



# Reframing rangeland systems science research in Kenya: a synthesis of social-science mixed methods to inform integrative analysis of landscape pattern and process

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Received: 22 March 2022 / Accepted: 26 June 2023  
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## Abstract

**Context** Interdisciplinary borrowing between ecology and the social sciences has produced numerous insights about pastoral livelihood practices and rangeland ecology, demonstrating how people practicing pastoralism constantly modify their practices to adapt to social, political, economic, and biophysical change.

**Objectives** I outline an approach for integrating research on pastoral livelihoods into a landscape ecology framework. I focus on access to land and resources, and an integrative approach to scale, to assess the relationship between landscape and social processes.

**Methods** I use remotely sensed data and ethnographic analysis of livelihood change in two semi-arid contexts in Kenya to compare broad scale changes in pastoral mobility to spatio-temporal patterns of

variability in rainfall and vegetation productivity. I then synthesize the political, economic, and social relations that have most prominently influenced access to land and restructured landscape process at finer scales.

**Results** Spatial controls have been imposed on land use that have increasingly partitioned landscapes and concentrated pastoral access to land. Access to land has also been influenced by changes in social norms, employment, and market relations. Informal rules and norms, social differentiation, and exclusionary partitions have produced socially differentiated land use intensity gradients and novel landscape processes that have not previously been considered in landscape analyses in Kenya.

**Conclusions** Understanding access, land use, and landscape processes as intertwined, with uneven processes of land and resource capture at different scales, would enable landscape ecologists to choose observational scales relevant to rural livelihoods and sensitive

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**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10980-023-01723-w>.

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to power asymmetries, creating robust analytical linkages between social and ecological processes.

**Keywords** Landscape process · Observational scale · Pastoralism · Access · Livelihoods

## Introduction

The knowledge produced by scholars working in anthropology and development studies has converged on describing pastoral practices as fundamentally adaptive, flexible strategies that optimize livelihood benefits under conditions of high environmental variability (Krätli and Schareika 2010; Scoones 1994). This contrasts sharply with historically dominant rangeland management paradigms over the last 100 years, which are closely linked to culturally specific ways of thinking about ecological stability that developed in the context of the American West (See Sayer 2017; Briske 2017; Davis 2016). The steady-state equilibrium model at the core of historical rangeland management paradigms focused on achieving maximum sustained yield of resources, and provided support for pejorative assumptions that colonial rangeland scientists often made about the productive logics of pastoralists throughout Africa (Niamir-Fuller 1999; Sayer 2017; Note S1). Equilibrium models of rangelands have been heavily critiqued, following arguments that high spatio-temporal variability and stochasticity of rainfall can create dynamics that decouple relationships between herbivores and primary productivity (Ellis and Swift 1988; Behnke et al. 1993; Briske et al. 2003; Scoones 1994; Vetter 2005; Westoby et al. 1989). Recent understandings tend to center variability, rather than stability, in rangeland ecosystems, with processes such as herbivory and fire as integral components of these systems that influence landscape pattern (Bond 2019; Briske 2017; Maestre et al. 2021). Additionally, ecologists' views of rangeland vegetation assemblages have evolved to include rapid, unexpected shifts between 'alternative stable states' (Westoby et al. 1989; Briske et al. 2003). Together, these conceptual developments have gradually led to a shift in paradigm among ecologists who today tend to understand rangeland systems as exhibiting scale-dependent dynamics, varying degrees of stability and instability, and non-linear changes in structure and function, with

complex underlying casual mechanisms (Briske et al. 2003, 2020; Vetter 2005).

Landscape ecology's focus on pattern and process (Turner 2005) has informed rangeland systems science (Wilcox et al. 2017; Fuhlendorf et al. 2017). However, landscape ecology has yet to incorporate social science to the extent of other disciplines (Note S2). In this paper I compare patterns of changing pastoral livelihoods to illustrate how political, economic, and social processes have transformed landscape processes in two rangeland contexts in Kenya. In a synthesis of key findings on changes in mobility patterns and livelihoods, I focus on how a series of institutional interventions since the British colonial era have filtered access to land and create a typology of key factors that have influenced flexibility of land use at different spatial scales. I discuss the promise of expanding attention to the determinants of access to land and other resources as a way to integrate a broader conceptualization of social complexity into landscape analyses that includes power relations and socially differentiated livelihoods.

## Institutions, access, and social mediation of landscape process

Institutional analyses have been widely used to show how rules and norms at different spatial scales interact with and shape ecological processes (Cumming et al. 2006; Kepe and Scoones 1999; Note S3). Conceptually, institutional analysis provides a framework that has been argued could provide landscape ecology with a systematic basis for understanding how social processes respond to and generate landscape pattern and process (Cumming and Epstein 2020). To date, new institutional economics (NIE) analyses building primarily on the work of Ostrom (1990) have been applied to assess the 'fit' of institutions and to analyze how "getting institutions right" can lead to sustainable use of resources in landscape analyses (Cumming et al. 2006, Epstein 2015; Young and Gasser 2002). However, the assumptions at the heart of NIE about social processes and human behavior have hindered understandings of power relations surrounding allocation and control of resources and neglected dynamics of inequality, social conflict, and decision-making processes in access to resources (Clever 2012; Cleaver and de Koning 2015; Note S4). Further limitations of NIE approaches are

apparent when applied to extensive pastoralist systems. These systems are often characterized by fluid boundaries and flexible processes of accessing spatio-temporally variable resources; ‘fuzzy’, overlapping characteristics of private, common, or ‘open’ property systems (Fernández-Giménez 2002; Moritz 2016; Turner 2011; Robinson 2019); plural understandings of property and rights often at play (Schlager and Ostrom 1992; Sikor et al. 2017); and a high importance of informal institutions in natural resource access and control.

Ribot and Peluso’s (2003) ‘Theory of Access’ is an alternative framework that can be applied in studies of how social, political, and economic relations structure natural rural resource use in a variety of contexts and highlights structural and relational mechanisms and “webs of powers” that shape and maintain access to resources. This framework avoids many of the limitations of NIE by considering a wider range of political, economic, and social processes, and drawing closer attention to the uneven abilities of actors to access and control resources. This framework is also closely related to a proliferation of social science concepts that have been used to explore the relationship between land control, power, and authority (Sikor and Lund 2009; Peluso and Lund 2011). Together alongside critically-informed understandings of institutions that center the power relations, historical contingencies, and context-dependent processes that structure, reaffirm, and legitimize various institutional configurations (Cleaver 2012; Cleaver and de Koning 2015; Cleaver and Whaley 2018), these approaches enable increased analytical precision in the study of what has long been understood: that power is intertwined with institutional structures that shape ecological pattern and process (Scoones 1999). Below I build on these and additional conceptual developments that help to translate the way that different disciplines conceptualize and operationalize scale, to better integrate social science concepts into landscape ecology.

### Toward an integrative understanding of scale

Numerous recent conceptual developments in rangeland systems science have been informed by landscape approaches that have drawn attention to scale-dependence of biotic interactions, spatio-temporal variability in rainfall and temperature, and heterogeneity in vegetation assemblages, edaphic conditions,

and topography (Briske 2017). Recent landscape approaches in rangeland systems science rely on a sophisticated conceptual and methodological toolkit to guide research on how different types of ‘bottom-up’ eco-hydrological, vegetative, and edaphic feedbacks interact with ‘top-down’ processes such as herbivory and fire that together reinforce or drive changes between alternative stable states that can create emergent landscape patterns (see Wilcox et al. 2017). However, scale is a concept with important similarities, but also contrasts, in the way it is applied in the disciplines of landscape ecology and human geography (Higgins et al. 2012; Sayre 2005; Sayre 2009; Sayre 2017; Note S5). Ongoing debates about scale within landscape ecology stand in contrast with how geographers have critically interrogated observational scale as epistemologically relative, socially constructed, and rooted in power relations (Lebel 2006; Neumann 2009; Rangan and Kull 2009; Sayre 2005, 2017). Drawing from these differences integratively encourages careful thinking about intrinsic scale, scale-dependence of socio-ecological relations, and how socially-mediated processes contribute to our selection (i.e. imposition) of observational scale (see Sayre 2005; Sayre 2015; Higgins et al. 2012 for reviews; Note S6). Below, I build on past study of pastoral livelihood practices in two locations in Kenya (Note S7) to show how institutional changes (i.e. the rules and norms of resource use at different scales), asymmetric power relations, and social differentiation are entwined with landscape processes leading to constraints that access to land have placed on Maa-speaking groups’ livelihoods, as a means to reframe ecological analyses of rangeland landscapes. The two case studies draw attention to a bias in choice of observational scale that dominates ecological knowledge production in Kenya, and point to the need for integrative approaches to better understand landscape pattern and process.

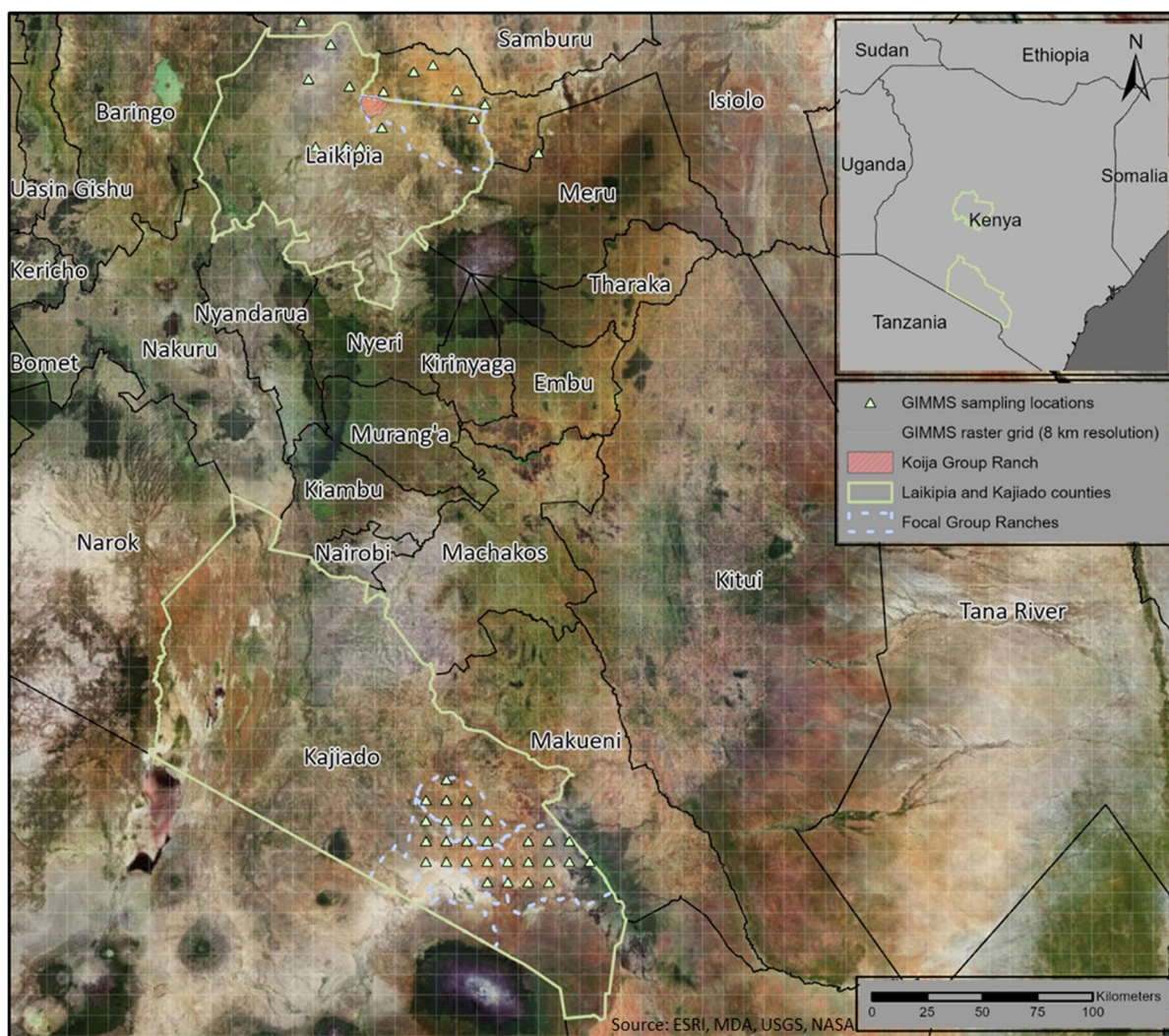
### Methods

A description of the history of the study sites including historical exclusions from national parks and settler ranches in Laikipia, establishment of group ranches (GRs), changes in livelihoods, and community-based conservation (CBC) interventions is provided in the supplementary materials (Note S8). I

completed 12 months of study during 2012–2016 at Koiya GR and surrounding areas in Laikipia County, and eleven months of study during 2018–2019 in three GRs surrounding Amboseli National Park (ANP) in Kajiado County (Fig. 1). Surveys and interviews were designed and completed together with hired research assistants who were members of the respective GRs and who translated surveys and interviews from Maa to English (Note S9). At Koiya GR, we completed eight focus group discussions with elder herders, which were then used to design surveys at 225 out of 245 total homesteads, with two brief follow-up surveys in 2014 and 2015. We also completed

20 semi-structured interviews with elders, supplemented with participant observation of livestock husbandry practices and informal interviews. In three GRs in Kajiado (Olgulului-Olororashi, Eselenkei, Imbirikani), we completed 132 interviews. Except for cases when permission was not granted, all interviews were recorded.

To supplement the above social science mixed-methods, I used archival satellite records to create time series data sets of rainfall and primary productivity across sampling extents that could be compared to broad scale spatial and temporal patterns of access to land (Fig. 1). NDVI monthly composites



**Fig. 1** Locations of the study sites, sampling locations, and the observational scale of GIMMS NDVI data in Kenya

of AVHRR imagery from the GIMMS NDVI3g.v1 dataset (Pinzon and Tucker 2014) were created for the time period of 1980–2015 using the gimms package in R software (Detsch 2021). Monthly rainfall estimates from the CHIRPS dataset (Funk et al. 2015) ( $0.05^\circ$ ,  $\sim 5$  km) were resampled to match the spatial resolution of GIMMS rasters ( $1/12^\circ$ ,  $\sim 8$  km resolution) using the bilinear method in R software. The observational scale of this imagery, though limited in its ability to account for important aspects of vegetation community heterogeneity, soils, and forage quality due to its coarse spatial grain ( $\sim 8$  km), provides the only comparable source of long term (1980–2015), high frequency (monthly), vegetation productivity data at a spatial and temporal extent that could be compared to the broad changes in pastoral mobility observed.

Two sampling strategies were used to match the scale of analysis of changes in mobility over the past 40 years that were most important for livelihoods in each study site, applying an observational scale appropriate only for understanding broad scale patterns of mobility and dynamics of spatio-temporally variable rainfall and vegetation. It should be noted that mobility and land use patterns are much more complex, heterogeneous, and temporally variable in practice than this analysis implies (Note S10). For the Laikipia study site (Koiya GR), where pastoral mobility had been most impacted by a lack of access to sites outside of group ranches, I created sampling points by georeferencing place names that more than 10 households (out of 225) indicated that they had formerly migrated to but had since been excluded from, as well as sites visited at the time of study ( $n=15$ , Fig. 1). I grouped sampling points by decades when they were accessed, and sampled monthly rainfall and NDVI to create a time series from 1980 to 2015. I then calculated mean and standard deviation by month for each location, as well as the maximum value of any single site available for access for each month. For the Kajiado GRs, where increasingly regulated access to land within GRs were the most salient changes in mobility since creation of GRs and exclusion from Amboseli in the 1970s, I created sampling points located in the center of GIMMS pixels. I then classified these sampling points according to my understanding of seasonal patterns of forage access at different times of the year ( $n=28$ , Fig. 1). These spatio-temporal patterns of land use were simplified

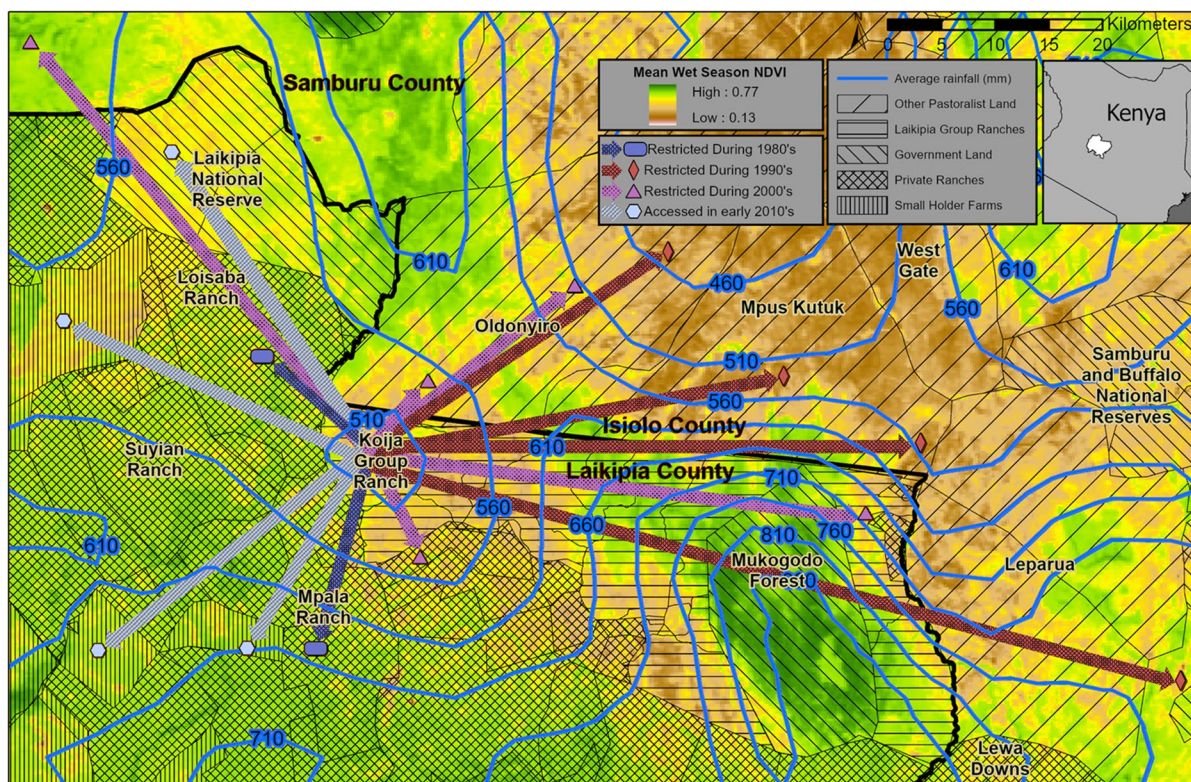
to permanent settlements, early dry season grazing reserves, and late dry season grazing reserves and conservancies for the present analysis. Because this sampling strategy was intended to capture patterns of seasonal access for many different settlements, the spatial distribution of which were established prior to the satellite record, I calculated mean and standard deviation statistics alone. Due to the low resolution of GIMMS data, the spatial patterns of swamps located with surrounding low productivity areas produced mixed pixels that were not representative of productivity within swamps, and thus NDVI measurements of swamps were excluded from analysis. To supplement this analysis with visual comparison to higher resolution data, spatial patterns of annual and monthly variability in native resolution CHIRPS rainfall and mean values of MODIS 250 m resolution MOD13Q1 16-day NDVI composites (from 2000 to 2020) were processed to create figures using R software.

Findings on livelihoods, access to land, and spatio-temporal variability of rainfall and vegetation productivity are organized according to two sections for each study site, (1) historical changes in ranges of mobility, and (2) livelihood changes corresponding to decreasing mobility. Supplementary notes discuss published work that informed the analysis reported here.

## Results

### Changes in ranges of mobility and access to land outside of Koiya GR

Elders at Koiya indicated that, until the early 1980's when they began to be denied access, it was common practice of households to combine herds and move to areas within ranches leased by settlers to the west (Fig. 2; Note S11). A second wave of exclusion from grazing occurred to the north and east of Koiya in the 1990's, primarily caused by conflicts rooted in disputes over land. This was linked to colonial-era boundaries, changes in administrative boundaries over time, and wider political conflicts (Fig. 2; Note S12). A third series of exclusions in the 2000's was driven by formation of conservancies in areas on GRs neighboring Koiya, and other lands to the immediate north, as well as additional land conflicts in the far northwest (Fig. 2; Note S13). At the same time,



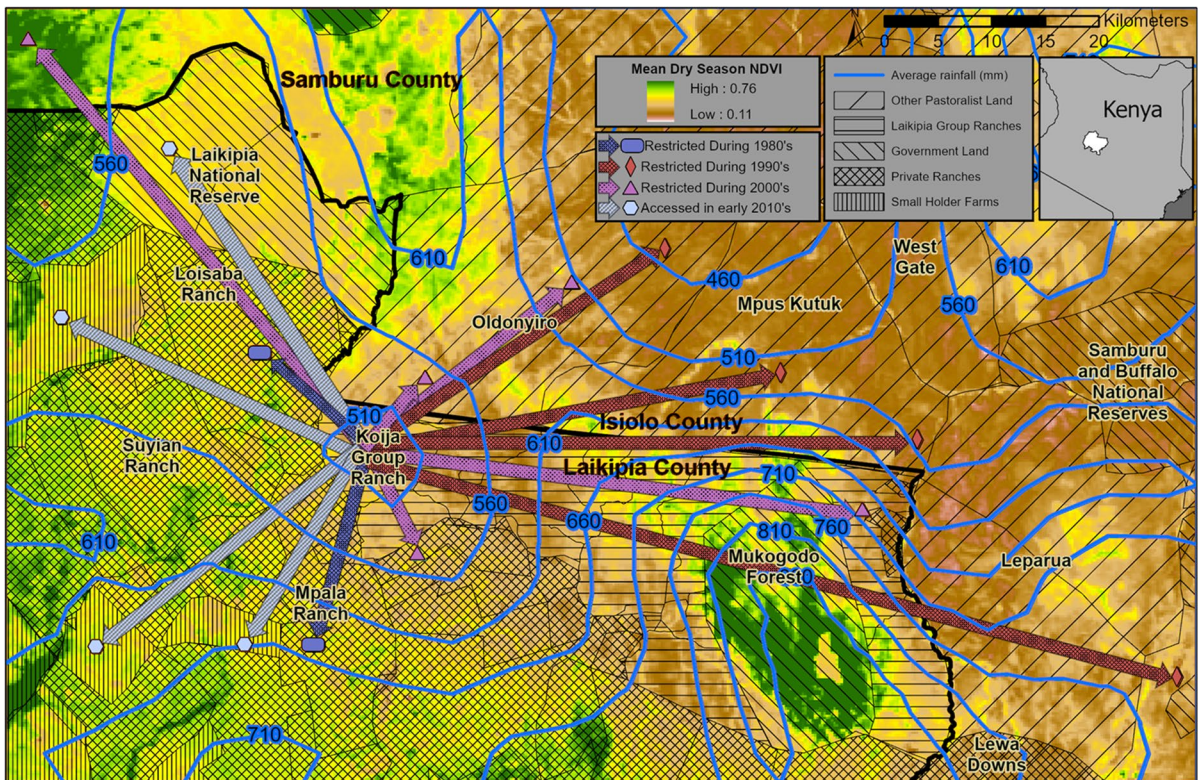
**Fig. 2** Mean annual wet season (June) MODIS NDVI on the borders of northern Laikipia, Samburu, and Isiolo counties

conservancies also began to become formalized in areas that Koiya residents had been excluded from in the previous decade. By the 2010's it had become increasingly difficult to access sufficient forage with livestock, as other nearby conservancies became formalized and restricted (Note S14).

Distinct patterns of spatial partitioning today (Fig. 2) correspond to the location of private ranches in Laikipia along rainfall gradients (Figure S1). The location of these ranches is a legacy of settlers claiming areas of highest productivity and lowest annual variability (Note S15), with the exception of Mukogodo Forest, which is state-held land and which Koiya residents did not indicate that they had accessed in the recent past (Fig. 2). Distinct temporal patterns of rainfall are salient; areas to the west and south of the GRs are more likely to receive rains in June-July (Figure S2). Rainfall is closely related to NDVI patterns observed at the end of the wet season (Fig. 2) and dry season (Fig. 3).

At the time of study, sheep and cattle usually required mobility within annual cycles when grass

within Koiya could no longer support them; sheep were able to subsist for longer on marginal grass relative to cattle. Livestock leaving Koiya were taken to few locations, and households mostly individually arranged access. Paid grazing on neighboring private ranches began in the early 2000s, where ranches set a quota on the number of cattle that could enter to graze for a fee (Note S17). This conferred high benefits for animal health, and guaranteed cattle's survival in times of drought. However, this access was not available for sheep and goats. Additional access beyond the set quota was granted to employees or other people with close relationships with ranch managers. In one year when grass was inadequate on Koiya, ~14% of Koiya's cattle gained access to private ranches through paid grazing, ~23% gained access to private ranches through personal relationships or through employment, ~6% were present in very low densities in absentee owned and government owned lands, and the remaining ~57% relied on extremely marginal forage present within Koiya (Note S18). Many were left with no recourse to prevent cattle from dying

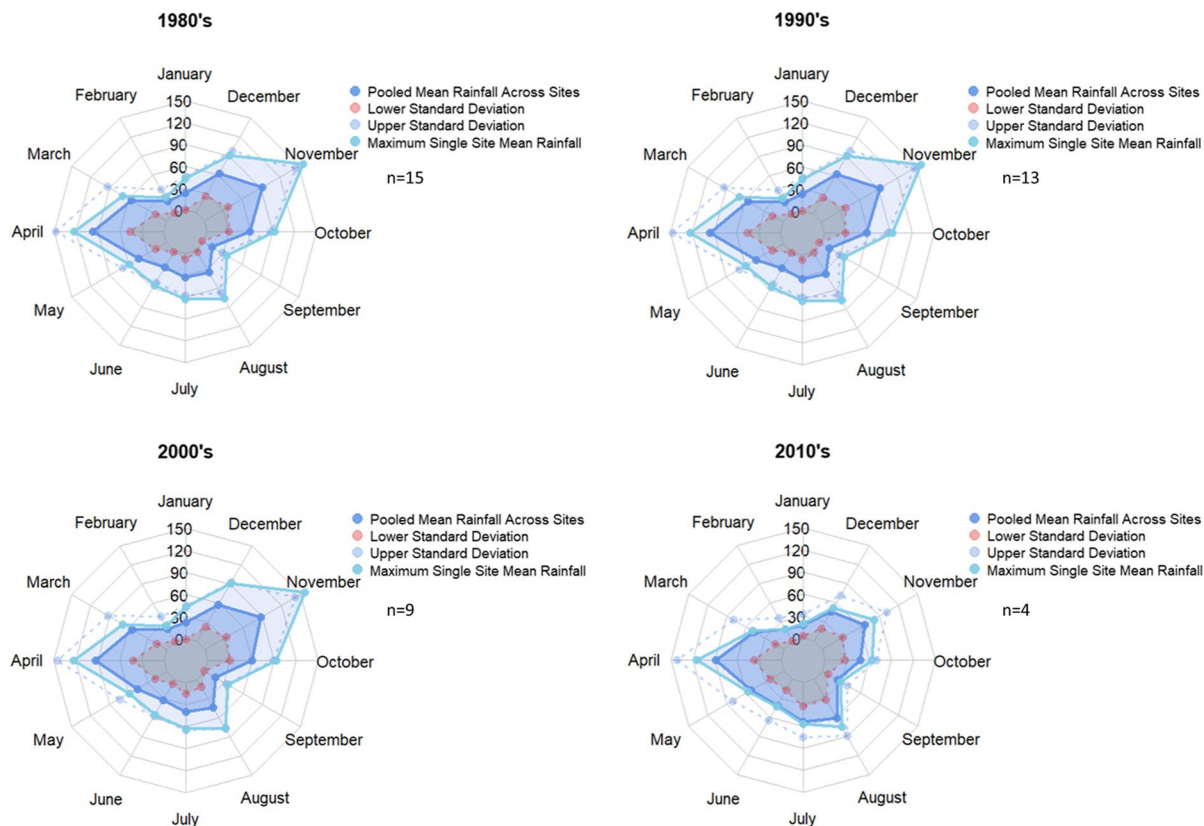


**Fig. 3** Mean annual dry season (September) MODIS NDVI on the borders of northern Laikipia, Samburu, and Isiolo counties

other than through unauthorized access to private lands, which posed high risks due to wildlife (e.g., buffalo, elephants, lions, and leopards), and potential monetary penalties, confiscation of livestock until a fine was paid, or jail sentences. Ten households, the wealthiest at Koiya, accounted for 25% of authorized access of cattle to private land, who also had higher use of absentee owned and government owned lands (Note S19). Goats at the time of the study rarely left Koiya and could be sustained by browsing locally on woody vegetation, in part due to the increasing abundance *Acacia mellifera* (Note S20). At the same time ~41% of Koiya's sheep were located in three absentee government owned parcels, and the other ~59% were located within Koiya. Absentee and government owned parcels were located primarily on vertisol soils that were dominated by *Pennisetum mezianum* grass, which was only palatable for cattle grazing following heavy rains (when there was also sufficient water for livestock; Note S21). Considering

productivity and rainfall at all of the sites available that could be accessed without payment, and the trend of increasing exclusion over time, the overall grazing locations available across the study site had been reduced to some of the areas with lowest rainfall (Fig. 4), the lowest primary productivity (Fig. 5), and an overall decrease in diversity of livestock forage options throughout annual cycles.

Under exclusions constraining access, migration was sustained differentially by those with a set of personal assets that enabled it (Note S22). These assets included available herding labor, outside income for costs such as livestock medicine, a second homestead and cattle enclosure located within informal areas, and means of transporting herders and items such as building materials. Herding labor was essential to migrate with livestock and to split households; historically, norms of labor sharing were common, but with many children now attending Kenyan schools, a new system of paid herding had emerged (Note S23).



**Fig. 4** Rainfall (1981–2015) by month (mm), considering the locations available to Koiija residents for unpaid grazing access by decade

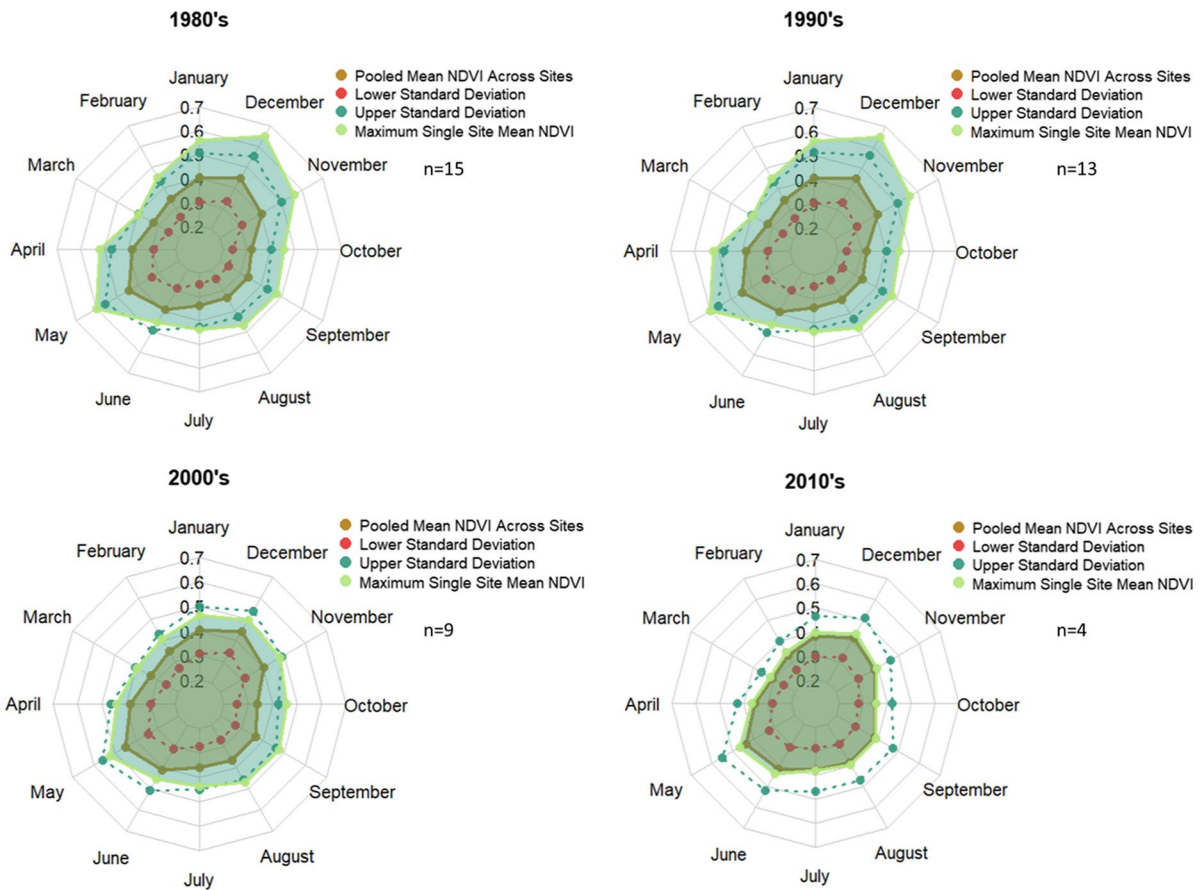
### Livelihood changes corresponding to decreasing mobility at Koiija

Human population size at Koiija had roughly doubled from the 1980's to 2016; concurrently, there was a ~35% decrease in cattle and an approximately tenfold increase in sheep and goats. There was also a marked increase in inequality, and cattle and sheep herd increases were more likely for households with a member that was employed (Note S24). The overall density of livestock at Koiija had increased over the past 30 years, but the average amount of livestock per person had decreased by 33.5%. Many indicated that conditions of drought (droughts occurred in 1997, 1999–2001, 2009, and 2014) and limited mobility were leading them to keep only goats, and some households had begun to keep camels (Note S25); ~30% indicated that they did not leave Koiija to access livestock forage. In addition to lack of mobility, goats had become favored due to their fast reproduction,

drought resistance, ease of slaughter and sale, and increased reliance on grain purchased in markets rather than livestock products for household diets (Note S26). Small stock sales also provided cash necessary to support cattle under this more individualized and monetized system of access. However, those with smaller herds or no access to outside cash were more likely to be forced to sell animals to buy grains to feed their families at times when prices were not optimal. Mobility thus was primarily shaped by relations with private conservation ranches, and a range of other household assets, with those that lacked these assets primarily adapting by keeping small, less mobile herds of goats (Note S27).

Although elders sometimes referred to both population increase and many areas now being occupied as limiting their livelihoods, they often emphasized the complex interactions among access, household assets, markets, and labor, as well as increases in livestock diseases and increasing rainfall variability.





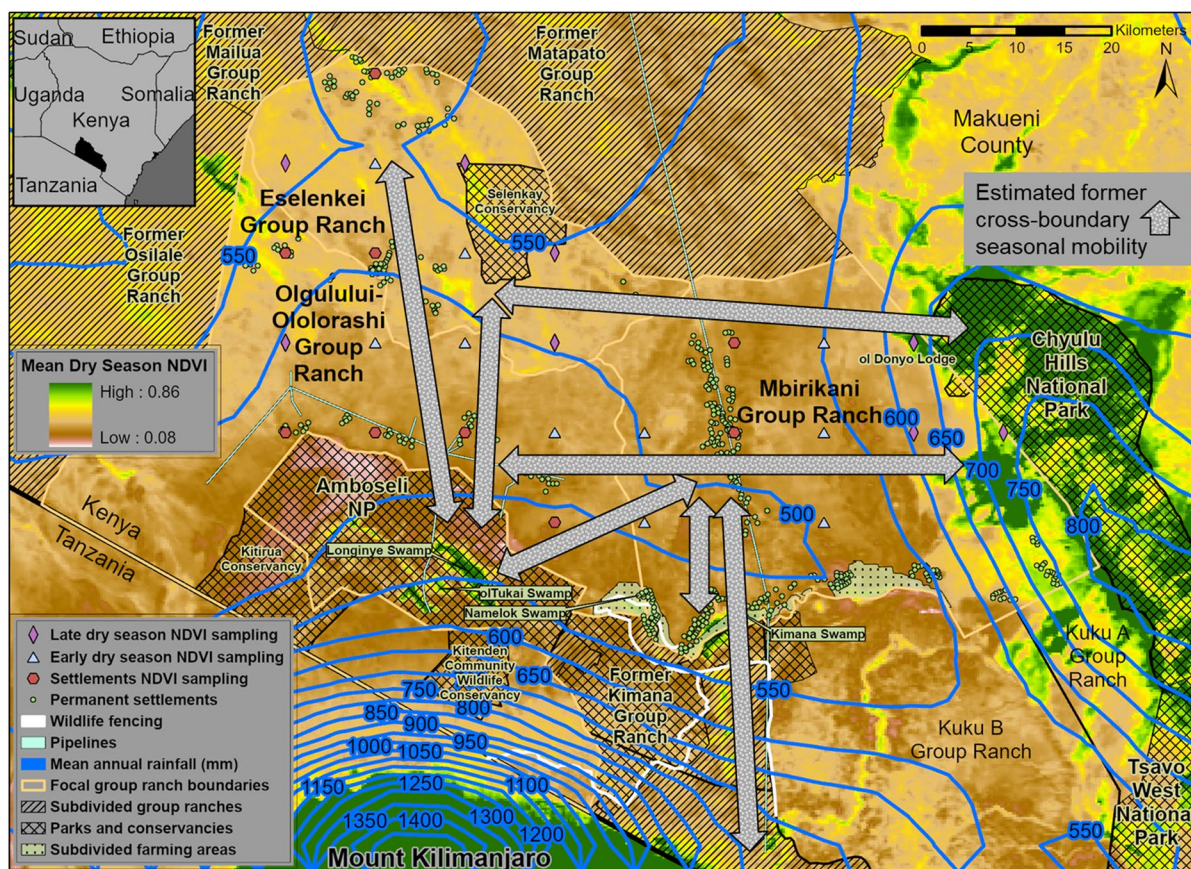
**Fig. 5** NDVI (1981–2015) by month, considering the locations available to Kojija residents for unpaid grazing access by decade

Satellite analysis showed that Kojija and other pastoralist lands were located in the driest, least productive areas within the study site (Figs. 2 and 3, S1, & S2) and limitation of ability to access a diversity of locations throughout the annual cycle (Figs. 4 and 5) had decreased the efficacy of mobility as an adaptive strategy to respond to spatio-temporal variability. Furthermore, many elders indicated that low mobility livestock and qualitative changes in herd composition had long-term implications at local scales, especially limiting the amount of time grass had to regenerate (Note S28). With goat herding remaining the only viable strategy for many that lacked the ability to be mobile, this was also likely creating a reinforcing feedback that was decreasing herbaceous forage growth near homesteads. This was compounded by private ranches beginning to cease paid cattle grazing immediately following rainfall, forcing cattle to return to Kojija before grasses had begun to grow

(Note S29). The ecological implications of exclusion from conservancies and private ranches were also discussed by elders at length. It was common for elders to state that conservation areas and areas on neighboring ranches were not grazed frequently enough, and that exclusion of livestock was leading to negative impacts on grasses that made them less nutritious for livestock (Note S16).

#### Changes in ranges of mobility and access in Ilkisongo land

In Kajiado, chiefs historically implemented a series of land use regulations that imposed important limitations on livestock mobility. The first rules chiefs implemented imposed boundaries that limited migration into Matapato and Kaupetei Maasai lands to the north and west (Fig. 6). Following establishment of GRs throughout the 1970s, movements between GRs



**Fig. 6** Mean annual dry season NDVI and approximate historical mobility patterns that have become constrained in the Amboseli ecosystem

also became discouraged. As part of GRs, permanent settlements were established at borehole locations and water points at junctures along pipelines (Fig. 6). New delineations of dry and wet season grazing were also established, and regulations were imposed on the distance that herds could move in a single day (Note S30).

Following exclusion from settlement within ANP in 1977, after it being gazetted as a national park, swamps within ANP were sometimes still accessed for water at the time of the study by those living in settlements on the edge of the park, but they were limited to several hours per day. Access to other nearby swamps was limited by their designation for crop cultivation and subdivision in Olgulului-Olorashi GR in the 1970s and Imbirikani GR in the early 2000s, as well as from Kimana sanctuary (Fig. 6; Note S31). Further exclusions occurred following

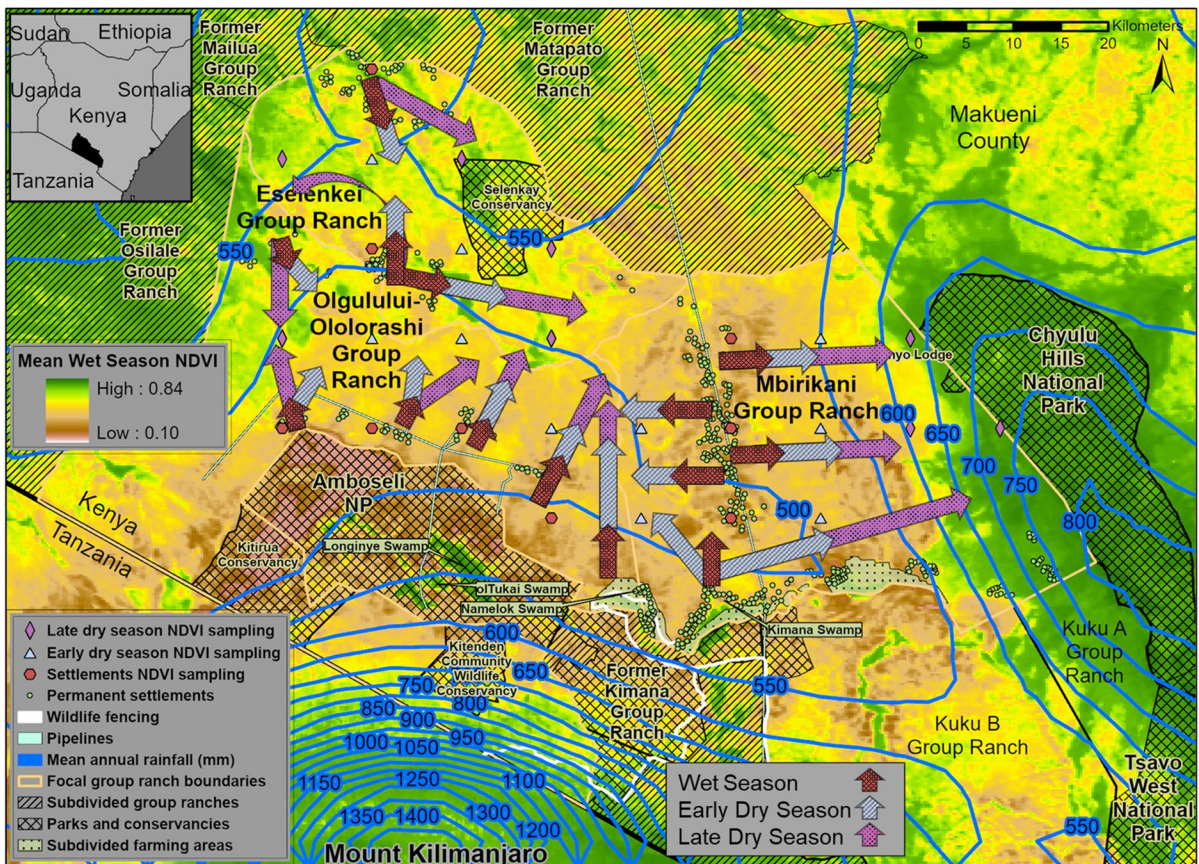
subdivision of GRs throughout the Ilkisongo section (i.e. from Kimana south; Fig. 6), as well as to the north and west in the Kaputei and Matapato sections, limiting movement to these areas with the exception of those with personal relations or an ability to pay for grazing access (Fig. 6). Exclusions from conservancies within GRs also limited access, and in the case of Selengay conservancy, settlements were relocated (Fig. 6; Note S32). More recently, movements to grazing areas allocated to different settlements have increasingly been discouraged, sometimes through access to water being limited or charged for, and water and forage access were sometimes limited by clan affiliation (Note S33). As of 2019, movement across boundaries required permission from a variety of authorities within Ilkisongo communities such as government chiefs, GR committees, community wildlife rangers, and members of different

settlements, with denial being common. Although this did not fully fragment the movement of herds, and rules became more flexible during drought conditions, it had become increasingly difficult for herders to access adequate forage.

These restriction in mobility are vital to consider in relation to annual mean, annual variability, and mean monthly rainfall patterns throughout annual cycles (Figs. S3 and S4). For example, rainfall is notably higher in April, November, and December on the eastern side of Mbirikani GR (Figure S4). Elders often contrasted grazing patterns at the time of study (Fig. 7) with historical movements (approximated in Fig. 6). Prior to establishment of permanent settlements, decisions about when and where to move were based on the availability, type, and quality of forage, and strategic use of rainfed catchments, ponds, and seasonal streams. Furthermore, mobility decisions

were historically made in a way that prioritized optimization of the health of livestock. One past pattern of movement that elders commonly described was migration near to depressions in upland areas that filled with water following seasonal rains, then shifting to the use of shallow wetlands when these water points were exhausted, and then finally moving to swamps (now within ANP) during the dry season (Fig. 6). Another common pattern of former movements was migration to areas within Imbirikani GR in the time corresponding to November (Fig. 6), when rains were more likely to create reliable forage there, followed by movement to Olgulului-Olororashi or to areas in Chyulu Hills National Park (CHNP) if rainfall had been limited elsewhere in that annual cycle (Fig. 6).

Social differentiation in ability to access late dry season grazing areas had increased within the



**Fig. 7** Mean annual wet season NDVI and approximate spatial mobility patterns according to current seasonal access rules across the Amboseli ecosystem

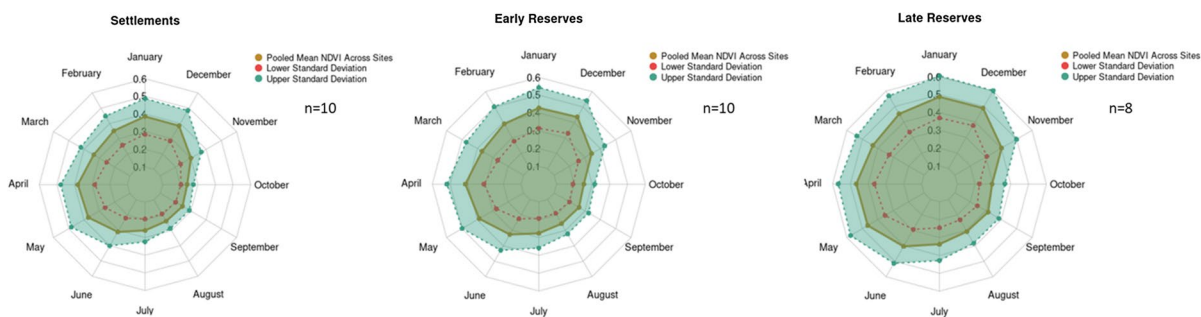
previous decade. Following establishment of settlements, locations where livestock enclosures could be constructed within dry season grazing reserves became limited by chiefs intending to minimize mobility. These late dry season grazing reserves correspond to areas that became largely designated as wildlife corridors by conservation NGOs (Note S34). Households' abilities to access and benefit from these areas in part relied on their ability to utilize trucks to transport water and feed, which enabled access to less-exploited forage and reduced walking strain on animals (Note S35). In turn, access to transport relied on both ability to pay and social relations (e.g., kinship, clanship, neighbors). While those using transportation were able to remain in dry season areas and reduce walking strain on livestock, others' cattle were forced to walk long distances for water. Additionally, with children increasingly attending Kenyan schools, and decreasing mutual assistance between people from different levels of wealth, grazing access had become differentially limited by herding labor (Note S36). Paid herding had become prominent, and at the time of study was important for maintaining and protecting cattle in remote dry season areas with higher densities of predators. Inequalities in labor and transportation use were also closely related to benefit streams other than livestock or farming (Note S37). Another key asset shaping grazing access was multiple homestead locations, which enhanced access rights across GRs and other boundaries. Multiple homesteads also enabled splitting of labor between locations and facilitated herd splitting to optimize production. Finally, once forage within GRs was exhausted, in an unpalatable state, or impossible to transport water to, outside relations became extremely

important for accessing nearby privately titled lands (e.g. through family, friends, or payments).

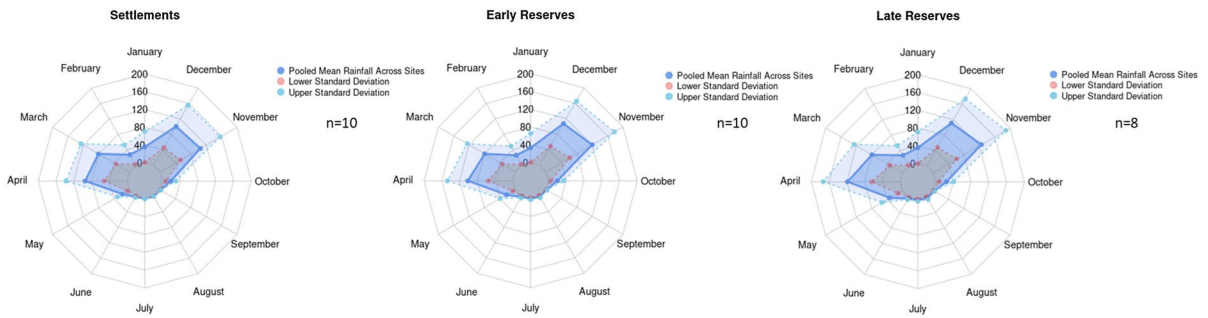
Analyzing the patterns of rainfall and productivity within the partitions that have been imposed on land access across the Amboseli ecosystem over time showed that settlements, aside from those in northern Eselenkei and those near to CHNP on the eastern side of Imbirikani, were located in areas that were on average the driest within GRs, with many located within the rain shadow of Mt. Kilimanjaro (Figs. 8 and S3). Settlements also had patterns of lower productivity relative to grazing reserves (Figs. 8 and 9) and concentrated the impacts of livestock on vegetation, and thus likely contributed to the lower NDVI levels measured near to settlements (Note S38). The areas of highest productivity were concentrated within late reserve grazing areas (Fig. 8) with higher mean rainfall, especially in April (Fig. 9). Settlement in these swamps during the dry season was formerly an essential component of pastoral livelihoods, especially cattle husbandry; exclusion had dramatic implications for livestock keeping, highlighting a key limitation of this analysis.

#### Livelihood changes corresponding to decreasing livestock mobility across the Amboseli Ecosystem

At the time of study, farming was differentiated between those that relied on cash crops, those who practiced subsistence farming, and others who primarily leased their land to non-Maasai farmers, typically for very low returns (Note S39). Having a farm plot also enabled some to sustain livestock during drought and contributed to the increasing prevalence of less mobile 'improved' breeds of livestock,



**Fig. 8** GIMMS NDVI (1981–2015) by month within approximate current seasonal livestock access partitions of the Amboseli Ecosystem



**Fig. 9** Rainfall (1981–2015) by month (mm) within approximate current seasonal livestock access partitions of the Amboseli Ecosystem

increasing use of livestock feeds, and patterns of accumulation of benefits from land (Note S40).

Market price fluctuations had important differential impacts across households. Those with larger herds, or a secondary source of income, were able to sell livestock and crops strategically when market prices were high. Some were forced to sell livestock at low prices when cash was required for household needs, especially to pay for food and school fees (Note S41). In general, those who had employment (often in wildlife conservation activities) were better able to benefit from livestock and farming activities (Note S42). Changing access conditions along with market relations have both contributed to increases in small stock and increased adoption of ‘improved’ livestock breeds that consumed more forage, were less able to migrate long distances, and required more intensive herding practices (Note S43). These changes in access, labor, and market relations also interacted with other practices such as supplementary feeding of cattle with grains during drought, all of which tended to benefit wealthier, employed Ilkisongo.

### Synthesis of findings

Colonial and post-colonial state authorities, local government authorities, elected GR representatives, and ‘non-state’ actors (e.g. settler colonial communities and NGOs representatives) have all played a role in ‘top-down’ formal and informal institutional changes that have imposed spatial controls (e.g. boundaries, changes in tenure, and other partitions such as conservancies) that have limited access to forage and

watering points required to support mobile pastoralism (Table 1). However, key differences and contingencies were present in the way that ‘top-down’ policies played out in local contexts. Farming cash crops in Kajiado for export to Nairobi, and recent conflicts surrounding land in Laikipia, are both important for understanding recent changes in access and are closely related to both national political economy and recent narratives specific to each location that have motivated wildlife conservation interventions.

In both study sites, access and land use practices had also been strongly impacted by market relations, changing mutual assistance practices, inequality, and differentiated human-wildlife interactions that all shape access to and benefits from land (Table 2). A key similarity between sites is that previously, assets that enabled livestock mobility (e.g. labor and multiple homestead locations) were pooled to a much greater extent. However, shifting norms of mutual assistance and new systems of access to land had made the costs and benefits of mobility increasingly borne by individual households (Table 2). In both cases, loss of ability to strategically respond to variable rainfall and primary productivity at broad scales with mobility, had necessitated adaptations, such as adjusting herd composition, or adopting farming, within localized areas where these practices are highly socially differentiated (Table 2). Some were able to sustain greater degrees of mobility than others, or to have more beneficial interactions with markets within new economic systems that required cash assets (Table 2).

**Table 1** Main institutional changes creating partitions and reconfiguring access to land at the two study sites

Main institutional changes creating spatial partitions and reconfiguring access to land	Laikipia	Kajiado
Enforcement of state and private land boundaries (formal)	Restrictions from settler-held, smallholder, and government parcels	Restrictions from national parks, private ranches, and subdivided group ranches
Exclusion through land conflict (informal)	Politically fueled land claims, conflict, and exclusions	N/A
Collectively titled group ranch boundaries (formal)	Restricted movement across group ranch boundaries	Restricted movement across group ranch boundaries
Partitions of grazing areas (formal and informal)	State-imposed and NGO-influenced regulatory practices constraining flexible mobility practices	State-imposed and NGO-influenced regulatory practices constraining flexible mobility practices
Leases within GRs (formal)	Restrictions due to leases of collective land for conservancies and tourism facilities	Restrictions due to leases of collective land for conservancies, tourism facilities, and cement mining
Internal partitions of land for farming (formal and informal)	Small enclosures designated for farming and private grazing	Areas designated for farming, increasing grazing enclosures with subdivision approaching

## Discussion

People who rely on pastoralism as a livelihood have been systematically limited by sedentarization and exclusionary wildlife conservation practices to areas with less rainfall and lower productivity in both study sites. Asymmetrical power relations have had a strong influence over CBC governance (German et al. 2017; Unks 2022), and many policies implemented with intentions of sustaining landscapes open to mobile wildlife have created new barriers to livestock mobility (Unks et al. 2019; Unks 2022), despite recognition of the close relationship between high densities of wildlife and pastoral livelihoods (Western et al. 2009), and widespread recognition of pastoralism's role in maintaining grassland states and influencing spatial heterogeneity of vegetation, both of which can be beneficial to wildlife (Augustine et al. 2003; Homewood 2008; Notenbaert 2012; Western and Gichohi 1993; Young et al. 1995). This constitutes a scalar mismatch (Cumming et al. 2006) between institutional structure and the social processes underpinning livestock mobility and ability to flexibly respond to spatio-temporal variability (Unks et al. 2019).

Key ecological insights from this analysis include a need for increased attention to reconcentration of land use along gradients, changes in the timing of responses to spatio-temporal variability in rainfall within annual cycles, and how adaptations to constraints can produce qualitative shifts in

landscape processes. Understanding these dynamics requires an approach that is sensitive to the complex interplay between 'top-down' interventions that have largely manifested in formalized hard boundaries and restrictions, but also informal and formal filters on access that act in a more 'bottom-up' way. This draws attention to how new gradients of use form, which in turn shape landscape processes and socially differentiated patterns of access that can be driving changes in landscape process. This approach would also be highly compatible with recent approaches that emphasize rangeland systems as structured by complex, multi-scalar interactions among rainfall regime, hydrology, herbivory, edaphic conditions, and fire (Bond 2019; Sankaran et al. 2005, 2008, 2013).

Findings from the current analysis, focused on an observational scale relevant to changes in livestock mobility, draw into question conclusions drawn about the ecological impacts of pastoralism through landscape analyses that have focused on observation scales that overlooked the intrinsic scale of pastoral livelihood practices. Actors spearheading conservation and development projects in both study sites often point to population, stocking rates, and land management practices in their explanations of limited forage resources available to support pastoralism (Unks et al. 2019; Unks 2022). Similarly, 'overgrazing' is commonly referred to in publications without qualification or precision (e.g. Scheetz et al.

**Table 2** Main institutions mediating access and livelihoods, and household factors mediating socially differentiated outcomes in the two study sites

Key institutions mediating access and livelihoods	Laikipia	Kajiado
Access norms for privately titled ranches and national parks (formal and informal)	Dependent on herd size and composition, personal relationship, and/or payment	Dependent on homesteads location, personal relationship, and/or payment
Access norms for smallholder private parcels (informal)	Dependent on personal relationship or payment	Dependent on personal relationship or payment
Access norms for absentee owner or open access state land (informal)	Dependent on household assets and herding labor	N/A
Access to partitions of grazing areas within GRs (formal and informal)	Dependent on household herding labor and assets	Dependent on household herding labor, assets, and local access rules
Access norms for movement between GRs (formal and informal)	Personal relationship usually required	Personal relationship or second homestead usually required
New access norms for leased conservancies (formal and informal)	Used mostly by those with homesteads nearby, during drought only	Used mostly by those with homesteads nearby, during drought only
Decreases of mutual assistance in labor sharing (informal)	Paid herding increasing, especially for those with income in addition to livestock	Paid herding widespread, ability to pay can be a key determinant of livestock husbandry success
Increasing need for cash incomes to support mobility (formal and informal)	Sources of income in addition to livestock are an important determinant of livestock care and mobility	Sources of income in addition to livestock are an important determinant of livestock care and mobility
Rules of wildlife conservation benefit distribution (formal and informal)	Primarily through employment and patron-client relations, closely related to cattle access on private lands	Primarily through employment and patron-client relations, closely related to ability to sustain farming and livestock
Market relations and benefits (cash crop and livestock, formal and informal)	Key factor shaping herd viability	Key determinant of cash crop and herd viability
Processes of livestock, water, and feed transport (informal)	Less important, and limited to wealthier herders, but influences market relations and access to land	Favors access to land for those with cash assets and social relations that facilitate transport

2022; Okello et al. 2015), contributing to narratives of problems in management, overuse, or overpopulation being the dominant drivers of landscape change. However, these narratives (1) overlook the relationship between land use practices and multi-scalar institutional changes, (2) neglect the close spatial correspondence between annual rainfall and primary productivity in both study sites and, (3) as a result, overlook the increasing partition and exclusion of land users from the areas of highest rainfall and productivity.

Some publications by ecologists acknowledge landscape fragmentation, but usually refer to sedentarization as socially uniform, do not discuss how state policies have coerced sedentarization, and do not consider spatiotemporal variability of rainfall or edaphic and hydrological heterogeneity; instead they draw generalized conclusions about shortfalls in forage productivity and changes in vegetation structure due to grazing (Western et al. 2015, 2021). One highly cited study about rangelands in Kenya draws conclusions about the impacts of livestock and human populations on wildlife using an observational scale corresponding to county boundaries (Ogutu et al. 2016). However, this analysis overlooks the importance of changes in mobility, finer-scale changes in intensity of livestock use, and the importance of spatio-temporal variability in rainfall and temporal dimensions of livestock use. Other publications have claimed that woody encroachment is driven by livestock pressure based on fine scale vegetation sampling (Kibet et al. 2021) or anecdotal observation (Liao et al. 2020). These claims overlook woody

encroachment as a widespread phenomenon influenced by increasing temperature, changing rainfall patterns, fire suppression, increasing atmospheric carbon dioxide (Archer et al. 2017; Venter et al. 2018; Stevens et al. 2017), and complex tradeoffs existing between functional characteristics of different shrub species in different edaphic contexts (Maestre et al. 2021). All of the above studies from Kenya also do not consider how the implications of extensive pastoralism for landscape pattern and processes depend heavily on the timing and spatial concentration of use, as well as the local biotic and abiotic heterogeneity and variability (Adler et al. 2001; McAllister et al. 2009; von Wehrden et al. 2012; Bestlemeyer 2017). Furthermore, the impacts of pastoral land use are usually not even across landscapes (Rasmussen et al. 2018), and there is increasing need for attention to gradients of use across such systems. These factors all limit extrapolation of small-scale experiments on grazing, even over long time periods, to the landscape scale (Sayre 2017).

To reframe analyses in rangeland systems in Kenya, in Tables 3 and 4 below I provide a brief example of how social science findings on pastoralism can be used to generate research question and hypotheses, and guide selection of observational scales for sampling and analysis. Through this reframing, questions about the relationship between pastoral livelihoods, landscape process, and landscape pattern are posed in a way that is intended to appropriately contextualize livelihood change (Table 3). This example is structured with a higher-level research question, “What are the implications of ‘top-down’

**Table 3** – Simplified process- and pattern-specific ecological questions informed by livelihood analysis

Processes modifying intrinsic scale of socio-ecological relations	Landscape process-specific research questions
‘Top-down’ (e.g. colonial authority, post-colonial state, and international NGO-led) interventions: (1) land grabs (2) land tenure policy changes (3) livestock commercialization policy (4) cash crop agricultural policy (5) formalization of, or creation of, new local authorities (6) informal, but systematic, behavior change interventions (See Unks 2022)	(1) How have spatial partitioning, limitation of herding mobility, and composition of herds (e.g., increasing small stock, changing breeds) reconfigured landscape herbivory processes? (2) How has partitioning of landscapes into zones of differing livestock access, coupled with practices of fire suppression, reconfigured landscape fire processes?
‘Bottom-up’ livelihood reorganization: (1) shifting norms of land use (2) shifting labor practices (3) shifting human-livestock relations	



**Table 4** Landscape partitions, implications for landscape process due to limitation of flexible mobility, and integrative research questions informed by livelihood research and process-oriented questions

Partitions of landscape process	Changes in landscape process (Laikipia)	Changes in landscape process (Kajiado)	Research questions
a. Conservancies	<ol style="list-style-type: none"> <li>1. Decreased grazing and browsing</li> <li>2. Fire due to accumulation of herbaceous biomass more likely</li> <li>3. Livestock enclosures restricted</li> </ol>	<ol style="list-style-type: none"> <li>1. Decreased grazing and browsing</li> <li>2. Fire more likely</li> <li>3. Livestock enclosures restricted</li> </ol>	<p>What are the impacts of loss of herbivory and changes in nutrient cycling for vegetation patch composition, structure, and forage quality within restricted areas?</p>
b. Late dry season grazing within GRs	<ol style="list-style-type: none"> <li>1. Dry season livestock use only</li> <li>2. Livestock enclosures usually restricted</li> <li>3. Grazing resources often exhausted</li> </ol>	<ol style="list-style-type: none"> <li>1. Dry season livestock use only</li> <li>2. Livestock enclosures limited to specific areas</li> <li>3. Grazing resources exhausted during drought years</li> </ol>	<p>What are the implications of dry-season-only access and limitation of livestock enclosures vs. opportunistic use and mobility, for vegetation patch composition, structure, and forage quality?</p>
c. Early dry season grazing within GRs	<ol style="list-style-type: none"> <li>1. Intensified grazing and browsing</li> <li>2. Grazing resources exhausted each annual cycle</li> <li>3. Low ability of grass to regenerate before grazing begins again</li> <li>4. Livestock enclosures restricted</li> <li>5. Fire unlikely</li> </ol>	<ol style="list-style-type: none"> <li>1. Intensified grazing and browsing</li> <li>2. Grazing resources usually exhausted each annual cycle</li> <li>3. Reduced ability of grass to regenerate before grazing begins again</li> <li>4. Livestock enclosures restricted</li> <li>5. Fire unlikely</li> </ol>	<p>What are the implications for vegetation patch stability due to spatial concentration of use and reduced regenerative ability of perennial grasses under temporally prolonged use?</p>
d. Settlements within GRs	<ol style="list-style-type: none"> <li>1. Highly intensified grazing, browsing, and woody biomass harvest</li> <li>2. Grazing resources exhausted each annual cycle</li> <li>3. Grazing begins immediately after rains</li> </ol>	<ol style="list-style-type: none"> <li>1. Highly intensified grazing, browsing, and woody biomass harvest</li> <li>2. Grazing resources exhausted each annual cycle</li> <li>3. Grazing begins immediately after rains</li> </ol>	<p>What are the implications of imposed settlements for net forage productivity and quality at broad scales, compared to opportunistic mobility practices?</p>

interventions and ‘bottom-up’ livelihood reorganization for landscape pattern and process?”. Building from the findings of the case study, the left-hand column of Table 3 highlights how numerous ‘top-down’ interventions have posed constraints on livelihoods, and how various ‘bottom-up’ socio-cultural changes have reorganized livelihoods. This contextualization encourages greater nuance at the initial stage of postulation of research questions (Table 3 right-hand column) (Note S44) and encourages development of questions that carefully consider broad scale changes in livelihood systems, and reduce the influence of dominant ‘just-so’ narratives that can create biased problem framings (e.g. reductionistic focus on variables such as population growth, stocking rates, and local management practices alone).

Building on questions 1 & 2 above (Table 3 right-hand column), which focus on landscape herbivory and fire processes, respectively, the responses to these questions (Table 4, columns 2 & 3) then guide development of research questions about the implications that changes in landscape processes have for landscape pattern (Table 4, right-hand column) that are grounded in existing ecological literature. For example, seasonal decreases in cattle mobility have implications for grass structure (Western and Gichohi 1993), decreased redistribution of nutrients (Rasmussen et al. 2018; Ayantunde et al. 2018), and reduction in the concentration of nutrients in livestock enclosures that create grazing lawns (Young et al. 1995; Muchiru et al. 2009; Table 4a). Local landscape processes have been influenced by spatial and temporal concentration of herbivory due to external constraints; furthermore, livelihood adaptation under these constraints has qualitatively changed landscape processes through the foraging habits of sheep, goats, and changing livestock breeds. This has likely created novel livestock herbivory pressure gradients that differ across the two sites (pressure ascending through rows a–d in Table 4) with observed shifts in vegetation in relation to decreasing seasonal pastoral mobility (Reid et al. 2004; Hobbs et al. 2008). This novel pressure also likely interacts with other important changes such as fire regime that shape herbaceous species composition and woody vegetation structure. Fire is known to be less frequent in areas with low dry season grass cover, and the probability of fire descends through rows a–d in Table 4. Settlements in both contexts also concentrate impacts of livestock

use on land (Augustine et al. 2003; Muchiru et al. 2009), leading to these areas experiencing the most intensive herbivory and reduced regeneration of herbaceous vegetation (Table 4d).

A more thorough approach would consider numerous other factors with implications for vegetation. It would also include dimensions of access to land and resources only hinted at here (e.g. see Ribot and Peluso 2003; Peluso and Lund 2011). However, through focusing on analyses of access to land and resources (Ribot and Peluso 2003), landscape ecologists could begin to develop flexible, systematic ways of studying the relationships between a wider range of socio-cultural, political, and economic processes that shape landscape processes (Note S45). In closing, I recommend that landscape ecologists focus on ecological variability from a livelihood perspective and integratively frame their research through engagement with contemporary social science concepts from geography, sociology, and anthropology. An insistence on ecological methods that adequately consider abiotic spatio-temporal variability and biotic heterogeneity, and an increased attentiveness to the ways that livelihoods can be limited by different socio-politically imposed constraints should be at the center of ecological research in rangelands. Given that rangeland system science research has converged on emphasizing that heterogeneity and scales of interaction are vital for understanding how livestock relate to vegetation, attention to scalar aspects of social and political power that shape livelihoods could help ecologists to recognize when landscape research is replicating narratives that have motivated past historical injustices. In particular, this could encourage greater reflexivity with respect to the role that ecological science has played in informing wildlife conservation interventions that have constrained the intrinsic scale of relations between pastoralism and land.

## Conclusions

A focus on wildlife habitat often constrains choices of observation scale in analyses of landscape vegetation change in Kenya. These analyses tend to include a limited range of variables corresponding to pastoral land use, and often treat pastoralism, a priori, as primarily an anthropogenic threat. This knowledge production process also often excludes

consideration of how pastoralism has been restricted over time. Past restrictions include colonial expropriation of land for private ranching, game hunting, and wildlife tourism; colonial establishment of boundaries between ethnic groups and ongoing politically-fueled conflicts along these administrative boundaries; legacies of imposed land use rules that have shaped land management institutions; and recent waves of wildlife conservancy establishment on community land that have further restricted land use. People who rely on extensive pastoralism throughout Kenya have been forced to concentrate their land use in relatively small, arid, unproductive areas, and today the use of these limited areas are highly socially differentiated due to shifts in husbandry practices, adoption of agriculture, increasing inequality, and changes in norms of mutual assistance. Analyses of vegetation changes across rangeland landscapes that follow an integrative methodology informed by analysis of access, coupled with explicit consideration of spatio-temporal variability of rainfall and heterogeneity of landscape contexts, could offer improved understandings of these complex landscapes. Through detailed understandings of livelihoods and asymmetrical power relationships that have reconfigured land use, landscape ecology could offer more reflexive insights about the social and ecological sustainability of rural livelihoods in Kenya.

**Acknowledgements** I am indebted to the people of Koiya, Imbirikani, Eselenkei, and Olgulului-Olorashi group ranches for generously sharing their time and knowledge, teaching me about their lives and land, and for welcoming me into their homes. This work would not have been possible without the assistance in interviewing and translation, and the guidance of, Naiputari Paul Wachira, Charles Ntimama Mutunkei, Richard Solonka ole Supeet, and Sakimba Kennedy Kimiti. The research benefitted greatly from supervision and mentoring by Elizabeth King, Laura German, Donald Nelson, Jeffrey Hepinstall-Cymerman, Forest Isbell, Mara Goldman, François Mialhe, and Yanni Gunnell. The manuscript benefitted from the comments of two anonymous reviewers and Anita Morzillo. This research was permitted by the Republic of Kenya's National Commission for Science, Technology and Innovation (permit nos: NACOSTI/P/16/8312/1355, NACOSTI/P/19/8312/30903).

**Author contributions** I collected data together with individuals credited in the manuscript acknowledgements. I completed all analyses, prepared all figures and tables, and wrote all of the manuscript text.

**Funding** This work was supported by The French Agence Nationale de la Recherche (ANR-16-CE03-0004 MaGNUM), U.S. National Science Foundation (Grant No. 1313659), a Phipps Conservatory Botany in Action Fellowship, a University of Georgia Innovative and Interdisciplinary Research Grant for PhD Research, and a University of Georgia Dean's Award for PhD Research. Analysis and writing was supported by the National Socio-Environmental Synthesis Center (SESYNC) under funding received from the National Science Foundation DBI-1639145 and the PASTRES (Pastoralism, Uncertainty, Resilience: Global Lessons from the Margins) programme under Advanced Grant funding from the European Research Council (Grant agreement No. 740342).

#### Declarations

**Conflict of interest** The authors declare no competing interests.

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