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Research, part of a Special Feature on Everyday Adaptations to Climate Change

Sedentarization as an adaptation to socio-environmental changes? Everyday herding practices in pastoralist communities in southern Ethiopia

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ABSTRACT. As humanity is faced with various changes in social-environmental systems, adaptation efforts have become increasingly important. Significant effort and resources have been spent on devising overarching, large-scale strategies in response to climate change and associated socioeconomic challenges. However, the mechanisms of adaptation employed by individuals and households in ordinary, daily life have received insufficient scholarly examination. This research aims to demonstrate the significance of everyday adaptation strategies of smallholder pastoralists who are on the front lines of changing socioeconomic regimes in East African drylands. We analyzed the daily spatiotemporal patterns of livestock behavior to understand everyday adaptation practices. Two different pastoralist communities in the Borana Zone in southern Ethiopia were compared, one of which keeps the traditional mobile pastoralism livelihood, while the other has sedentarized because of socio-environmental changes and policy incentives. The mobile pastoralists have larger grazing areas, and their cattle spend more time on foraging and resting. In contrast, the sedentarized pastoralists utilize the land near their settlements intensively and the cattle travel longer distances on average. Our findings suggest that sedentarization is a constrained adaptation strategy at best because it increases the recursive use of rangeland and its fragmentation and forces livestock to move more intensively on a daily and seasonal basis.

Key Words: *adaptation; Ethiopia; herding behavior; mobility; pastoralism*

INTRODUCTION

As humanity anticipates multifarious sustainability challenges in the Anthropocene, there has been a heightened focus on adaptation efforts, generally understood as adjustments that help to mitigate negative consequences of change (Adger et al. 2005, Engle 2011). Although adaptation in both natural and built environments has long existed, unprecedented shifts in climate regimes and environmental uncertainty call for novel, innovative, and forward-thinking strategies (Folke et al. 2004, Scheffer et al. 2012). Significant effort and resources have been spent to devise overarching, large-scale strategies (e.g., state-initiated policies) to adapt to climate change and associated socioeconomic challenges. However, adaptation strategies employed by individuals and households in ordinary, daily life have received relatively insufficient scholarly examination and their role should not be underestimated (Davidson 2016).

Individuals, households, and communities have long dealt with both acute shocks and chronic stressors related to climate change. Particularly in rural places where people have limited access to state-distributed aid or resources, daily decisions and behavioral changes made in reaction to or anticipation of social-ecological changes (e.g., drought, extreme heat, flooding) will continue to emerge as important coping mechanisms for preserving human well-being. As individuals and households face various socioeconomic and environmental challenges, they learn to adapt their livelihood strategies to continue meeting basic needs (Anh Tran 2020). Further, communities that share challenges of adverse conditions may work together to reform their social-ecological systems to meet changing biophysical/material conditions and needs (Ostrom and Basurto 2011). Some scholars suggest that adaptation strategies employed by small groups have the potential to create bottom-up institutional changes (May 2021) as an effective supplement to top-down approaches, which are likely to be slower, more technical, and expensive (Schofield and Gubbels 2019). However, the burden of individual and household adaptation falls unevenly on smallholder producers whose livelihoods depend directly on natural resources and who have imperfect access to information or lack institutional protections (Quealy and Yates 2021). Therefore, certain small-scale and ordinary coping mechanisms may result in unanticipated trade-offs (Smith et al. 2011). Despite the existing challenges associated with incremental and small-scale adaptive strategies, further understanding of effective, efficient, and equitable everyday adaptation strategies is an important undertaking in light of anticipated social-environmental changes, particularly in drylands.

Drylands cover about 41% of the earth's terrestrial surface and are home to a third of the global population (Reynolds et al. 2007, Huang et al. 2016). Global drylands are undergoing rapid changes, including environmental degradation, population growth, and climate change, and are home to high levels of poverty and hunger (Middleton et al. 2011). Pastoralism, as the dominant livelihood strategy across the global drylands, utilizes extensive grazing strategies to produce livestock and dairy products. In Africa, the spread of mobile pastoralism was historically prompted by a major climate regime shift around 4500 years ago, resulting in an increased arid landscape and a dissipating rain belt (Smith 1992, Orton 2015). Mobile pastoralism, a widely adopted ancient form of land use and livelihood, involves migrating herds of cattle, sheep, goats, and camels in pursuit of resources such as water and high-quality forage, and is a mode well suited to the dryland environment with low and highly variable levels of precipitation (Swift 2004).

A number of socio-environmental changes in drylands have profoundly transformed the traditional mobile pastoralism worldwide. Importantly, a rise in population accompanied by human settlement in remote areas traditionally used for grazing has contributed to increased competition for forage and water resources (Gemtessa et al. 2005, Liao et al. 2017). Increasingly,

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pastoralists have begun to diversify their livelihoods through engaging in crop cultivation in order to meet their food needs in the face of climate change and environmental degradation. Because many social services (e.g., food aid) can barely reach the most sparsely populated areas, households tend to settle in clusters to access such services (Gemtessa et al. 2005). Higher drought frequency and intensity induced by climate change can exacerbate issues related to grazing land and water quantity and quality, forcing pastoralists to deviate from their regular grazing and watering areas or to settle (Adriansen and Nielsen 2005, Agade 2015). Sedentarization has been further promoted through land tenure reforms. In countries where land is state owned, such as China and Ethiopia, governments are motivated to implement sedentarization schemes to pursue modern development and management ideologies (Homann et al. 2008, Fan et al. 2015). Infrastructure development and exploitation of resources can also constrain mobility and access to resources among pastoralists (Johannes et al. 2015). Particularly, development projects tend to disrupt the contiguity of land because large infrastructure projects require significant amounts of space (Schilling et al. 2012). For example, before the construction of the Kenyan–Ethiopian border, pastoralist groups moved freely to whichever side was beneficial to livestock grazing (Galaty 2016). Additionally, the proliferation of conflict and violence can occasionally deter pastoralists from pathways in their migration (Schilling et al. 2012, Nelson et al. 2020). Although conflicts motivated by wealth redistribution have not been rare in pastoralist communities (Hendrickson et al. 1998), they have intensified as technology and weapons have become more advanced (Agade 2015).

Over the past centuries, pastoralists have developed a series of risk management strategies to sustain themselves in drylands (Scoones 1994, Goldman and Riosmena 2013). The aforementioned changes taking place in pastoralist communities, however, can challenge the indigenous institutions that mobile pastoralists take advantage of to cope with environmental constraints. The need to adapt to various changes in dryland social-ecological systems is becoming increasingly urgent as development and institutional changes occur alongside changing climate patterns. Furthermore, because adaptations are inherently novel and unknown compared with long-formed conventions, it is important to understand the mechanisms and implications of such behaviors.

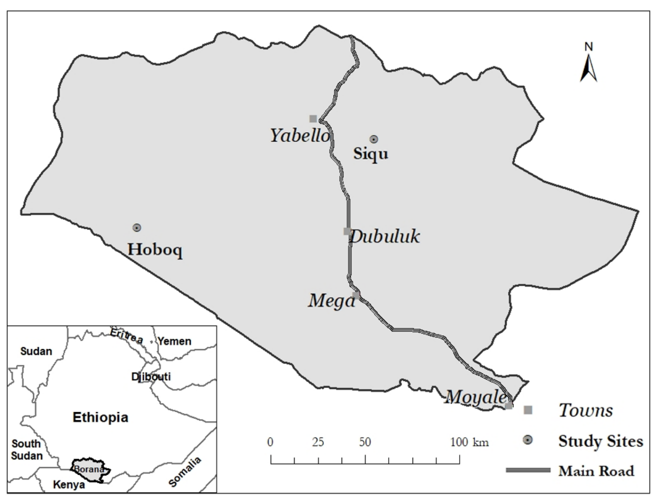
We aim to demonstrate the everyday adaptation of smallholder pastoralism in the face of changing socioeconomic regimes in east African drylands through the lens of livestock behavior and mobility. Modern tracking technologies, such as global positioning system (GPS)-based telemetry, have largely advanced the understanding of the ecology of wildlife animal movement to animate conservation and ecosystem management (Nathan et al. 2022). Nevertheless, the usage of tracking livestock to understand pastoral behavior has been limited and can have great potential in revealing the resource use patterns of livestock herds. Because the movement of livestock largely depends on pastoralists' decision making, we investigate the daily spatiotemporal patterns of livestock movement with GPS tracking technology that shed light on pastoralists' adaptation practices. Two different pastoralist communities in the drylands of southern Ethiopia are compared, one of which keeps the traditional mobile pastoralism livelihood, while the other one has been sedentarized because of changing availability of resources and policy incentives. In this way, we expect to illustrate the characteristics and implications of the household-level adaptation under a larger scale background.

METHODS

Study area

This study focuses on the Borana Zone in southern Ethiopia (Fig. 1), a dryland region where pastoralism is the major livelihood strategy. With an area of 43,000 km², the region supports a population of over 350,000 people and around one million livestock (Coppock 2016). The landforms in the region are diverse with elevation ranging from 500 m to 2500 m. Precipitation is also heterogeneous, with an increasing gradient from the lowlands to the highlands. The mean annual rainfall ranges from 300 mm to 1000 mm. The temporal distribution of precipitation is bimodal, with the primary wet season from April to May (60% of the total annual rainfall) and the secondary wet season from October to November (30% of the total annual rainfall; Coppock 1994). However, the precipitation has become more unpredictable in past decades, and pastoralists have had to adapt to such changes accordingly. The majority of Borana inhabitants live below the poverty line (Tache and Oba 2010, Dika et al. 2021) and face many of the challenges happening in the world's drylands, commonly drought. Because of the low water availability, low agricultural production, lack of infrastructure, and poverty in general, malnutrition is widespread in the Borana Zone (Lasage et al. 2010).

Fig. 1. The mobile (Hoboq) and sedentarized (Siqu) communities of study in Borana, Ethiopia.



The Boran pastoralists practice two forms of livestock herding to better access resources at different times and locations. One is *worra*, a herding strategy in which livestock are kept close to settlements (base camps), and is used particularly with herds possessing young or lactating cattle. The other is *forra*, which involves traveling far away from settlements to find higher quality foraging areas around satellite camps (Liao et al. 2017). Pastoralists can practice both forms of herding through splitting their herds.

Because Ethiopian land is state owned, the Borana Zone governance has promulgated schemes incentivizing pastoralist households who are willing to settle down to enclose a piece of land as a crop field for their domestic use of food production. We aim to investigate the differences between traditional pastoral mobility patterns and a more recently developed strategy to understand how sedentarization, as adaptation practice to local socioeconomic changes, has modified the traditional nomadic pastoral behavior and associated land use patterns. Two villages in Borana, Hoboq and Siqu, are selected for empirical investigation (Fig. 1). The former, located farther from towns and with a smaller population compared to the latter, largely keeps the traditional mobile pastoralism livelihood on the dry bushlands of the Rift Valley that ranges between 700 m and 1000 m. In contrast, the majority of households in Siqu have settled down and enclosed farm plots for crop cultivation, while maintaining highly sedentarized herding on the dense scrublands of the Borana Plateau with an elevation around 1500 m.

Data

From August 2011 to March 2012, our research team deployed custom-built GPS tracking collars to cattle (*Bos indicus*), with the verbal consent of the owners, namely four households in each of the two villages. The cattle herd sizes of the four households in Siqu were 5, 13, 20, and 40, and those in Hoboq were 6, 13, 16, 51. Because cattle move in herds, each cow was considered representative of its herd (Moritz et al. 2012). The GPS collars were designed to record the geographic location of each cow every five minutes. The Boran pastoralists usually put bells worn around the neck of selected cows, so they can better keep track of their herds when they graze freely in the open rangelands. The GPS collars weigh less than 0.3% of the body weight of a mature cow so that their impact on cattle movement was negligible. Because of equipment malfunction in the field, three of the GPS collars (two in Siqu and one in Hoboq) were not able to keep recording cattle locations up to March 2012, but the data are still valid and are taken into account in this study. The other five collars collected data for over 210 days, recording more than 50,000 location points. The data of each recorded observation point contain the Coordinated Time Zone (UTC) time of recording and the longitude and latitude of the location.

In order to understand the spatial pattern of livestock movement within the local context, our research team conducted participatory mapping with household heads and elders at the two study sites. Specifically, we mapped the extent of perceived community herding boundaries and rangeland reserves (for calf grazing during dry season) at both sites and enclosed crop fields at Siqu. During the mapping sessions, we also verified the movement characteristics inferred from GPS-tracking data with the local residents, such as camp locations and travel distances. In addition, we investigated the environmental and socioeconomic factors that affect pastoralists' decision making, including forage abundance, crop cultivation activities, and interventions by government agencies.

Analysis

The points recorded by the GPS collars were plotted to reveal the spatial patterns of the cattle movement tracks for the two villages. We estimated the 95% level kernel home range (i.e., the area in which an animal lives and moves) according to the utilization density distribution of each cow. We digitized the major features drawn from the participatory mapping sessions, and calculated the areas of participatory-mapped herding areas, rangeland reserves, and enclosed farmlands.

We further analyzed the livestock behavior with the GPS-tracking data. The GPS tracks formed by concatenating the GPS points were projected and the displacement distance between each pair of consecutive locations was obtained, followed by the mean moving velocity of each segment. Segments with mean velocity of over 12 km/h were considered erroneous and removed, because Boran cattle can hardly run as fast as this speed. Then each segment was classified into one of five movement categories (stationary, heavy grazing, medium grazing, light grazing, and traveling), according to the velocity range gradient proposed by Liao et al. (2018), in which traveling behavior not only means displacement but also corresponds to the fastest movement and least grazing or resting. The track composition of each cow was analyzed in terms of time and displacement distance. The proportion of each type of behavior in every hour of a day and the total daily displacement distance throughout the observation period were also calculated to explore the temporal patterns on different scales. Time was transferred from UTC to the East Africa time zone. Maps were generated with ArcMap 10.8.1. Quantitative analyses were conducted with R 3.6.0 (R Core Team 2019). R package "adehabitatHR" (Calenge 2006) was used to estimate the 95% level kernel home range and package "bcpa" (Gurarie et al. 2009) was used to obtain the moving velocity of each track segment.

RESULTS

Spatial movement as adaptation

The four cattle in the two villages demonstrated distinct spatial movement patterns (Fig. 2). Pastoralists in Hoboq enjoyed a much larger herding extent, which allowed them to move across *worra* and *forra* herding areas as an adaptation strategy to environmental variability. In contrast, pastoralists in Siqu had a much smaller herding extent without satellite camps and practiced herding that revolved around their permanent settlement. Table 1 shows the areas of mapped herding areas, rangeland reserves for calves, and enclosed farmlands of the two sites obtained from participatory mapping. The scope of movement of pastoralists in the mobile community was nearly eight times as large as that of the sedentarized pastoralists. In addition, despite a small herding extent, pastoralists in Siqu enclosed over 10% of the available grazing land for crop production. Both communities enclosed a similar size of rangeland reserve for calf use during the dry season, but the proportion of reserve to the total available land in Siqu was much higher than that in Hoboq.

The tracks and estimated home ranges of the cattle in the two villages are shown in Fig. 3. The recorded tracks of cattle in Hoboq, the traditional mobile community, appeared far more dispersed than those in Siqu because pastoralists utilized both *worra* and *forra* herding areas. In Hoboq, herds migrated from base camps to satellite camps across seasons, while the tracks of cattle in Siqu, the sedentarized community, were fundamentally in radial shapes around the major settlements. The home ranges of cattle in Hoboq were larger and usually consisted of more than one patch because of seasonal migration. In contrast, the home ranges of cattle in Siqu were distributed near the settlements.

Fig. 2. The perceived herding boundaries, enclosed rangeland reserves, and crop fields in Hoboq (a) and Siqu (b).

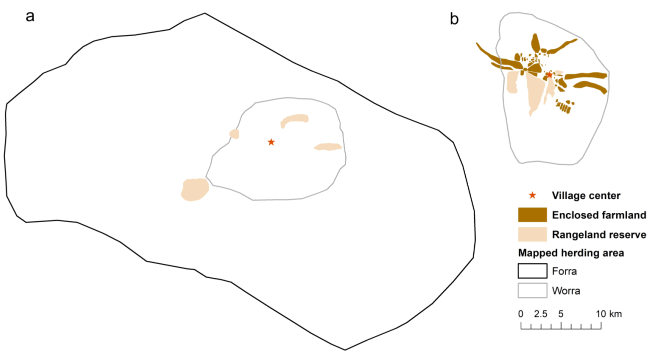


Table 1. The areas of herding areas, rangeland reserves and enclosed farmlands of the two sites

Site	Worra herding area (km²)	Forra herding area (km²)	Rangeland reserve (km²)	Enclosed crop field (km²)
Hoboq (mobile)	168.27	1543.50	14.66	0
Siqu (sedentarized)	202.67	0	13.56	21.82

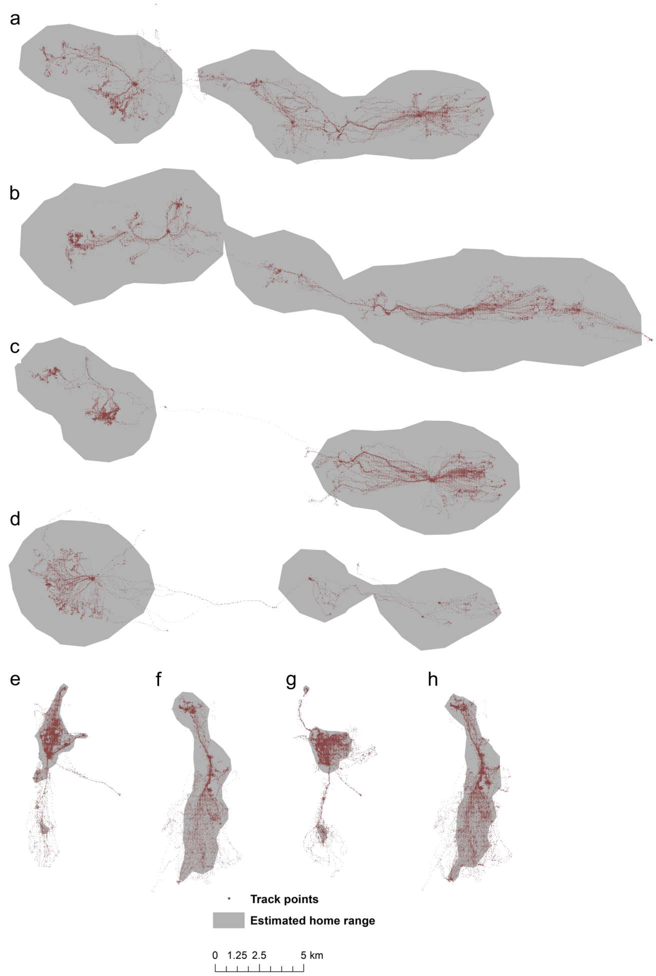
Cattle behavioral change as adaptation

Table 2 summarizes the results of characteristic movement statistics of each cattle, including mean displacement distance per day; proportion of time spent on resting, grazing, and traveling; and home range size. Quantitative analyses demonstrate that on average the cattle in Siqu had a home range size of almost 1/10 of that in Hoboq, but cumulatively moved 2 km more than the latter on a daily basis. The sedentarized group of livestock also spent less time resting (time staying stationary) and grazing and more time traveling.

The hourly patterns of cattle behavior in both villages, as revealed by Fig. 4, exhibited bimodality, with two peaks of traveling behavior appearing at 8:00 to 9:00 and around 18:00. The bimodal movement patterns of cattle in Siqu were more acute than those in Hoboq, which, aligning to the numeric results in Table 2, were mainly attributed to more traveling activities. During the resting period at noon, the cattle in Siqu were also more likely to move to access forage resources. Additionally, the cattle in Siqu started their daily activity at around 7 am, earlier than the cattle at the mobile site at around 8 am.

The daily travel distance also demonstrated distinct daily and seasonal patterns across the two study sites. Fig. 5 shows how long the cattle at two sites traveled each day (i.e., displacement distance identified as traveling behavior) across seasons. Overall, cattle in the sedentarized site traveled a much longer distance on a daily basis, where daily travel distance can more frequently exceed 5 km/day. The cattle in Siqu also displayed much higher fluctuations in daily travel distance. In dry seasons, the Siqu cattle generally traveled longer distances than in wet seasons, possibly as a result of diminishing forage availability near the settlements and the necessity to go farther and search more extensively to ensure forage intake.

Fig. 3. The movement tracks and home ranges of the four tracked cattle in the mobile community Hoboq (a-d) and the sedentarized community Siqu (e-h).



DISCUSSION

In this research, the adaptation behavior of the pastoralist communities to socioeconomic and environmental changes in southern Ethiopia is studied mainly through the lens of livestock mobility and behavior. The spatiotemporal patterns of cattle behavior, obtained from GPS tracking collars, in two villages practicing traditional mobile and sedentarized pastoralism are compared. Our findings advance the understanding of daily adaptation decisions made by both mobile and sedentarized pastoralists.

Borana's pro-sedentarization policy has provided choices and incentives for local pastoralists to make changes to their daily life. However, pastoralists in Hoboq did not respond to the incentive to sedentarize, because the local socio-environmental conditions did not compel them to a livelihood change. In contrast, Siqu

Table 2. Summary of the data and movement characteristics of each cattle herd.

Cattle ID	Duration (d)	# Observed points	Mean daily displacement distance (m)	Time of stationary (%)	Time of grazing (%)	Time of traveling (%)	Home range (km²)
Hoboq1	213	58199	13436.69	62.22	35.83	1.94	175.53
Hoboq2	214	58723	14085.17	60.88	36.73	2.39	290.50
Hoboq3	213	58634	13418.41	61.92	36.14	1.94	146.81
Hoboq4	97	26822	13266.25	63.26	34.52	2.22	130.24
Hoboq (mean)			13551.63	62.07	35.81	2.12	185.77
Siqu1	218	60208	12924.71	64.38	33.12	2.49	10.07
Siqu2	129	35822	17803.19	57.73	35.85	6.42	30.28
Siqu3	171	46904	13211.04	61.16	36.60	2.24	7.97
Siqu4	214	56605	17019.73	58.75	35.50	5.75	26.34
Siqu (mean)			15239.67	60.51	35.27	4.23	18.67

Fig. 4. Hourly composition of behavior types of cattle in the mobile (a) and sedentarized communities (b), calculated as average values of the four cattle at each study site.

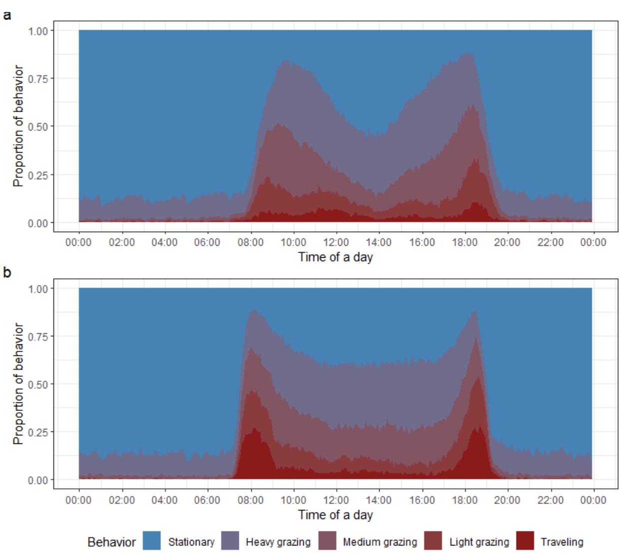
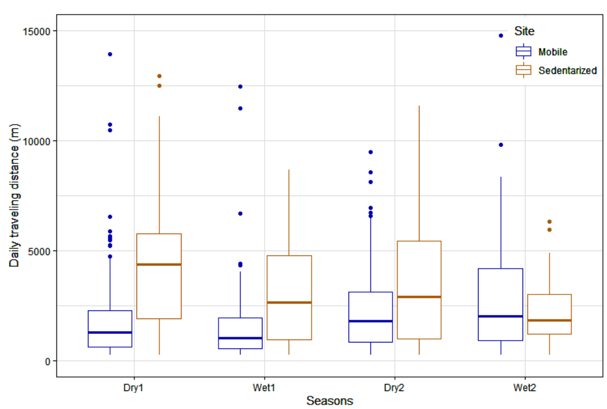


Fig. 5. Daily displacement of traveling behavior in different seasons of cattle in the two sites. Dry1, Wet1, Dry2 and Wet2 refer to the first and second dry and wet seasons during the study period.



pastoralists made the choice to settle down in response to local socioeconomic changes, such as increasing population, loss of seasonal grazing sites, and better access to wage labor and trade opportunities because of its proximity to the main road and the regional capital. In Siqu, a relatively new livelihood strategy, smallholder farming, has been implemented as a supplement to traditional pastoralism. The allocation of the community land as private crop fields requires the pastoralists to settle down near the village center, which leads to a different set of adaptation strategies, including traveling increased distances in daily herding, cultivating crops, and enclosing a larger proportion of community grazing areas as rangeland reserves.

Our comparison between livestock movement patterns across the two sites reveals characteristics of two different herding practices. The home ranges for all four of Hoboq cattle were extensive (average of 185.77 km²), while Siqu cattle had significantly less land available (average of 18.67 km²). As displayed in Fig. 2, the cattle in the mobile Hoboq community generally graze at and migrate among different satellite camp locations, while those in Siqu, the sedentarized community, cannot be too far away from the fixed settlement. Traditionally, mobile pastoralists have extensive grazing areas like those found in Hoboq. For traditional mobile pastoralism, the opportunity to relocate close to seasonal grazing resources can be important during dry seasons or periods of drought. However, shrinking availability of grazing areas and land fragmentation can disrupt traditional grazing strategies and resource use patterns. Because of the smaller available rangeland area in Siqu, pastoralists utilize the land more intensively. They do not have the same opportunity to access better grazing areas beyond their herding extent and have to keep foraging near the settlement. Because of heavy utilization of the same area of land, Siqu pastoralists have to reserve more high-quality rangeland for calf grazing during the dry season (6.7% of the main herding area compared to 0.9% in Hoboq, Table 1), which further limits the available land for grazing. Previous studies have provided evidence that intensive utilization may exacerbate rangeland fragmentation (Tache and Oba 2010) and degradation (Gemtessa et al. 2005). Research on dryland rangeland elsewhere in the world has also suggested implications on the landscape sustainability of such mobility-reducing strategies (Vetter 2005, Wu et al. 2015). Furthermore, climate change will likely continue to increase pastoralists' need for grazing areas, placing even greater pressure on rangelands adjacent to sedentarized pastoralists (Debela et al. 2015).

Because the available grazing land in Siqu is confined to areas close to their settlements, Siqu pastoralists do not travel as far from their home as Hoboq pastoralists. However, they travel longer distances within their site boundary than the latter. As highlighted in Table 2, the average Siqu cattle spent more time traveling each day and less time grazing than the average cattle in Hoboq. On a seasonal basis, Siqu cattle travel longer distances to feed themselves than Hoboq cattle do, especially in dry seasons. Less grazing and more traveling translate into less calorie assimilation and more energy consumption, which is considered inefficient for livestock husbandry according to movement ecology theories (Shepard et al. 2013). The energy spent on traveling farther to access grazing resources also increases the needed caloric intake, reinforcing even longer traveling distance to consume more. When cattle are required to travel farther, their milk yield decreases, which has impacts on both calf rate survival and food security for pastoralists (Coppolillo 2001). Additionally, cattle in the sedentarized site need to start grazing earlier in the morning and rest less in order to obtain sufficient amounts of forage. In contrast, Hoboq cattle do not spend as much time traveling and they are able to allocate more time on leisurely grazing and resting.

Pastoralist groups have long been adapting at the household and community level in response to social, economic, and environmental changes and challenges. Although there is often emphasis on large-scale and long-term adaptation represented by state actions, how they are translated into incremental adaptation employed by individuals and households should not be disregarded. Pastoralist communities play a significant role in adapting to the changing socio-environmental regimes. Often, high-level policy makers are less aware of the specific local context in which the effects of climate change affect daily life and face practical limitations of policy implementation (Smit and Skinner 2002). This can bring about maladaptation that can lead to negative consequences or exacerbate pre-existing issues. Local pastoralists have the greatest understanding of their community system, and their local knowledge and socio-cultural values must be centered in determining adaptation strategies within their own communities.

It has been noted that not all local adaptation measures in Borana pastoralist communities in response to climate stressors are sustainable (Berhanu and Beyene 2015). For the sedentarized community in this study, potential trade-offs of this adaptation are twofold: first, there are ecological consequences of intensive pastoralism, such as the undermining of landscape sustainability; second, the herd may be less productive, impacting food security and pastoralist well-being. Therefore, future research should evaluate how local actors perceive the larger scale adaptation strategies and make decisions to understand the interactions between adaptations at different scales. High-level decision makers can in turn gain insights from investigating how the implemented policies are dissolved into actors' daily life, whether the initial goals are met, and what trade-offs arise at different scales. Although in the case of this study we can speculate generally about what has prompted the sedentarization adaptation from quantitative analysis and the narratives of local residents, we do not sufficiently understand the specific institutions and information that individuals, households, and communities have utilized in their adaptation decision making. Only in understanding the mechanisms of such inter-scale adaptations can national and state governments work toward increasing community agency and promoting effective and efficient local adaptive capacity.

Future research on livestock mobility and adaptation behavior can be improved in several ways. The data used in the study was collected nearly a decade ago. Climate and the socioeconomic conditions are constantly changing, which, together with unexpected events, such as the COVID-19 pandemic, are likely to affect livestock herding practices in various ways and lead to different adaptation strategies. Therefore, it is necessary to conduct long-term monitoring of livestock mobility to understand how pastoralists respond to different socioeconomic and environmental challenges. In addition, besides GPS tracking data, future research can integrate different data sources (e.g., interview, participatory mapping, satellite images) with GPS tracking data to better understand mobility patterns and their determinants.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13503

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Data Availability:

The data/code that support the findings of this study are available on request from the corresponding author, C.L. None of the data/code are publicly available because they contain information that could compromise the privacy of research participants, namely the pastoralists in Borana Zone, Ethiopia.

LITERATURE CITED

Adger, W. N., N. W. Arnelland, and E. L. Tompkins. 2005. Successful adaptation to climate change across scales. Global Environmental Change 15(2):77-86. https://doi.org/10.1016/j.gloenvcha.2004.12.005

Adriansen, H. K., and T. T. Nielsen. 2005. The geography of pastoral mobility: a spatio-temporal analysis of GPS data from Sahelian Senegal. GeoJournal 64(3):177-188. https://doi.org/10.1007/s10708-005-5646-y

Agade, K. M. 2015. Changes and challenges of the Kenya Police Reserve: the case of Turkana County. African Studies Review 58 (1):199-222. https://doi.org/10.1017/asr.2015.10

Anh Tran, T. 2020. Learning as an everyday adaptation practice in the rural Vietnamese Mekong Delta. Climate and Development 12(7):610-613. https://doi.org/10.1080/17565529.2019.1664974

Berhanu, W., and F. Beyene. 2015. Climate variability and household adaptation strategies in southern Ethiopia. Sustainability 7(6):6353-6375. https://doi.org/10.3390/su7066353

Calenge, C. 2006. The package "adehabitat"for the R software: a tool for the analysis of space and habitat use by animals. Ecological Modelling 197(3-4):516-519. https://doi.org/10.1016/j.ecolmodel.2006.03.017

Coppock, D. L. 1994. The Borana plateau of southern Ethiopia: synthesis of pastoral research, development, and change, 1980-91. Volume 5. International Livestock Center for Africa, Addis Ababa, Ethiopia.

Coppock, D. L. 2016. Pastoral system dynamics and environmental change on Ethiopia's north-central Borana Plateau—influences of livestock development and policy. Pages 327-362 in R. Behnke and M. Mortimore, editors. The end of desertification? Springer, Berlin, Germany. https://doi.org/10.1007/978-3-642-16014-1_12

Coppolillo, P. B. 2001. Central-place analysis and modeling of landscape-scale resource use in an East African agropastoral system. Landscape Ecology 16:205-219. https://doi.org/10.1023/A:1011148503303

Davidson, D. 2016. Gaps in agricultural climate adaptation research. Nature Climate Change 6(5):433-435. https://doi.org/10.1038/nclimate3007

Debela, N., C. Mohammed, K. Bridle, R. Corkrey, and D. McNeil. 2015. Perception of climate change and its impact by smallholders in pastoral/agropastoral systems of Borana, South Ethiopia. SpringerPlus 4:236. https://doi.org/10.1186/s40064-015-1012-9

Dika, G., D. Tolossa, and S. M. Eyana. 2021. Multidimensional poverty of pastoralists and implications for policy in the Boorana rangeland system, Southern Ethiopia. World Development Perspectives 21:100293. https://doi.org/10.1016/j.wdp.2021.100293

Engle, N. L. 2011. Adaptive capacity and its assessment. Global Environmental Change 21(2):647-656. https://doi.org/10.1016/j.gloenvcha.2011.01.019

Fan, M., Y. Li, and W. Li. 2015. Solving one problem by creating a bigger one: the consequences of ecological resettlement for grassland restoration and poverty alleviation in Northwestern China. Land Use Policy 42:124-130. https://doi.org/10.1016/j.landusepol.2014.07.011

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annual Review of Ecology, Evolution, and Systematics 35:557-581. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711

Galaty, J. 2016. Boundary-making and pastoral conflict along the Kenyan-Ethiopian borderlands. African Studies Review 59(1):97-122. https://doi.org/10.1017/asr.2016.1

Gemtessa, K., B. Emana, and W. Tiki. 2005. Livelihood diversification in Borana pastoral communities of Ethiopia-prospects and challenges. WABEKBON Consult, Ethiopia. https://saga.cornell.edu/saga/ilri0606/24gemtessa-emana-tiki.pdf

Goldman, M. J., and F. Riosmena. 2013. Adaptive capacity in Tanzanian Maasailand: changing strategies to cope with drought in fragmented landscapes. Global Environmental Change 23(3):588-597. https://doi.org/10.1016/j.gloenvcha.2013.02.010

Gurarie, E., R. D. Andrews, and K. L. Laidre. 2009. A novel method for identifying behavioural changes in animal movement data. Ecology Letters 12(5):395-408. https://doi.org/10.1111/j.1461-0248.2009.01293.x

Hendrickson, D., J. Armon, and R. Mearns. 1998. The changing nature of conflict and famine vulnerability: the case of livestock raiding in Turkana District, Kenya. Disasters 22(3):185-199. https://doi.org/10.1111/1467-7717.00086

Homann, S., B. Rischkowsky, and J. Steinbach. 2008. The effect of development interventions on the use of indigenous range management strategies in the Borana lowlands in Ethiopia. Land Degradation & Development 19(4):368-387. https://doi.org/10.1002/ldr.845

Huang, J., H. Yu, X. Guan, G. Wang, and R. Guo. 2016. Accelerated dryland expansion under climate change. Nature Climate Change 6(2):166-171. https://doi.org/10.1038/nclimate2837

Johannes, E. M., L. C. Zulu, and E. Kalipeni. 2015. Oil discovery in Turkana County, Kenya: a source of conflict or development? African Geographical Review 34(2):142-164. https://doi.org/10.1080/19376812.2014.884466

Lasage, R., A. Seifu, M. Hoogland, and A. de Vries. 2010. Report on general characteristics of the Borana zone, Ethiopia. Report 10(03). Instituut voor Milieuvraagstukken, Amsterdam, The Netherlands.

Liao, C., P. E. Clark, S. D. DeGloria, and C. B. Barrett. 2017. Complexity in the spatial utilization of rangelands: pastoral mobility in the Horn of Africa. Applied Geography 86:208-219. https://doi.org/10.1016/j.apgeog.2017.07.003

Liao, C., P. E. Clark, M. Shibia, and S. D. DeGloria. 2018. Spatiotemporal dynamics of cattle behavior and resource selection patterns on East African rangelands: evidence from GPS-tracking. International Journal of Geographical Information Science 32(7):1523-1540. https://doi.org/10.1080/13658816.2018.1424856

May, C. K. 2021. Institutional panarchy: adaptations in socio-hydrological governance of the South Dakota Prairie Pothole Region, USA. Journal of Environmental Management 293:112851. https://doi.org/10.1016/j.jenvman.2021.112851

Middleton, N., L. Stringer, A. Goudie, and D. Thomas. 2011. The forgotten billion: MDG achievement in the drylands. In United Nations Convention to Combat Desertification, Bonn, Germany.

Moritz, M., Z. Galehouse, Q. Hao, and R. B. Garabed. 2012. Can one animal represent an entire herd? Modeling pastoral mobility using GPS/GIS technology. Human Ecology 40:623-630. https://doi.org/10.1007/s10745-012-9483-6

Nathan, R., C. T. Monk, R. Arlinghaus, T. Adam, J. Alós, M. Assaf, H. Baktoft, C. E. Beardsworth, M. G. Bertram, A. I. Bijleveld, T. Brodin, et al. 2022. Big-data approaches lead to an increased understanding of the ecology of animal movement.

Science 375(6582):eabg1780. https://doi.org/10.1126/science.abg1780

Nelson, E., S. Khan, S. Thorve, and P. Greenough. 2020. Modeling pastoralist movement in response to environmental variables and conflict in Somaliland: combining agent-based modeling and geospatial data. PLoS ONE 15(12):e0244185. https://doi.org/10.1371/journal.pone.0244185

Orton, J. 2015. The introduction of pastoralism to southernmost Africa: thoughts on new contributions to an ongoing debate. Azania 50(2):250-258. https://doi.org/10.1080/0067270X.2015.1019262

Ostrom, E., and X. Basurto. 2011. Crafting analytical tools to study institutional change. Journal of Institutional Economics 7 (3):317-343. https://doi.org/10.1017/S1744137410000305

Quealy, H. M., and J. S. Yates. 2021. Situated adaptation: tackling the production of vulnerability through transformative action in Sri Lanka's Dry Zone. Global Environmental Change 71:102374. https://doi.org/10.1016/j.gloenvcha.2021.102374

R Core Team. 2019. R: a language and environment for statistical computing. https://www.R-project.org/

Reynolds, J. F., D. M. S. Smith, E. F. Lambin, B. L. Turner, M. Mortimore, S. P. Batterbury, T. E. Downing, H. Dowlatabadi, R. J. Fernádez, J. E. Herrick, E. Huber-Sannwald, et al. 2007. Global desertification: building a science for dryland development. Science 316(5826):847-851. https://doi.org/10.1126/science.1131634

Scheffer, M., S. R. Carpenter, T. M. Lenton, J. Bascompte, W. Brock, V. Dakos, J. Van de Koppel, I. A. Van de Leemput, S. A. Levin, E. H. Van Nes, M. Pascual, and J. Vandermeer. 2012. Anticipating critical transitions. Science 338(6105):344-348. https://doi.org/10.1126/science.1225244

Schilling, J., F. E. Opiyo, and J. Scheffran. 2012. Raiding pastoral livelihoods: motives and effects of violent conflict in north-western Kenya. Pastoralism: Research, Policy and Practice 2:25. https://doi.org/10.1186/2041-7136-2-25

Schofield, D., and F. Gubbels. 2019. Informing notions of climate change adaptation: a case study of everyday gendered realities of climate change adaptation in an informal settlement in Dar es Salaam. Environment and Urbanization 31(1):93-114. https://doi.org/10.1177/0956247819830074

Scoones, I. 1994. Living with uncertainty: new directions in pastoral development in Africa. Intermediate Technology, London, UK. https://doi.org/10.3362/9781780445335

Shepard, E. L., R. P. Wilson, W. G. Rees, E. Grundy, S. A. Lambertucci, and S. B. Vosper. 2013. Energy landscapes shape animal movement ecology. American Naturalist 182(3):298-312. https://doi.org/10.1086/671257

Smit, B., and M. W. Skinner. 2002. Adaptation options in agriculture to climate change: a typology. Mitigation and Adaptation Strategies for Global Change 7:85-114. https://doi.org/10.1023/A:1015862228270

Smith, A. B. 1992. Origins and spread of pastoralism in Africa. Annual Review of Anthropology 21(1):125-141. https://doi.org/10.1146/annurev.an.21.100192.001013

Smith, M. S., L. Horrocks, A. Harvey, and C. Hamilton. 2011. Rethinking adaptation for a 4° C world. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369:196-216. https://doi.org/10.1098/rsta.2010.0277

Swift, J. J. 2004. The global drylands imperative: pastoralism and mobility in the drylands. United Nations Development Programme Drylands Development Centre, Nairobi, Kenya.

Tache, B., and G. Oba. 2010. Is poverty driving Borana herders in southern Ethiopia to crop cultivation? Human Ecology 38 (5):639-649. https://doi.org/10.1007/s10745-010-9349-8

Vetter, S. 2005. Rangelands at equilibrium and non-equilibrium: recent developments in the debate. Journal of Arid Environments 62(2):321-341. https://doi.org/10.1016/j.jaridenv.2004.11.015

Wu, J., Q. Zhang, A. Li, and C. Liang. 2015. Historical landscape dynamics of Inner Mongolia: patterns, drivers, and impacts. Landscape Ecology 30(9):1579-1598. https://doi.org/10.1007/s10980-015-0209-1