Drought frequency, conservancies, and pastoral household well-being

Article *in* Ecology and Society · January 2024

DOI: 10.5751/ES-14872-290127

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Boone, R. B., C. K. Lesorogol, and K. A. Galvin. 2024. Drought frequency, conservancies, and pastoral household well-being. Ecology and Society 29(1):27. https://doi.org/10.5751/ES-14872-290127

Research

Drought frequency, conservancies, and pastoral household well-being

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ABSTRACT. Portions of group ranches of northern Kenya communally held by pastoralists have been removed from grazing to support wildlife and encourage tourism and the resources that follow. These community-based conservancies (CBCs) were designed to benefit CBC members through regular payments, potential for wages, improved security, etc. We used a coupled-systems simulation approach to quantify potential changes in livestock numbers and pastoral well-being associated with the presence of CBC core and buffer areas, and we did so under the current frequency of droughts and increased frequency associated with climate change. The interannual precipitation coefficient of variation (CV) for our focal CBCs in Samburu County was 22% (706 mm average precipitation). We altered precipitation variability to span from 10% to 60% CV while maintaining the average. Compared to a simulation with observed precipitation and all rangelands available, when herders did not use the CBC core areas and seasonally avoided buffer areas, there was an 11% decline in tropical livestock units supported. More predictable precipitation patterns supported more livestock and improved pastoral well-being. At CVs above 30%, dramatic declines in livestock populations were simulated. When drought was made moderately more frequent (i.e., CV from 22% to 27%) there was a 15% decline in the number of livestock. Members receive a variety of benefits as part of CBC communities, but payments are small for these CBCs, and most households do not receive payments. Our results suggest that, from an economic perspective alone, payments must be raised to make membership of residents in conservancies more tenable. Additional adaptive pathways and perhaps external supports will be needed in the future as the frequency of drought increases and livestock populations decrease.

Key Words: *community-based conservancies; DECUMA; drought frequency; Kalama; L-Range; livestock; Nkoteiya; pastoralism; Samburu County; simulation; West Gate*

INTRODUCTION

Kenya is a leading destination for tourists in sub-Saharan Africa, and tourism is an important contributor to the country's economy (10% of Gross Domestic Product pre-pandemic; Muragu et al. 2023). Northern Kenya is a popular tourist destination within the country, although declines in wildlife populations have been described (e.g., Ogutu et al. 2016). Protected areas are the focus of wildlife viewing by tourists, but areas outside of protected zones are important for wildlife as well (Western et al. 2009). It is estimated that 65% of wildlife live outside protected areas and reserves (KWCA 2023). Pastoral people and their livestock are typically excluded from protected areas and do not benefit directly from tourism revenues, and as an alternative, community conservation has become popular (Adams and Hulme 2001).

Historically, pastoral people in northern Kenya moved broadly across the landscape to locate sufficient forage for their livestock, with populations much lower than today (Schlee 1989). Samburu pastoralists are the majority of people who live in Samburu County in central-northern Kenya. Samburu pastoralists historically focused on cattle husbandry but today they have increasing numbers of sheep, goats, and camels (Ogutu et al. 2016). The Ewaso Nyiro River is the only permanent natural water source, but pastoralists also access water through wells and earthen dams. Livestock movements to access forage seasonally or during times of drought must be socially negotiated (Pas 2018). Samburu households have become more settled over the last century, and this has coincided with livelihood diversification including production from small stock and camels, and non-pastoral activities like small businesses (Little et al. 2014). Herding has also changed so that young men, who are largely responsible for cattle herding, take and defend their livestock across county, ethnic, and privatized land borders during drought (Pas 2018). Inter-county or ethnic movements have led to conflict that has gotten worse in recent decades (Greiner 2013). This has occurred in part because of hardened boundaries through group ranches, conservancy lines, and settlements. Processes of exclusion to the land are becoming dominant, which is difficult in northern Kenya given the landscape's fluctuating resources and increasing uncertainty under climate change. Further, increasingly more children go to school, which sets them apart from their peer herders in terms of life goals (Lesorogol et al. 2011, Bruyere et al. 2018), which can cause community tensions.

In the 1970s, following Kenyan independence, lands in parts of northern Kenya were demarcated into group ranches that assigned collective title to members (Pas 2018, Lesorogol 2022), with the intent to create tenure security and investment among members of a given ranch, commercialize livestock production, and promote maintenance and improvement of held rangelands. Individuals were hesitant to be listed as members of group ranches when they were first formed, and ultimately, the ranches had limited success in accomplishing the goals for which they were formed, although group ownership did reduce risks of land acquisition by outside interests (Kimani and Pickard 1998). Schools and other shared resources were sometimes constructed, but in general, benefits of group ranch membership did not flow to ranch members. Lands excised to create protected areas were managed by the government, and pastoral people remained poor, marginalized, and suspicious of government involvement.

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With encouragement from Kenya Wildlife Service and others (history reviewed in Western et al. 2015), a pattern of conservation grew in popularity in the 1990s that had greater likelihood of sharing benefits more broadly called the community-based conservation model. With the new constitution of 2010, devolution of power to county governments and the Land Act of 2012 and the Community Land Bill of 2016, conservancies are now legal entities (Galvin et al. 2020). The Kenya Wildlife Conservancies Association (KWCA) oversees 184 conservancies across the country that includes community conservancies, group conservancies, private conservancies, and those that are co-managed (KWCA 2023). Most conservancies are those established by a community, on community land (KWCA 2023).

Community-based conservation goals across Africa vary (Galvin et al. 2018), but in our area of interest, biodiversity conservation and ecotourism are foci. Ideally, communities are partners in hosting wildlife on lands that may be a subset of the area they own or co-occurring with other land uses (Western et al. 2015, Galvin et al. 2018, Lesorogol 2022). When group ranches adopt the community-based conservancy (CBC) model, members of the group ranch become CBC members and forego access to core areas and constrain use of buffer areas of CBCs by their livestock, and those areas are used to support wildlife and associated tourism. Conservancies regulate these two areas to limit livestock access to times when livestock forage is severely limited around settlements. Conservancies have implemented bunched cattle grazing, grass reseeding, and removal of unwanted trees to rehabilitate some core zones (Kimiti et al. 2017, Odadi et al. 2017). Some of the money that tourists contribute or that is provided by tourist lodges within the core areas and that have contracted with the CBC may be shared with CBC members or used to address community needs. People benefit in less direct ways, such as through payment of school fees, improved rangelands and biodiversity, wage positions in the CBC or tourist facilities, and through security provided by game wardens who will also defend livestock from theft (NRT 2018, 2021, Pickering 2021, Lesorogol 2022). In contrast to a modest organizing committee with few resources who may manage a group ranch (we distinguish group ranches and CBCs as terms below), many CBCs in northern Kenya are actively managed under the umbrella of the Northern Rangelands Trust and their partners (NRT 2018).

Northern Rangelands Trust (NRT) was founded in 2004 following the establishment of several conservancies in northern Kenya. It is the oldest non-governmental organization with this focus and now supports 43-member community conservancies spread across 10 counties in northern and coastal Kenya (NRT 2023). Community conservancies under the NRT umbrella are legally registered entities, governed by a representative Board of Directors and run by a locally staffed management team. With support from NRT, conservancies protect wildlife, manage rangelands and fisheries, improve peace and security, and help develop local economies. Conservancies have evolved since the beginning with more devolved governance. Moreover, the Community Land Act of 2016 and the Wildlife Conservation and Management Act of 2013 have provided conservancy recognition and protection (KWCA 2021, Republic of Kenya Community Land Act 2016, Republic of Kenya Water Act 2016). NRT has supported community land registration (allowed under the new 2010 constitution) so that in 2022 eight community conservancies secured land tenure rights (NRT 2023).

Yet, there are challenges to NRT, its conservancies, and the region. For example, the human population has increased, and there are declining cattle numbers and increasing small stock (i.e., sheep and goat) numbers (TNC 2020). In addition, the climate has changed with more frequent droughts (Lyon and DeWitt 2012, Ayugi et al. 2020), leading to increased pressure on existing vegetation, especially near water sources (Kimiti et al. 2017), increasing woody vegetation (Kimiti et al. 2017, NRT 2019a), and the potential for insecurity (NRT 2018, TNC 2020, Galvin et al. 2021).

Pastoralists were well adapted to droughts at frequencies seen historically (Ellis and Swift 1988). Practices such as mobility, altering herd mixes, and reliance on large social networks allowed pastoralists to adapt to stressors and to make use of ephemeral forage patches to limit livestock losses (Turner 2011). Formal and informal institutions reinforced behaviors that promoted appropriate adaptations (Lesorogol 2022). Changes such as landscape fragmentation, government settling schemes, increasing violent conflict, changes in reciprocity, and landscape degradation (Hobbs et al. 2008, Lesorogol and Boone 2016, Pas 2018) have constrained mobility and reduced adaptive capacity. Livestock movement and associated territorial conflict are not new to pastoralism (McCabe 2004, Greiner 2012). Conflict is historically rooted in competition over scarce natural resources (water and forage), cultural practices, and pastoralist identity (Scoones 2020). Arid and semi-arid rangelands are inherently unstable climatically, and livestock movement through negotiated territories has been the norm (McCabe 2004). Although livestock movement is a central management strategy for pastoralists, the opportunities that community conservancies offer like tourism, diversification of livelihoods, and educational opportunities tend to make pastoralists more sedentary (Reid et al. 2014). Climatic changes increase challenges to livestock movement. Community conservancies may make it harder to negotiate livestock movements (Glew et al. 2010, Pas 2018). NRT conservancy grazing committees make grazing plans and provide a forum for dialogue between neighboring, often conflicting communities. However, they may or may not have a clear mandate so cattle movement, reciprocal grazing arrangements, and negotiation with other herders are variable. Another challenge is that grazing plans occur on a smaller scale than overall livestock movements (TNC 2020).

Conservancies are established to counteract rangeland fragmentation but excising CBC core and buffer areas from communally used lands is a form of fragmentation (i.e., dividing land into smaller and perhaps less accessible patches) from the pastoralists' perspective as well (Western and Wright 1994, Lesorogol 2022). This can cause tension and conflict and end up replacing customary governing bodies (Bedelian and Ogutu 2017, Pas 2018, Cockerill and Hagerman 2020). Moreover, programs can be implemented with limited community input or approval leading to confusion in rangeland management and inequitable outcomes (Bedelian and Ogutu 2017). In any case, fragmentation, including both habitat loss and habitat isolation, reduces the numbers of herbivores a landscape can support (Boone and Hobbs 2004, Hobbs et al. 2008).

In addition, recent increases in the frequency, severity, and length of droughts in Kenya (e.g., Lyon and DeWitt 2012, Ayugi et al. 2020) associated with increasing greenhouse gas concentrations due to anthropogenic release (IPCC 2014, 2021) have been documented, and precipitation has decreased in northern Kenya (NRT 2018, Muthoni et al. 2019, NDMA 2022). Increasing temperatures increase evaporation and cause precipitation to be more variable, and warming can shift storm tracks, increasing uncertainty. Drought frequencies are projected to increase into the middle of this century before potentially decreasing near the end of the century (Tan et al. 2020), although Kenya is projected to get wetter in general (IPCC 2014, 2021). Thus, pastoralists face stressors that pull in opposite directions: changes in adaptive capacity that can limit access by livestock to landscapes and make mobility more difficult, and more frequent droughts that demand greater mobility to find sufficient forage for their animals.

Moreover, pastoralists are dependent upon livestock rebuilding their populations between droughts (Vetter 2005). Increasingly frequent droughts threaten to move more pastoral areas from those that may be characterized as having primary production and livestock in some equilibrium to areas where production and livestock stocking are disconnected through frequent die-offs (Ellis and Swift 1988). The spatial scale over which this non-equilibrium response may occur and the degree to which it does is debated (Illius and O'Connor 2000, Derry and Boone 2010), but we may say with confidence that more frequent droughts increase strains on pastoralists' livelihoods.

We adopted a means to quantify the effects of loss of access to CBC areas and changing drought frequencies that used a coupled-systems approach to simulate a social-ecological system (Schlüter et al. 2012) of northern Kenya inhabited by the Samburu people. Our approach is now frequently used in coupled-systems analyses, where a spatially explicit process-based ecosystem model is joined to a rule-driven agent-based model representing households and their decision making (e.g., Boone and Galvin 2014, Boone and Lesorogol 2016, Lesorogol and Boone 2016). The models are loosely linked discrete-time simulations, where the passage of time is simulated in steps and information is passed between the tools. Ecological theory and data are used to apply the ecosystem model to an area, and expertise and a suite of household survey data are used to describe the nature of the pastoral community. Because households have explicit locations on the landscape, they have local areas from which to gain ecosystem services (Fisher et al. 2009). Their decisions, such as where to graze animals, can in turn affect ecosystem services, forming a coupled system.

In scenarios, we changed spatial surfaces used in simulations to include or exclude the use of core and buffer CBC areas. To represent varying frequencies of drought, we altered the coefficient of variation (CV) of interannual rainfall for the area (Boone 2007, Boone and Wang 2007). A CV in this context is the standard deviation in annual precipitation over several years divided by the mean, and in the region can vary from less than 10% in western parts of Uganda, Tanzania, Rwanda, and Burundi, to 55% in northeastern Kenya (Muthoni et al. 2019). We altered the CV to be lower than the observed value, meaning annual precipitation was more predictable across years than observed, to very high values, where droughts and very wet years happen often.

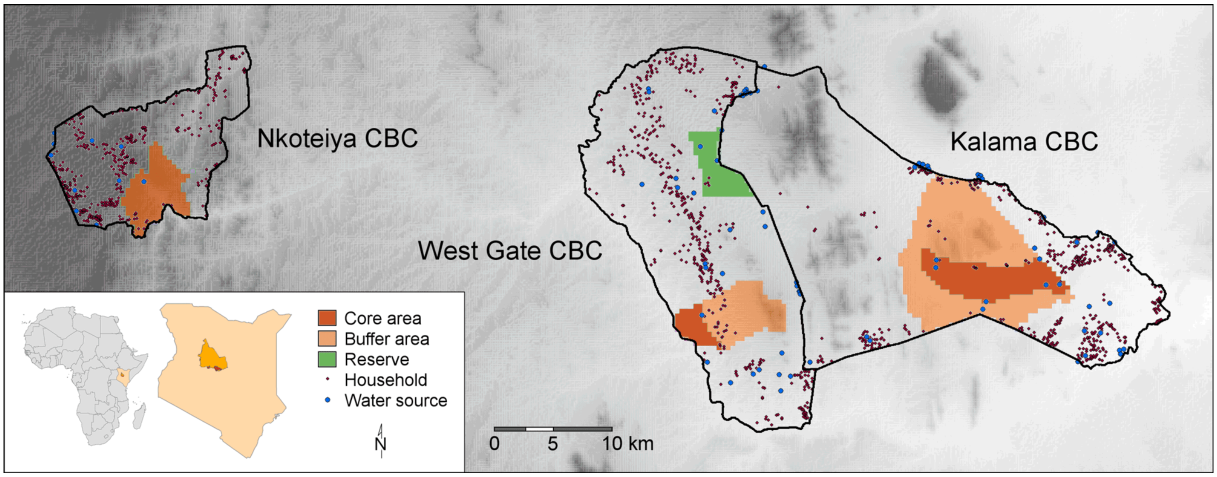
STUDY AREA

Group ranches and CBCs are related in complex ways (reviewed in Lesorogol 2022). Group ranches have the longer history and provide title to their communally held lands. Group ranches contain CBCs (but some CBCs fall within more than one group ranch). Governing boards and councils of elders influence land use and other decisions of a group ranch; but the governing boards for ranches and their CBCs are often the same people (as is the case for our three CBCs, cited below). There is an imbalance in resources, however, with group ranches having few resources and CBCs or their collaborators having vehicles, offices, scouts that protect wildlife and livestock, plus funds that may include bursary fees, regular payments to families, health care fees, or other payments cited below. For brevity, we will speak of the areas in which we work as CBCs, with the term including the core and buffer areas of the CBC and its encompassing group ranch. We will speak of CBC core and buffer areas to cite the locations where wildlife tourism is supported.

Our study sites are in Samburu County, Kenya, and include Kalama, West Gate, and Nkoteiya CBCs (Fig. 1). The county is topographically diverse, with our study region sloping upward toward the west and varying from lowland Kalama (~800 m elevation in the east) and West Gate (~1000 m) to the higher elevation Nkoteiya (~1740 m in the west). Annual precipitation mirrors that change in elevation, with the lowest 510 mm yr^{-1} in eastern Kalama and 1090 mm yr^{-1} in south-central Nkoteiya. Precipitation is variable spatially and through time in the region. We used monthly TerraClimate data (Abatzoglou et al. 2018) from 1990 to 2009 in modeling (see below), and the precipitation surfaces from that source averaged 706 mm yr^{-1} with an interannual CV of 22%. Serious droughts in the area in recent decades occurred in 1990–1993, 2000, 2006, 2008–2009, 2014, 2016–2017, and 2020–2022. Rainfall is bimodal in the year, with long rains from March to May and short rains in October. West Gate and Kalama CBCs border a protected area, Samburu National Reserve, to the south and east and so CBC core and buffer areas benefit from dispersing wildlife. Vegetation in the three CBCs is typical Kenyan rangeland, including deciduous shrubland and grassland dominating in Nkoteiya and those types plus deciduous bush grassland in the eastern CBCs. Vegetation includes mixed grasses (e.g., *Themeda triandra*, *Digitaria scalarum*, *Pennisetum schimperi*, and *Oropetium capense*), dwarf shrubs (e.g., *Duosperma eremophilium*), shrubs (e.g., *Commiphora* spp.), and trees (e.g., *Vachellia nilotica*, *Acacia tortilis*, and the damaging and spreading *Vachellia reficiens*, which is subject to control efforts; Shaabani et al. 1992, NRT 2018).

Both Kalama and West Gate Conservancies began before NRT existed and all three conservancies became members of NRT after they were independent conservancies. West Gate Community Conservancy was established in 2004 when they converted their group ranch into core and buffer zones to improve their rangelands and conserve wildlife. West Gate lies just to the west of Samburu National Reserve (NRT 2023). Kalama Conservancy was first established in 2002 and became an NRT member in 2009. It is a vital corridor for large herds of elephants moving between the Samburu and Marsabit areas. It has a high-end lodge and several campsites that generate revenue. Funding from carbon offsets were used in 2022 to build a scouts' outpost and provide food to community members in its 15 settlement zones (NRT 2023). Nkoteiya Community Conservancy was established in 2005 and became an NRT member in 2016. Pastoralism, dryland farming, and beekeeping are the community's main sources of income. A community lodge, built in 2021, directly benefits the community in healthcare, education, water supply, and rangeland improvement.

Fig. 1. The study area in Samburu County, Kenya includes three community-based conservation (CBC) areas, Kalama to the east, Nkoteiya to the west, and West Gate. Core and buffer areas of CBCs and a reserve in West Gate are shown, with households indicated. Grey tones indicate elevation, increasing toward the west from ~800 m in eastern Kalama to 1740 m in central Nkoteiya. Insets show the location of the area in Kenya and Africa.



Samburu people have been diversifying livelihoods that include activities such as wage labor, livestock and small-scale trade, and handicrafts (Boone and Lesorogol 2016). That said, livelihoods are dominated by livestock ownership, which includes cattle, goats, and sheep, and often camels, especially in drier areas. The main livestock product is milk, but meat and other products are valued, and herds serve as a form of savings, cash holding, and a cultural touchpoint as well. Large shifts in herd composition have occurred in recent decades as range conditions have changed, with cattle numbers declining and small stock and camels increasing rapidly (NRT 2018). A means to standardize livestock species so that they may be fairly summed uses tropical livestock units (TLUs) where a cow is 1 TLU, a sheep: 0.12, goat: 0.13, and camel: 2.5. A similar metric is used for humans, active adult male equivalents (AAME), with an adult male at 1.00, adult female: 0.86, children 11–17: 0.96, children 6–10: 0.85, and children 0–5: 0.52. The 299 households interviewed by Lesorogol (2022) cited a total TLUs of 5551.7, with Kalama at 1159.1, West Gate at 1961.7, and Nkoteiya at 2430.9. Mean (and median) livestock holdings per person were 3.56 (2.07) TLUs $AAME^{-1}$ [Kalama: 2.18 (1.03); West Gate: 3.58 (2.32); Nkoteiya: 4.86 (3.14)]. Farming occurs in the CBCs but it is modest, although more common in more mesic Nkoteiya. Agricultural plots can be damaged in Nkoteiya by elephants (Lesorogol 2022), and West Gate and Kalama CBCs experience human-wildlife conflict associated with neighboring Samburu National Reserve.

Regarding CBC benefits and constraints, members agree to not graze in core ecotourism areas throughout the year and grazing in the buffer zone is only allowed in the dry season, with limits placed on use (Lesorogol 2022). The three conservancies in this study all have core conservation areas and so have tourism facilities, but not all NRT conservancies have core conservation areas. Members receive other benefits as cited, such as payment of some medical bills and bursary payments for secondary or higher education, although those payments often offset the cost of one child's school attendance or a small fraction of real costs of more expensive education. Wildlife scouts paid by the CBCs make livestock keeping safer and reduce the threat of theft, and scouts can help recover stolen livestock. Some members earn wages from CBCs, which can be substantial. Those wages aside, of the 299 households interviewed by Lesorogol (2022), 84% reported not receiving annual dividends from CBC membership. The 16% that reported receiving payments cited an average of KSH 1833 (~US$15) annually.

METHODS

The coupled natural-and-human modeling application used here has antecedents in previous work we describe below, in part to trace the progression of our use of modeling tools, but primarily to provide citations to lengthy model descriptions. Our global rangeland model G-Range (Boone et al. 2018) was modified to create the L-Range model used here and our household agent-based model DECUMA was joined with L-Range using methods described in Model Integration to yield a coupled-system perspective. We then review the model application to the study site and the methods used to address the scenarios of interest, changes in access associated with CBCs, and changing drought frequency.

Modeling antecedents

We created G-Range as an ecosystem model and used it to address potential effects of climate change on global (i.e., the "G" in G-Range) rangelands and livestock (Boone et al. 2018, Sircely et al. 2019, Godde et al. 2020). The tool uses a simplified means to represent vegetation, as herbs, shrubs, and trees, and richer structural representation for landscape patches. Herbs are represented with leaves and stems, seeds, and fine roots, and perennial and annual herbs are included. Shrubs and trees are represented by leaves, fine branches, coarse branches, fine roots, and coarse roots, and evergreen, deciduous, and facultative deciduous woody plants are modeled. Biogeochemical dynamics are represented for each landscape cell using a simplified version of the Century model (Parton et al. 1993). Carbon and nitrogen concentrations are tracked in the plant parts cited, both live and dead, as well as standing dead, layers of detritus, and decomposition pools. A series of spatial surfaces inform the landscape cells about sub- and top-soil attributes, herbaceous, shrub, evergreen, and deciduous cover, land cover, and landscape unit identifiers, which are homogeneous regions for which parameters are provided. Plant populations are tracked using a plant-packing approach, with proportions fitting within a representative 1 km^2 within each cell (regardless of cell resolution). Parameters controlling whole-plant establishment and death alter populations, which in turn influences percent cover of herbs, shrubs, trees, and bare ground. As in Century, herbivores are not represented directly, but rather offtake is specified for each landscape unit. Biomass is removed by grazing and nutrients are returned to the soil through animal wastes. The G-Range model uses a monthly time-step for simulation and output production. Detailed descriptions of the model and its use are in Boone et al. (2018) and Sircely et al. (2019).

To address scenarios in western Samburu County, we used a very detailed ecosystem model called Savanna (Coughenour 1992) in Boone and Lesorogol (2016) and Lesorogol and Boone (2016) joined with an agent-based model called DECUMA to represent human decision making. Savanna is powerful but requires significant investment of time and resources to apply to an area. We wished to conduct scenario analyses using a version of the simpler G-Range model, and so modified that tool as we will describe to create L-Range. DECUMA allowed us to add pastoralists and their livestock to the landscape being simulated in a spatially explicit way. Household agents in DECUMA have specific positions on the landscape that allow them to have access to ecosystem services in their area to support decision making, and their decisions (e.g., where to graze animals) may modify ecosystem services through the coupled simulation. Any number of pastoral households may be represented, with each characterized by household surveys to set the number of male and female adults, teenagers, and youths, livestock numbers for different species, monthly incomes and expenses, areas in cultivation, assets, and debts. People gain calories from the milk they drink, butter and sugar they use, meat and home-grown crops they consume, and maize they purchase (Boone and Lesorogol 2016). In simulations, the tool initializes using a small set of spatial surfaces, and then a mixed time-step is used. Livestock are grazed using a weekly time-step, with them being distributed in subherds on the landscape each week according to rules, their grazing simulated, and energy acquired tracked. The rules affecting grazing distributions include a grazing orbit limit, forage biomass availability, distance to water, and limits on slope, woody cover, temperature, and snow cover, if present. Energy acquired by subherds from forage is based on its nutrient content and influenced by maximum intake rates, preferences by animals for different biomass pools (e.g., cattle selecting grasses and goats selecting browse), a waste fraction, and the digestibility and metabolizability of the forage acquired. The main time-step occurs monthly. Energy used by livestock is calculated, considering basal metabolism, gestation, lactation, thermal regulation, and distance traveled to water sources. Weight change is determined for subherds by comparing energy acquired and energy used. If acquisition exceeds use, the animals gain body mass. If the opposite is true, the animals lose body mass. The simulated body mass of animals is compared to expected body masses for animals of the given age and sex class for the species and condition indices assigned, within a constrained range. If animals are 20% heavier or more than expected, their condition index is 1.0; if 20% lighter or more, their condition index is 0.0, and if as expected, for example, their condition index is 0.5. Ages of livestock advance in DECUMA and reproduction is simulated. Condition indices influence birth rates in a minor way, with females in poorer condition less likely to produce offspring. Condition indices more strongly influence the risk of mortality, adding to a nominal mortality rate, with animals in poor condition more apt to die than those in good condition.

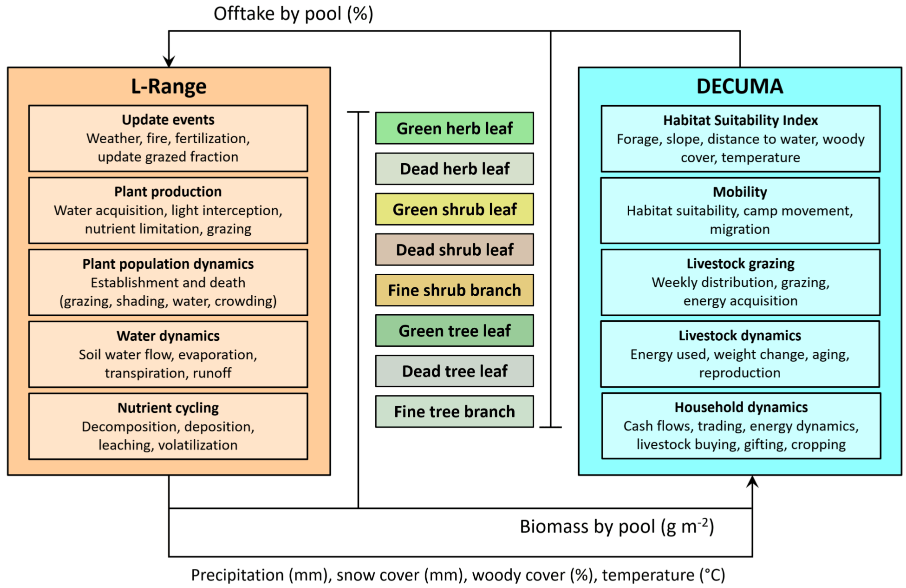
Crops are then harvested in DECUMA, with plantings and areas informed by household surveys and yields influenced by annual rainfall. Monetary flows are calculated for households considering 9 income sources and 6 types of expenses (see below). To inform the need for livestock trading, households then look ahead to the expenses they anticipate in the following three months. If those expenses are larger than the money on-hand, households may sell animals: sheep or goats if the deficit is small, cattle if the deficit is large. In turn, if ample funds are available, livestock may be purchased.

Energy acquisition by families is simulated, with DECUMA aware of family sizes and the caloric needs of family members. People gain calories from food sources in a regular order, first from milk, sugar, and butter, then from meat consumed, and from crops produced by household members. If there remains a deficit in calories needed and funds are available, the family buys and consumes maize. Remaining needs, if any, are met through supplemental foods, which may represent gifted foods from neighbors, national or international aid, or other sources. As part of the social network of support, livestock gifting is simulated, where as part of a social support network, households who have lost their herds may be gifted animals from wealthy neighbors. Household members may move to temporary camps within the conservancies and remain in those locations for several months. Outputs from DECUMA include spatial and temporal products at monthly intervals. Boone et al. (2011) includes a detailed description of DECUMA and its application to a portion of Kajiado County, Kenya to address questions regarding fragmentation, and an ODD (Overview, Design concepts, and Details) description of the model (Grimm et al. 2010).

Model integration

The global model G-Range was modified to run on an area determined by the user, yielding a model that runs locally (L-Range; http://l-range.com/). L-Range was adapted to apply to a study area that encompasses the three focal conservancies plus a buffer of 10 km (Fig. 1); areas outside the CBCs were included to address scenarios not reviewed here. Making L-Range suitable for joining to DECUMA to represent a coupled system required several changes to both models. In Boone and Lesorogol (2016) and Lesorogol and Boone (2016), the Savanna model included detailed simulation of herbivore habitat selection and energy dynamics, but L-Range does not represent herbivores directly, and so those dynamics were incorporated into DECUMA. The main linkage between L-Range and DECUMA connects vegetation production to livestock foraging (Fig. 2). Eight vegetation pools are calculated for output and use by DECUMA,

Fig. 2. A schematic of the linked L-Range and DECUMA tools, with L-Range simulating ecosystem services in a process-based manner and DECUMA simulating household decision making using an agent-based approach. Each month, after simulating ecosystem dynamics, eight biomass pools represented in L-Range (e.g., green herb leaf, dead shrub leaf) are passed to DECUMA in a spatially explicit way, along with other surfaces used in assessing habitat suitability (e.g., woody cover, temperature). Households distribute livestock based on habitat suitability and access rules. The animals forage from the biomass pools and household dynamics are simulated. DECUMA then passes to L-Range the spatially explicit percent offtake from biomass pools, and the processes continue.



including biomasses of (1) green herbs, (2) dead standing herbs, (3) green shrub leaves, (4) dead shrub leaves, (5) fine shrub branches, (6) green tree leaves, (7) dead tree leaves, and (8) fine tree branches. In G-Range, herbivore offtake follows the Century parameterization, with offtake constant for a given landscape unit. In contrast, livestock owned by pastoralists in DECUMA may graze one group of patches in a landscape unit and leave others ungrazed, and so L-Range was edited to track per-cell fraction grazed for live and dead material.

Climate in the first month of simulation and select spatial surfaces are written out during L-Range initialization for use by DECUMA pastoralists in decision making prior to simulation. Then each month after simulation of ecosystem dynamics, L-Range writes layers for use by DECUMA and then pauses while that model continues simulation. Green and dead herb biomass are summed separately, including leaf and seed biomass in the herb facet, herbs under shrubs, and herbs under trees. Analogous components are separately summed for green shrub biomass, dead shrub biomass, the same components for shrubs under trees, green tree biomass, and dead tree biomass. In addition, fine branch biomass is calculated for shrubs and shrubs under trees, and for trees. Lastly, surfaces describing the environment are written by L-Range for use in judging habitat suitability by DECUMA household heads. These include slope (%), snow (cm), total woody cover (%), and average temperature (°C). Those surfaces are written out in ASCII format along with a timestamp, and an end-of-file marker is written that DECUMA uses to trigger its continuing with its simulation.

DECUMA was edited to read the available biomass layers (and confirm the time-steps of the models are in-sync) and environmental surfaces. Pastoralists distribute their animals each week based on species-specific preferences for slope, snow (if applicable), woody cover, temperature, distance to water, and forage availability within a grazing orbit of their home or camp. Subherds of livestock graze on biomass in cells, feeding from the different biomass pools according to indicated preferences. That offtake is used to calculate energy acquisition, and energy use and weight change modeling follow. The model then calculates the fraction of biomass removed in each cell and for each of the eight biomass pools, and those are written as ASCII files for use by L-Range to calculate a cell-based proportion offtake (Fig. 2). DECUMA pauses execution until the next biomass availability layer is produced by L-Range. The two tools trade control until the requested years to be simulated have been completed. Cultivation may be represented in DECUMA and uses the monthly precipitation layer passed by the ecosystem model to estimate yields.

Model application

A series of spatial surfaces inform L-Range and DECUMA about landscapes, and these surfaces were processed to be coincident and at a 400 m spatial resolution. Slope was calculated from Shuttle Radar Topography Mission 30-m data (Farr and Kobrick 2011), and land cover was from AFRICOVER (Kalensky 1998). Soil attribute data were drawn from the Regridded Harmonized World Soils Database (Wieder et al. 2014), with more resolved polygons from the Kenyan soils database KENSOTER (KARI 2004) used. Herbaceous, shrub, deciduous, and evergreen tree cover were taken from the EarthEnv 1-km dataset (Tuanmu and Jetz 2014). Spatial surfaces describing core and buffer CBC areas and other landscape units were digitized from Kalama and West Gate community development plans (KCC [date unknown], WGCC [date unknown]) and spatial data we collected for Nkoteiya. Our on-site collection of water sources supported creation of wet season and dry season water availability, used to guide livestock habitat selection in DECUMA.

Monthly mean minimum and maximum temperature and monthly precipitation drive L-Range. Weather stations are uncommon in the study region and so we used a highly resolved interpolated product with wide availability, TerraClimate (Abatzoglou et al. 2018). The 4-km resolution surfaces were downloaded, trimmed to the study area, resampled to 400 m resolution (nearest neighbor), and formatted in GRIDASCII format for use in L-Range. We selected the most recent complete decades in the data set for use in simulations, 1990 to 2009.

Lesorogol (2022) interviewed 299 households in 2018, and those data were used to initialize households in DECUMA. Survey results informed: the number of household members in six age-sex classes (adult female, adult male, females 13 to 17 years old, males 13 to 17, children 6 to 12, and children younger than 6); female and male cattle, goats, sheep, and camels; monthly income from nine sources (i.e., wages, livestock trading, livestock products, remittances, conservancy payments, government subsidies, milk sales, other businesses, and other income sources); monthly expenses (i.e., food, tea, sugar, and oils, plus school fees, household supplies, and veterinary inputs). Cultivation is uncommon in the region, and so we did not enable that portion of DECUMA. Northern Rangelands Trust (2019a) reported human populations of 9958 in Kalama CBC, 4494 in West Gate, and 3285 in Nkoteiya. Interviews from Lesorogol (2022) yielded mean household sizes of 7.39, 6.64, and 6.86 for the three areas, respectively. Division yielded estimates of 1500 households in Kalama, 608 in West Gate, and 479 in Nkoteiya, summing to 2587 represented in DECUMA.

Of the 299 households surveyed in Lesorogol (2022), 71 had geographic positions available. To ensure that the remaining households were distributed in a way that was represented on the landscape, we digitized the locations of 1376 households in the three CBCs based on inspection of Google Earth Pro (Mountain View, California, USA) images, where pastoral households were generally evident. The locations of the 71 placed households were used directly, and for the remaining 2516 households, a household survey from the given CBC was selected randomly to initialize a household and a spatial location from the collection of digitized households was selected and shifted up to 200 m in any direction, and the household established at that location. That process repeated until 2587 households were created, with numbers in CBCs as cited above. The 299 household surveys were therefore used to initialize the 2587 simulated households, with field-based surveys drawn randomly from within a given CBC to initialize a household within that CBC. Drawing randomly from the houses digitized from Google Earth ensured that the distribution of simulated households mirrored their observed distribution. With that, attributes for households within CBCs had attributes that mirrored those of the household surveys in the given CBC.

Landscape units used in the application were the land cover polygons from AFRICOVER, including 14 types, with 11 having rangeland vegetation (e.g., closed to very open herbs, closed to very open herbs with sparse shrubs, closed trees with sparse shrubs, open trees with shrubs); the others were bare rock, rural settlements, wetlands, and water. Parameters were initialized based on those used in Boone et al. (2018) and modified using values from Boone and Lesorogol (2016). A FORTRAN tool associated with L-Range converted the binary files from simulations into GRIDASCII files that were then summarized and compared quantitatively to the reference surfaces to minimize differences using a Python script. Surfaces processed included potential evapotranspiration (cm mn^{-1}), annual evapotranspiration (cm mn^{-1}), net primary production (g m^{-2} yr^{-1}, summed from monthly values), carbon to nitrogen ratio (unitless), facet (i.e., herb, shrub and tree) covers plus bare ground (%), soil total carbon (g m^{-2}), total aboveground live biomass (g m^{-2}), total belowground live biomass (g m^{-2}), water available (cm), and fraction live- and fraction dead- removed by grazing (proportion; summed from monthly values). Parameters were adjusted and model fit assessed repeatedly until fit was optimized relative to MODIS gross and net primary production surfaces (MOD17; e.g., Running et al. 2004) and reported annual net primary production (Shaabani et al. 1992). We adopted a pattern-oriented approach (Grimm et al. 2005) to assessment, comparing a suite of simulated responses to gathered data, such as the proportion of livestock that died during recent droughts as reported in interviews (Lesorogol 2022). Annual trends for responses such as facet cover, evapotranspiration, primary production, and fractions grazed, plus household incomes and expenses, livestock holdings, and energy acquisition were important to inspect. Integrative tools such as those used here are difficult to assess for goodness-of-fit to observations, but the pattern-oriented assessment comparing results with the sources cited provide evidence for suitability in research (Grimm et al. 2005). Also, an application with multiple stable responses with reasonable dynamics in each of them suggests an internal consistency sufficient to use to address scenarios (Rykiel 1996).

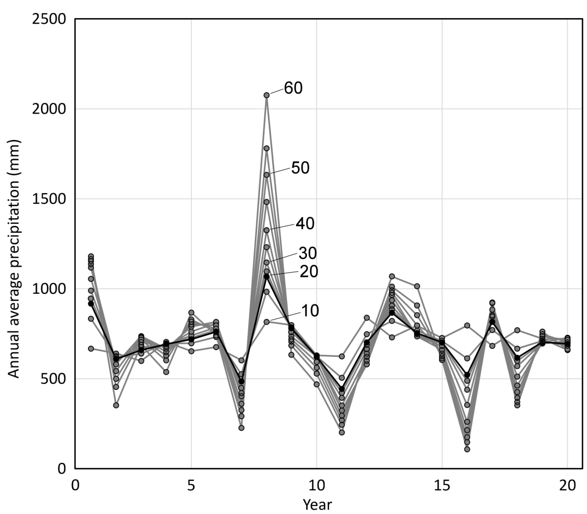
Scenarios addressed

Our scenarios were defined by two dimensions, access to areas of the CBCs by livestock, and changes in the frequency of droughts and wet years associated with a changing climate. Our baseline application includes the simplest access, with entire CBCs available to pastoralists and their livestock throughout the year (at the 400 m cell resolution simulated, 499.7 km² for Kalama, 363.2 km² for West Gate, and 154.1 km² for Nkoteiya). In contrast, in scenarios and in typical years in Samburu in reality, livestock are prevented from using the core areas, buffers, and reserve of the CBCs during the wet seasons (March–May and October–December). In the dry seasons (January–February, June–September), animals are only prevented from using the core areas and reserve; they may use the buffers. The CBC in Nkoteiya makes no distinction between core and buffer areas (Lesorogol 2022), and so the area was treated as core. Core areas were 33.0 km² in Kalama, 8.6 km² in West Gate, and 26.2 km² in Nkoteiya. The buffer zone in Kalama was 92.2 km² and in West Gate was 28.2 km². West Gate also included a grazing reserve that is part of the conservancy of 17 km². In summary, 75% of Kalama CBC, 85% of West Gate, and 83% of Nkoteiya were available for open grazing. Reserves may be used legally and core areas illegally in extreme drought, but we did not have information on the quantitative triggers of those uses, and their incorporation would make interpreting results difficult, and so those cases were not represented.

More (and less) frequent droughts were represented by modifying the monthly precipitation surfaces used in L-Range using methods adapted from Boone (2007) and Boone and Wang (2007). A Python script that used ArcPy (ESRI, Redlands, California, USA) procedures was run repeatedly, adjusting a coefficient multiplied by each pixel in images. The process essentially stretched or compressed the variability in monthly spatial precipitation surfaces and added a small scaler offset as needed to maintain the observed mean precipitation (706 mm yr^{-1}) while altering the interannual CV from 1990 to 2009. Given that observed CV was 22% and drought frequency is increasing and projected to continue doing so, we explored CVs near that value at finer intervals than others. We created precipitation surfaces all with mean precipitation of 706 mm yr^{-1} and CVs (%) of 10, 15, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 50, 55, and 60, plus the observed at 21.97% (Fig. 3). The range of these CVs approximated the range of the most stable and most variable areas of East Africa (Muthoni et al. 2019).

We used a base simulation for each combination of scenarios and five replicates for each combination. That said, preliminary analyses showed CV in livestock numbers across the six replicates to be 1% or less, for example, and so means of the six simulation results are presented rather than a baseline and very narrow error bars. We conducted 240 simulations (i.e., open versus CBC access to lands x 20 CVs x 6 replicates) and summarize results graphically, with results of smaller magnitudes for anticipated CVs in the near future (i.e., the CVs in the 20s) in a tabular summary. Some graphical portrayals show select results for CVs from 10% to 60%, and others use 10% to 40% to improve appearance, given that results from higher CVs represent extremes.

Fig. 3. Average annual precipitation (mm) for the 20 years of surfaces used as input into simulations. The surfaces were modified to retain the observed mean (706 mm yr^{-1}) but the interannual coefficient of variation (CV) was such that precipitation was more predictable than observed (< 22% CV) and with fewer droughts, or less predictable than observed (> 22% CV), with more frequent droughts and wet years.



RESULTS

In simulations, average livestock populations were sensitive to changing interannual coefficients of variation (CVs) in precipitation, in the directions one may predict (Fig. 4). More stable precipitation from year-to-year allowed more livestock to be supported, and CVs greater than the baseline (bold line in Fig. 4) supported fewer livestock. A threshold response emerged, with CVs greater than ~30% leading to a collapse of livestock numbers with the number of livestock per person being about one-third that of the baseline value (Fig. 4). Annual average stocking in TLUs in the last year of simulation show declining livestock under increasing CVs with access to the CBC core and buffer areas and without access to the core area and only seasonal access to the buffer areas (Fig. 5). Reported differences in stocking rates in the more populous Kalama and more mesic Nkoteiya CBCs compared to West Gate CBC are clear in simulations. Changes in precipitation CV telegraphed through the ecosystem through direct changes associated with rainfall such as a reduction in annual net primary production and responses associated with both changes in rainfall and in livestock numbers, such as shrub cover (Fig. 6, with no access to CBC core and buffer areas).

An integrative measure of pastoral well-being used in DECUMA is the amount of supplemental food required for households to meet their caloric needs each month. Any change to ecosystem services and livestock holdings, income, or expenses, etc., may alter caloric intake by family members and be reflected in changes in the supplemental energy needed to meet their needs. Declines in livestock associated with increasing interannual precipitation CV and when livestock could not use CBC core and buffer areas led to people having less milk available and fewer livestock sales, less meat available, etc., which reduced caloric availability and increased the need for supplemental energy. Effects of differences

Fig. 4. Changes in tropical livestock units per active adult male equivalents under different coefficient of variations (CV) and no access to community-based conservation areas. The bold line is the response under observed precipitation (22% CV). Tropical livestock units are standardized values assigned to livestock of different types such that they summed to represent 250 kg body mass, and active adult male equivalents are similar standardized values applied to humans.

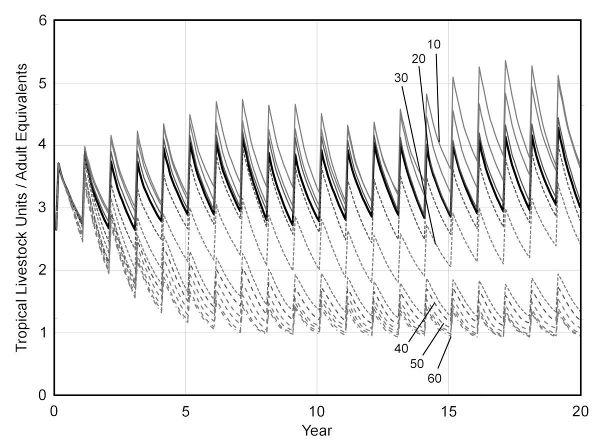


Fig. 5. The distribution of the average annual tropical livestock units in the last year of simulation with access to community-based conservation (CBC) core and buffer areas (left column) and no access to CBC core and buffer areas (right column) for selected precipitation coefficient of variations (CVs). Nkoteiya CBC has been shifted east in each set to improve visualization; it is ~28 km west of West Gate CBC. Tropical livestock units (TLUs) are standardized values assigned to livestock of different types such that they summed to represent 250 kg body mass.

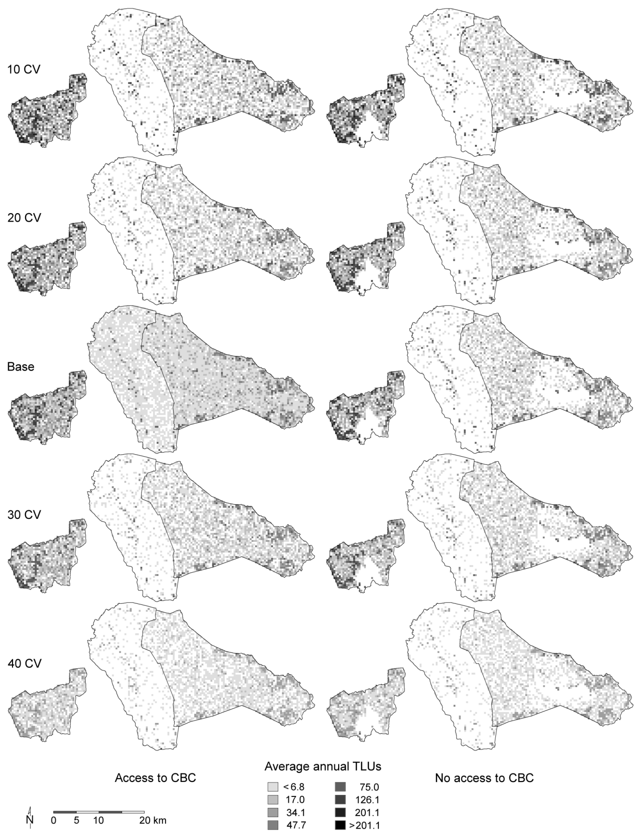
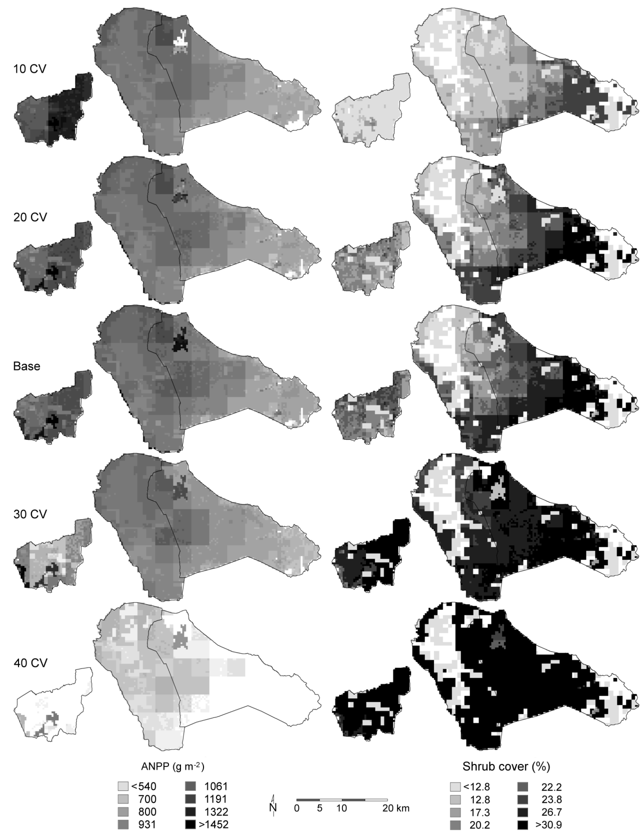


Fig. 6. Average annual net primary production (g m^{-2}; left column) and shrub cover (%; right column) for simulations with no access to community-based conservation (CBC) areas for selected interannual precipitation coefficient of variations (CVs). Nkoteiya CBC has been shifted east in each set to improve visualization; it is ~28 km west of West Gate CBC.



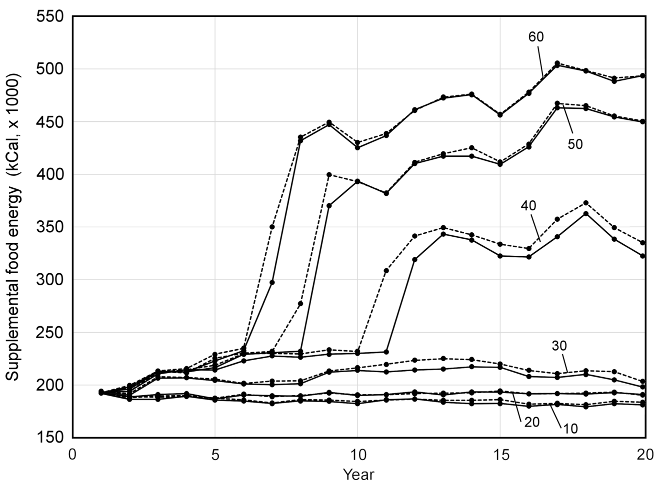
in access to CBC areas were smaller when compared to changes in the frequency of drought (Fig. 7), with up to 25% of a given CBC becoming unavailable to livestock.

Individual household responses are summarized in Figure 8 using histograms that include access to CBC core and buffer areas or no access to those areas and selected CVs. Reduced herd sizes under higher CVs shifted the high counts of households with a given number of livestock toward lower values, monthly net income per month shifted slightly lower, and monthly supplemental energy needs increased as CVs increased (Fig. 8). Herd sizes declined under increasing CVs as more frequent droughts increased mortality that was unable to be offset by reproduction during wetter periods. Fewer livestock reduced incomes from trading livestock and their products. The response was buffered though by other income sources that do not change with herd size and the need by some families to sell livestock to meet their monetary requirements, contributing to net income.

Fewer livestock also produced less milk and meat, and less energy from this and lower income to purchase grain from sources outside the family contributed to greater needs for supplemental energy (Fig. 8). Shaded bars in Figure 8 represent differences when pastoralists had access to CBC core and buffer areas. Overlaid on these are hollow bars where herders did not have access to those areas. As suggested in other results shared here, access to CBC core and buffer areas yielded smaller changes than differences in CVs (Fig. 8).

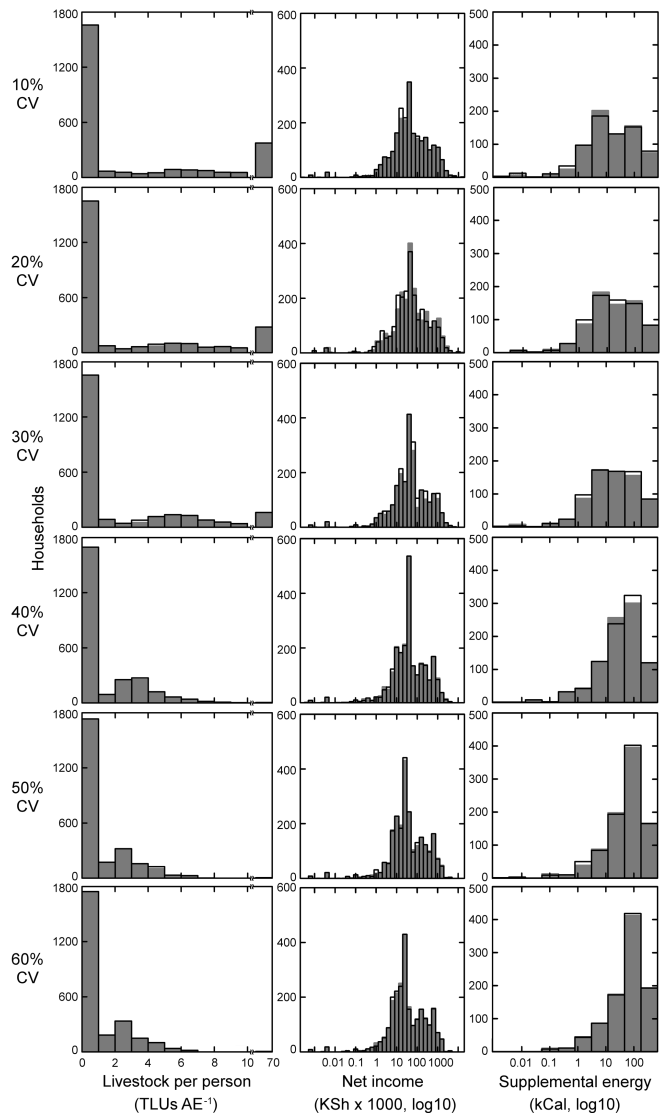
We have shown through simulation that livestock held by pastoralists in Samburu CBCs are unstable under very high CVs and that changes in pastoral well-being are more extreme under more frequent droughts than those caused by changes in access to CBC core areas. More modest increases in interannual precipitation CVs may be expected in the near future, and so we share average results from the last five years of simulations for a suite of responses reflecting pastoral household well-being for CVs from 20% to 29% (Table 1). In baseline simulations of the three CBCs, loss of access to core areas and seasonal loss of access to buffer areas contributed to about 7100 fewer TLUs. Numbers

Fig. 7. Average supplemental food energy (kCal x 1000) required by households each month with access to community-based conservation (CBC) core and buffer areas (solid lines) and no access to CBC core and buffer areas (dotted lines) for selected interannual precipitation coefficient of variations.



of TLUs and related TLUs $AAME^{-1}$ declined almost monotonically with increases in CVs. Animals sold and gifted declined with increasing unpredictability in rainfall and was smaller if access to CBC areas was prevented (Table 1; camels were not traded). The number of TLUs bought is not shown, in that it was programmatically limited and was always near 1130 mn^{-1}. Without that limit, wealthy pastoralists in the model or those with high wages may buy many animals, causing the condition indices of animals to decrease because of overstocking, making interpretation of results difficult, and promoting a tragedy of the commons pattern (Harden 1968) of grossly imbalanced ownership rather than the type seen when social norms are observed. Income $AAME^{-1}$ and income from selling declined steeply as CVs increased, with surplus animals no longer available for sale at higher CVs. Similar declines are seen for meat and especially milk energy sold, with fewer surplus products available for sale. That said, energy acquisition by families did not change markedly; declines in milk energy acquired and supplemental energy needed were almost monotonic and in the direction expected, but at these more modest increases in interannual precipitation CVs, families could meet most of their needs with milk their animals produced and grain they could purchase (Table 1).

Fig. 8. Changes in histograms showing counts of individual households, showing average values from the last year of simulation for livestock per person (tropical livestock units [TLUs] AE^{-1}), net income (Kenyan shillings), and supplemental energy needed (kCal). Grey-filled bars portray responses when herders have access to community-based conservation core and buffer areas. Hollow bars show responses when herders do not have access to those areas. Rows show responses for different coefficient of variations (CVs) of annual precipitation, from 10% to 60%.



DISCUSSION

Our coupled-systems model represented changes in ecosystem services provided to pastoral households and decisions by household heads in response to those ecosystem services. Those decisions in turn modified the ecosystem and services provided. Creation of CBC core and buffer areas essentially fragmented communal lands, from a perspective of access. In baseline simulations with and without access to core areas and seasonally to buffer areas, about 7100 fewer TLUs could be supported on the three CBCs if access to those areas was denied, about an 11% decline. Weighing that magnitude of loss against the small average annual payments received by a minority of households from CBCs may cause members to question their involvement. Of course, individual costs and benefits are idiosyncratic and include benefits beyond monthly stipends that community members must weigh, such as wages for family members, bursary payments, improved security, and transport by scouts or CBC personnel (Lesorogol 2022).

Table 1. Metrics reflecting household economies averaged across the last five years of simulations.

	CV (%)	TLUs†	TLUs sold‡	TLUs gifted‡	TLUs AAME^{-1}§	Income AAME^{-1}‡	Income selling‡	Milk energy‡	Bought energy‡	Meat energy‡	Supplemental energy‡	Milk energy sold‡	Animal energy sold‡
Access													
	20	71,658	914	749	3.590	39,391	10,689	35,346	58,932	13,898	15,986	2446	10,195
	21	70,492	903	738	3.535	39,033	9913	35,263	58,960	13,913	16,036	2160	10,054
	Base	69,116	892	727	3.469	38,843	9158	35,110	58,932	13,940	16,094	2076	9895
	22	68,877	891	726	3.463	38,710	9172	35,103	58,904	13,921	16,118	1928	9882
	23	67,502	878	713	3.398	38,075	8422	34,949	59,013	13,896	16,127	1768	9720
	24	65,209	856	693	3.297	37,410	7420	34,768	58,949	13,840	16,279	1524	9482
	25	63,343	843	683	3.207	36,778	6490	34,694	58,975	13,736	16,244	1402	9379
	26	61,435	828	670	3.109	36,336	5649	34,513	59,089	13,662	16,289	1328	9218
	27	58,828	813	657	3.031	35,959	4948	34,414	58,993	13,614	16,396	1207	9012
	28	57,524	795	640	2.898	35,163	4271	34,358	58,946	13,509	16,507	1175	8748
	29	54,283	771	616	2.736	34,356	3542	34,074	58,832	13,356	16,753	1093	8347
No access													
	20	64,777	886	724	3.222	37,303	10,287	34,735	58,263	13,690	15,999	2432	9965
	21	63,277	873	712	3.143	36,440	9868	34,634	58,265	13,666	16,018	2217	9791
	Base	61,992	861	700	3.081	37,264	8995	34,483	59,310	13,646	16,097	2051	9622
	22	62,053	861	700	3.081	36,557	8830	34,509	58,260	13,683	16,121	2140	9628
	23	60,357	844	684	3.004	35,621	8494	34,416	59,254	13,595	16,195	1901	9419
	24	58,697	819	664	2.931	34,991	7134	34,129	59,358	13,573	16,192	1529	9144
	25	57,026	810	656	2.848	34,566	6530	34,031	59,340	13,465	16,279	1502	9015
	26	55,428	792	640	2.775	34,150	5815	33,868	59,231	13,375	16,472	1343	8630
	27	54,270	775	627	2.723	33,855	4949	33,726	59,082	13,310	16,701	1228	8209
	28	52,474	754	607	2.629	33,476	4329	33,577	58,913	13,212	16,926	1254	7882
	29	50,401	732	585	2.531	33,118	3671	33,230	58,839	13,098	17,202	1067	7552

† - TLUs are tropical livestock units, representing 250 kg biomass.
‡ - Metric is mn^{-1}.
§ - AAME are active adult male equivalents (see text).

Our results point to larger concerns associated with more frequent droughts and higher interannual variation in precipitation, as projected to occur in the future under a changing climate. Being consistent in our means of quantifying precipitation, we used TerraClimate (Abatzoglou et al. 2018) to look at precipitation and CVs through time in our study area. The record (1958 to 2018 at the time of acquisition) allowed 20-yr mean and CV calculations from 1977 to 2018. When viewed as these decades-long running averages, precipitation was high in the late 1970s (i.e., 750 mm yr^{-1}) and declined steadily to a minimum of 662 mm yr^{-1} in 1988, and has since slowly increased to about 700 mm yr^{-1}. The interannual precipitation CV was higher in the 1970s and early 1980s, with a maximum of 27.7% in 1980, and then declined to about 20–22% seen recently. Too many changes in the last 40 years (e.g., demographic, rangeland decline, invasive species, fragmentation; Hobbs et al. 2008) prevent us from drawing conclusions about livestock population responses then that may be applicable now, but our simulations suggest a return to higher CVs would reduce pastoral well-being. For example, an increase of interannual precipitation CV of 5%, from about 22% (baseline) to 27%, caused a decline of 10,288 TLUs, or about 15%. Implications of that decline telegraph through metrics of pastoral well-being, such as the probability of gifting, income, and energy acquisition (Table 1). More frequent and severe droughts reduce the forage available for animals and increase their needs for movement. These responses in-turn reduce the energy animals acquire and increase the energy livestock use in travel, decreasing their condition indices. Lower condition indices are associated with an increased risk of mortality. Fewer livestock lead to less milk available for consumption, fewer animals to trade, a greater need for gifting between neighbors, and a need for more supplemental energy.

Moreover, our modeling suggests a non-linear response in livestock populations as CV increased above 30%, with rapid declines in livestock numbers and weak relationships between vegetation productivity and stocking, with rangelands dominated by non-equilibrium dynamics (Ellis and Swift 1988, Vetter 2005). Frequent droughts kill livestock and losses are not able to be offset by wet years of high forage production and more rapid growth because the intrinsic rate of increase for the animals is limited. More mobility will be required to offset loss of access to forage from frequent droughts, which is apt to be challenging in a landscape dominated by CBCs where mobility and reciprocity are reduced.

Lesorogol (2022) reviewed the prospect that CBCs helped to engrain in community members an understanding of rules of access beyond those determined by social norms to which pastoralists are long accustomed. Membership in group ranches has been contentious, especially given the prospects of subdivision to individual parcels, but group ranches as governing bodies had few resources and so conflicts were generally smaller. Elders maintained an adaptive and flexible approach to the use of grazing lands. Access under CBCs is more stringent and fixed. CBCs have reinforced boundaries and hardened views that grazing access is controlled by rules and that communities are composed of members and that outsiders without rights cannot enter. Lesorogol (2022) demonstrated awareness among members of rules imposed by the CBC, and members have become increasingly exclusionary, especially to those outside the CBC. This continues a long trend in decline in reciprocity seen among Samburu (Lesorogol and Boone 2016). Lesorogol also ran stylized games with groups of participants in the same or in different CBCs where they chose to invest a part of a stake in a (unspecified) development project in a cooperative way that advantaged individuals, or they could save some or all of the stake provided. Participants from Nkoteiya were more cooperative than those from Kalama or West Gate; seemingly the best performing CBCs included members least apt to reciprocate. In summary, "CBCs do not appear to enhance cooperation and reciprocity and may even lessen it." (Lesorogol 2022:196). That said, although core areas are formally off limits to livestock year-round with the areas left purely for wildlife so that the animals may survive droughts, in reality, core areas are opened for livestock grazing in a coordinated way when conditions are poor. Tourism operators agree to allow livestock grazing if it is done peacefully (Pickering 2021).

In Samburu (and most other African pastoral systems) traditional pastoral land and resource governance systems do not necessarily operate within the framework of communal tenure and management (Coppock et al. 2017, Pas Schrijver 2019). Pastoral governance of rangelands relies on negotiation and relations of reciprocity (Robinson et al. 2017). An analysis of NRT's rangeland program shows that to make conservancies work for pastoralists and conservation, building of social capital and information sharing may improve effective resource governance that benefits a greater proportion of the population than is now compensated for by participating in a conservancy (Galvin et al. 2021). Community conservancies must consider inclusivity including social groups (women and youth) and traditional grazing institutions (Robinson et al. 2021). Elders tend to lead grazing committees, but elders lack the cultural authority they once had (Robinson 2019, Lesorogol 2022) and so bringing women and herders into these committees can reinforce traditional practices (TNC 2020). Where traditional governance is strong, grazing plans work (Robinson et al. 2017). Negotiations among conservancies on grazing areas, livestock species and numbers, and movement patterns require dialogue among conservancies, which is a long-term process.

Besides improving conservancy governance to include a greater proportion of conservancy members, modeling results show that negative drought effects on livestock numbers are not tenable. Conservancy grazing orbits are simply too small for adequate livestock foraging needs especially under drought. Herders in NRT conservancies often take their livestock out of conservancies, sometimes long distances in Samburu County and beyond, in search of water and forage. This results in tensions and conflict among ethnic groups. NRT is looking at ways to partner with other conservancies and county governments to expand the geographic scale of community-based conservation to encourage livestock movement (NRT 2019b, Galvin et al. 2021).

Notes of caution in our methods include that our treatment of precipitation patterns is an extrapolation, and so assessment of responses for conditions never having been seen is difficult. We rely on assessments such as those using spatial surfaces (see Methods) and the broad applicability of the tool and parameters to variable areas in the global version of the ecosystem model (Boone et al. 2018). Our changes in precipitation are instantaneous, whereas we may expect rangeland plant community members to change over time in response to the (still relatively rapid) changes in precipitation patterns that are expected. Those community shifts may be expected to dampen effects as plants that are better adapted to climate variability become more common. Lastly, we adopt a narrower view of pastoral household well-being than others may, relying on quantifiable attributes such as livestock holdings, economic fluxes, and caloric intake.

Responses by livestock populations to having access to CBC areas or not may appear muted to some. A common decision point in coupled-systems modeling exercises such as this is the means to quantify livestock populations. An analyst may use reported statistics for the area, although these values are difficult to know for our CBCs. Instead, we calculated CBC livestock populations based on human population estimates (NRT 2018) and average household sizes and livestock holdings reported in interviews (Lesorogol 2022). The results were reasonable and effects of access to CBCs were responsive to stocking rates, but we cannot attest to the total numbers of livestock of each type in the CBCs.

Regarding limits to modeling, livestock, especially cattle, may be taken outside the CBCs to locate sufficient grazing (Lesorogol 2022). These long-distance migrations decrease reliance on CBC core and buffer areas and are not represented in our coupled models. Also, core and buffer areas, and indeed Nkoteiya in general given its wetter conditions, are considered "green magnets" in the region (NRT 2018). Young males herding cattle from elsewhere may be unaware or dismissive of CBC rules and be attracted to the areas of higher biomass and graze their animals in core and buffer areas. These outsiders may enforce their use of the areas with violence, with the local population powerless to exclude them from the CBC areas (NRT 2018, Lesorogol 2022). Payments are beginning to be made for carbon offsets. The Northern Kenya Rangelands Carbon Project is the world's largest soil carbon project, but it is quite new and includes many unknowns about how funds will continue to be distributed and how much may be available, and so is not included here. Yet we know that NRT's carbon project gave over US$200,000 in levy fees to the Isiolo, Laikipia, and Samburu County governments in 2022, largely to support drought relief efforts. NRT also provided clean water and tons of food rations to households hardest hit by drought (NRT 2023).

The data presented here shows that tourism funds flowing to a select few conservancy households is not fair, just, nor enough for self-sufficiency, especially under recurring droughts. However, this must be balanced against other advantages of being a member of a CBC (improved security, educational fees, etc.). The successful conservancies pay attention to culture (Galvin et al. 2018) and today need to pay attention to women and the youth (Grevy's Zebra Trust 2019, TNC 2020). Recognition and use of traditional knowledge and communities should be at the heart of conservancy governance and management. They can help improve the participation of communities in a way that benefits all. Pastoralists living in the drylands have traditionally negotiated access to resources and made use of varying informal institutions and social relations in times of stress. Yet the uncertainties that are currently being confronted are accelerating including climate change, land appropriation, and globalization of markets. Many of these shifts are beyond the control of pastoralists themselves, limiting their customary practices. This makes it essential for them to engage with others and organize collectively to transform high uncertainty and variability into a reliable flow of goods and services (e.g., forage, water, food security, health, and educational services; Scoones 2022, 2023). Engaging with others means relying on external support, technology, and information with other pastoral communities as well as with others such as NRT, aid agencies, and the state who can help design investments that are suited to pastoral needs and contexts (Krätli et al. 2013, Konaka and Little 2021, Tasker and Scoones 2022).

We would be remiss in our discussion of theory, process, and simulation to fail to recognize the recent severe drought affecting Samburu peoples' well-being (rains returned in 2023). Milk consumption had ceased in Samburu in 2022 (NDMA 2022). Vegetation conditions were poor, livestock prices were low but other staple food prices were high, water availability was poor and required transport from long distances to meet household needs, and malnutrition in young children was common. Dry conditions increased risks of intertribal conflict as competition for land increased. The National Drought Management Authority (NDMA 2022) linked the drought and changing precipitation frequencies in Samburu to effects of climate change. International aid has decreased as well, it appears, whether part of a concerning long-term trend or a pandemic-related transient response, we cannot say. Pastoralists have been successful in surviving in this difficult environment and have lessons to be shared about adaptation and resilience, but genuine dialog is required between interested parties who at present share a deficit of trust.

Lesorogol (2022) framed her discussion of the effectiveness of CBCs using a Samburu saying that captures benefiting from tourism dollars, "milking the elephant." She demonstrates that the monetary advantages of being a rank-and-file member of a CBC are small or absent (e.g., US$15 yr^{-1}, or about 1–3% of total non-livestock income for the household, to 16% of households; the other 84% receiving no payment), and the wealthy and powerful are more likely to benefit (Galvin et al. 2018). In addition, the majority of funds used for conservancy operations are not derived from tourism; 86% are from donors (NRT 2018). We demonstrate that the effects of loss of access to CBC core areas that sum to 6.7% of the three CBCs and wet-season loss of access to buffer areas that comprise an additional 12% were sufficient to be a concern for a perennially food-insecure population. Most importantly, those losses were relatively modest compared to livestock declines we may anticipate as droughts become more frequent. In short, "milking the elephant" is not improving pastoral livelihoods, and more variable rainfall reduces the amount of milk of any kind.

Acknowledgments:

RBB dedicates this paper to the memory of Dr. Carolyn Lesorogol, who died in May 2023 while this paper was being revised. Her intellectual contributions and the improvements she made to Samburu peoples' lives are lasting legacies. We extend our appreciation to the Samburu participants in interviews supporting this work and our respects to all Samburu who are adapting to a changing climate. Our continued thanks to those involved in the creation of the L-Range model (see Boone et al. 2018). The comments of four anonymous reviewers are appreciated. Funding was provided by U.S. National Science Foundation award BCS 1733817.

Data Availability:

The L-Range code and spatial surfaces that support the findings of this study is available from http://l-range.com/ and from request from the corresponding author, RBB. Code for DECUMA may be requested from the corresponding author as well. Household data used in DECUMA include geographic specificity and detailed attributes, and so are unavailable in that their release would compromise the privacy of research participants. Human subjects research was conducted under Washington University IRB approval #201706162.

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