists reach the conclusion that the only approach to stop overgrazing and degradation is to fence more rangelands.

In addition to crop cultivation, Boran pastoralists established micro-finance cooperatives to work on saving and credit. The idea was to identify a group of pastoralists who were interested in doing business and willing to contribute a certain amount of money to the group. Anyone in the community could join the group, but that person must have a good reputation. The group typically conducted small trading using this money. However, any member could borrow money from the group and do his/her own business, as long as he/she paid back the loan including the interest rate. There were different forms of saving and credit in practice. The most common activity was to buy livestock in the community and sell them in regional markets. Some cooperatives started a grocery store at the community center. Pastoralists believed that having the extra labor engage in these non-pastoral livelihoods was a crucial supplement to household welfare.

The Kazaks were also diversifying their livelihood portfolio. The most commonly mentioned non-pastoral source of income in Altay was crop cultivation. According to my research findings, about 30% of households had crop fields. Popular crops cultivated in Altay were the cash crops such as beans and melons. Pastoralists there indicated that they adjusted their cultivated crops each year as an adaptation to changing prices in the regional markets.

In addition, Kazak pastoralists were deriving income from wage labor, hired herding, and small business to supplement household income. A substantial proportion of households were engaged in wage labor in cities or townships nearby. Taking care of others' livestock to earn a "hired herding fee" was also emerging as an income source. This has become prevalent especially in recent years. Except for a small proportion of hired herders who took care of others' livestock throughout the year, most of them only did so during warm seasons from May to September. In addition, some households sold raw and processed milk products to dairy businessmen or tourists, or ran a small grocery store in their yurts, as access to grocery items was very limited in such remote areas.

Despite the fact that non-pastoral livelihoods were commonly practiced, some pastoralists also pointed out their limited contribution to household welfare and resilience. Indeed, it might take generations for pastoralists to become professional and efficient in their newly adopted non-pastoral livelihoods. Currently, pastoralists held no advantages in crop cultivation or other non-pastoral livelihoods over their sedentary neighbors. In Borana, there was little evidence that pastoralists have become self-sufficient through grain production. Their yields were only 31% of the Ethiopian national average, and grain per capita met only 26% of the annual requirement for each household (Tache & Oba, 2010).

In both Borana and Altay, wage labor was gaining popularity; however, this was far from being a stable source of income. In Borana, wage labor positions were largely created by NGOs in the pastoral communities. They started "cash for labor" projects and paid pastoralists to clear bushes and construct water facilities. Pastoralists were paid three US dollars for six hours of their labor each day. Such programs usually phased out in less than three months, which could hardly become a stable source of income. In Altay, nearly 20% of participant households are engaged in wage labor (Liao et al., 2015). However, due to their lack of schooling and poor Chinese language proficiency, they were mostly hired in bottom-level office positions, or worked at construction sites and crop fields based on a temporary contract.

Doing small business in the form of cooperatives was commonly advocated by NGOs in Borana. The development agents taught pastoralists how to establish micro-finance cooperatives. However, due to poor leadership and a shortage of accounting skills, nearly half of these cooperatives were experiencing dropout. Pastoralists also mentioned that there were quite a number of cooperatives that were planned several months ago but never got started due to the lack of seed funds and accountants. In addition, when members could not directly benefit from the cooperatives, they refused to continue contributing money and attending regular meetings. Therefore, the seemingly innovative micro-finance cooperatives were very limited in terms of promoting household welfare.

5. Discussion

Built on my empirical findings in the Borana Zone of Ethiopia and the Altay District of Xinjiang, China, the conclusion chapter of my dissertation aimed at operationalizing the concept of resilience in the pastoral contexts. Both Boran and Kazak pastoralists' subjective definition of resilience centered on the maintenance of decent livelihoods throughout time. They also interpreted three surrogate indicators of pastoral resilience, including mobility, land use pattern and livelihood diversification. Mobility allowed pastoralists to survive and prosper in the ASAL environments. Rangeland zoning was crucial to ensure rotational grazing at multiple scales while meeting the nutritional demands of livestock. Livelihood diversification was also considered a crucial smoother for household income, despite of its controversial role in the pastoral settings.

Mobile livestock herding based on flexible access to rangelands in strategic locations at times of need has proven to be successful in both Borana and Altay for centuries. However, such a traditional livelihood strategy has been subject to a series of socio-ecological threats. Forage and water resources were either diminishing, or becoming susceptible to change in availability as a result of drought and rangeland degradation, which threatened the feasibility of maintaining a viable number of livestock for each household. In addition, external interventions from government and other agencies strongly affected pastoralists' herding practices and choices of livelihood strategies. These interventions have delegitimized the customary institutions of pastoralists in terms of governing the pastoral commons on both savanna and steppe. As a result, development interventions largely failed to achieve their asserted objectives of enhancing pastoral resilience in both Borana and Altay.

My empirical research on the operationalization of resilience suggested that mobility and well-designed land use management schemes allowed the pastoral systems to absorb environmental disturbances, such as drought and snowstorm, and contributed to the system's overall resilience. However, even among the Boran and Kazak pastoralists themselves, there were divergent perspectives regarding how to balance the need to maintain traditional livestock herding and the demand to diversify into non-pastoral livelihoods. Therefore, it is necessary to examine the strategies in terms of how to resolve such a dilemma and develop innovative pathways towards pastoral resilience in the long run.

6. Future Research Directions

"The more I learn, the more I realize how much I don't know."- Albert Einstein.

Although I gained knowledge and insight on pastoralism from my dissertation research, I also realized how little I actually know about the complexity in open grazing systems. My graduate studies on pastoralism informed me and motivated me toward three broad research topics in my future academic career.

First, I will study the collective actions in pastoralists' resource-use behaviors. Management of common-pool resources is fundamentally collective. Effective coordination of individual herders' herding practices could potentially minimize recursive and unsustainable use of communal rangelands and maximize rotational grazing. Such a "mutually agreed-upon" strategy has been long recognized as the fundamental principle in designing community rangeland management policies. However, monitoring and quantifying collective actions is extremely challenging. That's why analysis of the movement of individual animals or households has been discussed in literature, but collective movement and resource-use strategy is yet to be explored and articulated.

There are two specific barriers to studying collective behaviors of mobile pastoralists. The first one is logistics, which means it is difficult to monitor a large group of mobile resource users in a study site. Only when there is a large sample of individual movements can certain resource-use patterns emerge at the community level. The second one is how to derive measurements to quantify what kind of collective action indicates higher degree of coordination, which can potentially translate into sustainable use of rangelands.

Although only four households were involved in each study site in Borana, the GPS-tracking data made it possible to make initial inference on collective resource-use behaviors. Results of preliminary exploration suggested that divergent collective behaviors have emerged in these communities. In the study site showing the highest degree of mobility, pastoralists demonstrated greater synchronicity in their spatio-temporal movement (Figure 4). During the dry season, all four households were making use of patches of rangelands that are 20 – 30 km west of community center (Figure 4 top). They continued herding there until early November, and then all herded animals back to their settlements. Analysis of home range (Calenge, 2011) indicated that these households also set camps at an intermediate distance from each other (Figure 4 bottom). Their 95% home range largely overlapped with each other; however, their 25% home range only partly covered one another. Such a pattern suggested that individual households were able to set up camps at an intermediate distance from each other, which not only reduced grazing competition but also promoted rotational grazing. Such collective migration allowed different patches of rangelands to rest and rebound within their extent of movement.

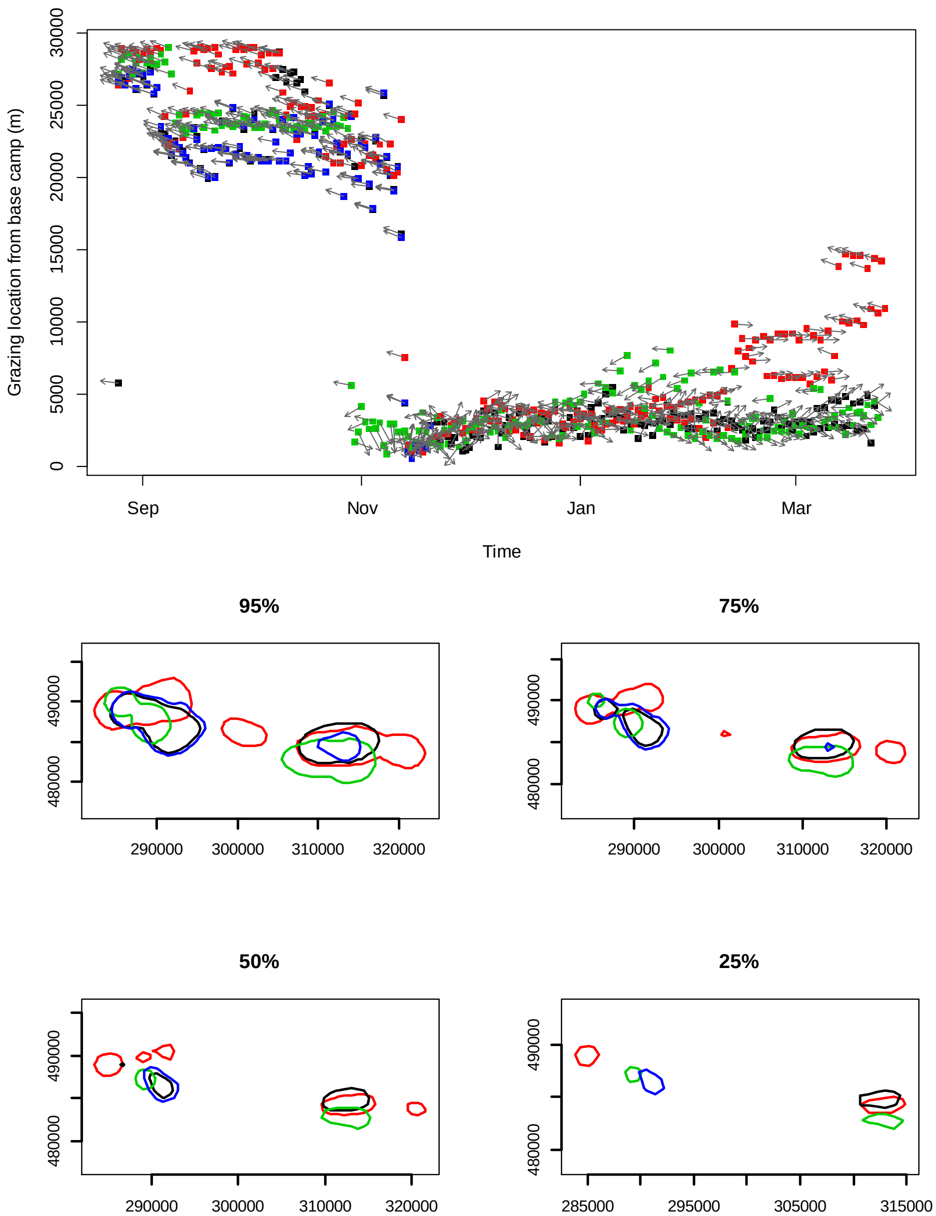

Figure 4. Collective movement patterns of four households in El Dima. The top figure shows the average distance and direction of daily herding from community center over the tracking period. The bottom figure shows the 95%, 75%, 50% and 25% home range of four households. Each color represents one household.

In contrast, in the study site that is highly sedentarized and constrained herding extent, pastoralists tended to follow their own schedule of movement, which showed little evidence of coordination at the community level (Figure 5). In this study site, seasonality had less impact on the broader movement patterns. For two of these households (black and green in Figure 5 top), the average daily herding distance and direction from the community center barely varied throughout the tracking period. The other two households (red and blue in Figure 5 top) herded livestock at locations that are more distant from community center from November to February. However, for the rest of the time their herding locations largely overlapped with the first two. In terms of home range, one household maintained an intermediate distance from others. The other three households' home ranges largely overlapped with each other from 95% to 25% (Figure 5 bottom). This preliminary evidence suggested that households in this study site were more likely to be involved in greater competition with each other given a small movement extent, and collective rotational grazing was hardly practiced.

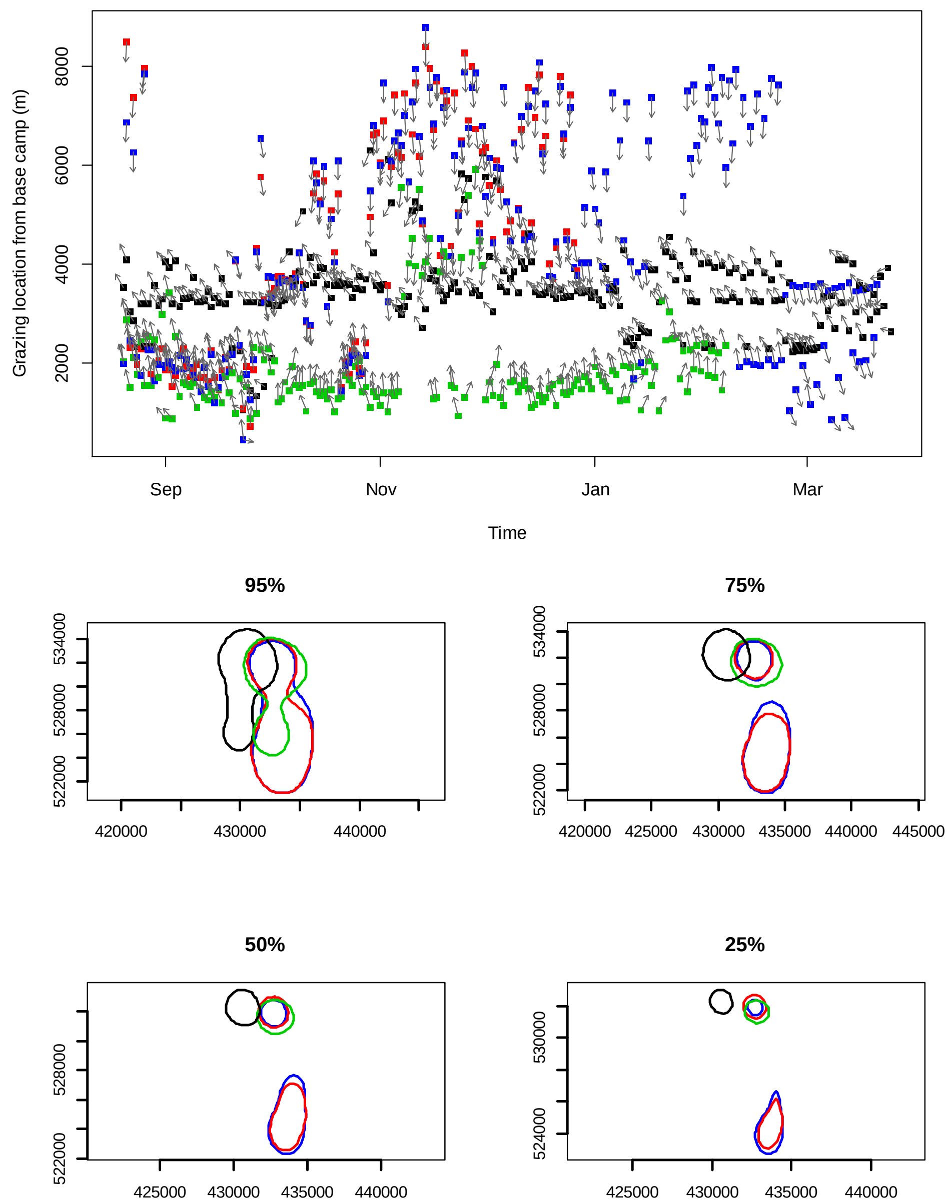

Figure 5. Collective movement patterns of four households in Siqu. The top figure shows the average distance and direction of daily herding from community center over the tracking period. The bottom figure shows the 95%, 75%, 50% and 25% home range of four households. Each color represents one household.

The second potential research topic that emerged out of my dissertation is the complex feedback loop within the open grazing system. Causal mechanisms are yet to be explored to determine what contributes to good rangelands and what attracts animal grazing. To be more specific, we do not fully understand whether the existence of good forage is due to lighter grazing intensity, or it is a source of attraction to animal grazing. The former represents typical thinking in plant ecology, while the later represents the perspective of animal ecology. Both assumptions were used in my dissertation. For example, in Chapter 3, I investigated the impact of grazing intensity on the cover of herbs, shrubs and trees. This assumed that plant cover and vegetation structure is a result of grazing. In contrast, in Chapter 6 in which I examined the determinants of cattle's resource selection behaviors, I applied the reverse logic: cattle herding patterns are driven by chasing green patches of rangelands that showed higher NDVI values.

Making different assumptions is completely acceptable given different research questions. However, one research question that is left behind is how cattle grazing and vegetation growth interact with each other. Integrating the above two assumption to investigate the feedback loops between vegetation dynamics and cattle's resource selection will shed light on the complex interaction between resource base and resource users. Answering this question certainly requires substantial and intensive data collection of both plants and animals, and probably an in-depth analysis of plant physiology, growth and nutrition. Meanwhile, agent-based modeling might serve as an alternative approach to study such complexity in the pastoral systems. By treating each patch of rangeland and each cattle as individual agents, I can first simulate the mechanisms of interaction and explore what resource-use patterns will emerge at a higher level given different environmental endowment and herding management institutions.

The third future research topic is to study how to truly engage pastoralists in my research in a way that can contribute to community capacity building. The action research framework offers a promising alternative approach to the current development interventions in the pastoral regions. It needs to be recognized that community development occurs in complex, dynamic and adaptive systems. Whether it is clearing the bushes, developing access to water facilities, or preventing the degradation of communal rangelands, action research requires that development practitioners seek to understand how a series of variables interact with each other in a non-linear fashion. Practitioners and stakeholders must adopt an iterative adaptive approach that seeks progressive change through a process of learning by doing.

An iterative process of community development rests on close partnerships between development agencies and indigenous communities (Kassam & Tettey, 2003). However, such partnerships are often fragile. Cooperation can be undermined by each group's suspicion and distrust of the other and lack of willingness to cooperate. In fact, NGOs are perceived by some local pastoralists to be operating as an invisible hand of their donor countries, and there is an inevitably politicized interpretation of NGO interventions. Most NGO projects were implemented over a short term to meet the urgent needs of pastoral communities, but hardly included local people in the decision-making processes of development. This is particularly true for pastoralists who have long been excluded from development, and whose lifestyles have been perceived as a barrier to development (Watson, 2003). With this mindset, tokenism, rather than true participation, becomes the best scenario that communities can hope for (Kassam & Tettey, 2003). Therefore, in order for true partnership to prosper between communities and development practitioners, it is necessary to re-conceptualize the temporality of the relationship in community development in an approach that can truly contribute to building capacity and promoting resilience in the pastoral settings.

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