Supplemental Information for:

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

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1) Supplementary Notes

Note S1 Equilibrium models of ecology underpinned widespread, yet empirically unsupported, narratives that pastoralist common property regimes, growing human populations, and livestock stocking rates were the main drivers of 'degradation' and 'overgrazing' (e.g., see Abel and Blaikie 1989, Roba and Oba 2009, Turner 1993). Debates about ecological dynamics have also had notable influence on social scientists (Scoones 1999, Zimmerer 1994). In studies of pastoralism in particular, non-equilibrium dynamics have informed research that has framed pastoral mobility practices as a response to ecological variability that is facilitated by social processes of informal access and reciprocity (Niamir-Fuller 1999, Oba 2001, Potkanski 1999).

Note S2 Urban ecology, land system science, and other interdisciplinary framings informed by social-ecological systems (SES; Pickett et al. 2016, Schell et al. 2020, Verburg 2012, Wu 2019) have recently expanded their engagements with social science, though landscape ecology notably lags behind (Roy Chowdhury and Turner 2019). In particular, power relations are underexplored in analyses of SES, landscape ecology, and land system science perspectives alike (Calderón-Contreras and White 2020, Cote and Nightingale 2012, McSweeney and Coomes 2020). However, recent advances in urban ecology (Schell et al. 2020) and land system science (Meyfroidt et al. 2022) have incorporated more complex understandings of power and inequality from the social sciences.

Note S3 A proliferation of interdisciplinary studies of pastoralism have included both social and ecological perspectives (Fernández-Giménez et al. 2018, Galvin et al. 2008, Hruska 2017, Leslie and McCabe 2013, Niamir-Fuller 1999, Reid et al. 2014). Many of these studies were informed by new institutional economics (NIE) and an understanding that human-environment interactions are shaped by informal and formal institutions that "represent provisional equilibria in human interactions constantly under negotiation" (Agrawal, 1999), and that structure human/environment interactions at multiple levels and scales (Ostrom 2009). This understanding built heavily on Elinor Ostrom's (1990) work, which notably illustrated how institutional arrangements enabled sustainable use of common pool resources and rebuked Garret Hardin's (1968) "tragedy of the commons", showing this argument to be based on a conflation of common property regimes with open access regimes, and a neglect of local systems of resource use and regulation.

Note S4 In particular, rational choice theories of human behavior have been heavily criticized (Cote and Nightingale 2012). However, NIE has also tended to lack engagement with much of critical sociological, geographical, and anthropological theory, and has often focused on institutions such as markets and formal policies, included an inadequate consideration of the complexity of economic, political, and socio-cultural factors, and taken a managerial, normative, policy-oriented perspective that biases analyses toward questions of how institutions can be 'designed' or modified (Cleaver 2012, Cote and Nightingale 2012).

Notes S5 For example, landscape ecologists often consider how observational scale (e.g. grain, extent, coverage, and spacing; Wu and Li 2006) shapes what information is considered, and how sampling and measurement have implications for subsequent analysis and conclusions.

Notes S6 Sayre (2017) draws attention to how rangeland ecology historically neglected scales of relevance to pastoralist livelihoods, knowledge, and agency, and how this science was intertwined with a long line of colonial interventions in rangelands globally. Recognition of the dangers of these socio-cultural biases can create reflexivity in, for example, how common practices of using data that may offer complete coverage of a landscape (e.g. census, market, and tenure), predetermine observational scale, and in turn overlook important historical, political, socio-cultural, and economic factors that influence rural livelihoods (e.g. see Scoones 2009). A deeper engagement with social science perspectives, including an expanded consideration of informal institutions and power relations, could help landscape ecologists to reflexively, productively question some of their disciplinary assumptions and methodologies (e.g., Lélé and Norgaard 2005) and to engage with approaches that are appropriate for understanding power relations and social differentiation.

Note S7 These previous studies are described in detail in Unks (2017, 2022) and Unks et al. (2019a, 2019b, 2023).

Note S8 History of the study sites. Treaties signed under coercion in 1904 and 1911 excluded the Maasai from the Laikipia Plateau, which became part of the colonial 'White Highlands', and restricted the Maasai to 'reserves' in Kajiado and Narok counties in the south of Kenya (Herren 1987, Hughes 2006). Within these 'reserves', additional land was later expropriated for British settler ranches (Spear 1993), colonial game reserves, and private ranches claimed by Maasai elites (Campbell 1993, Galaty 1992, Kituyi 1990). In 1936 the British colonial authority relocated five ethnolinguistically distinct hunter-gatherer groups to the most arid lands of the Laikipia Plateau (Cronk 2004, Herren 1987), which today correspond to the location of thirteen pastoralist group ranches (7.45% of Laikipia County, Letai and Lind 2013). These different groups that had been relocated intermarried with Maasai and Samburu pastoralists over time, and at the time of the study all primarily relied on pastoralism as a livelihood and spoke a dialect of Maa (Herren 1987, Cronk 2004). Following Kenyan independence in 1963, large private ranches in Laikipia that did not remain leased to settlers were consolidated by land buying companies or demarcated for subdivision. Many of these were used primarily as collateral for loans by absentee owners, and pastoralists in Laikipia accessed these 'abandoned' lands, as well as other government lands for grazing (Letai and Lind 2013).

Chiefs, who were elders from pastoralist communities selected by the colonial authority, gained disproportionate influence within communities as part of the British system of indirect rule (Waller 1976, Mwangi and Ostrom 2009) and imposed a number of land use regulation practices that were imposed at different scales (Unks 2022). As colonial hunting and wildlife tourism came to prominence, boreholes were constructed in the late 1940s, intended to draw the Kenyan Ilkisongo Maasai away from game reserves (Lovatt Smith 1986, Rutten 2002). A series of commissions, grazing schemes, and colonial plans to impose systems of land tenure informed The Land Adjudication Act of 1968. This law was supported by numerous international development agencies and established group ranches (hereafter GRs) as subdivisions within 'reserves'. GRs created formal collective tenure arrangements intended to introduce new land management plans, reduce livestock densities, commercialize livestock production, and provide

collateral for loans (see Grandin 1991, Mwangi and Ostrom 2009, Rutten 1992, Mwangi 2007 for detailed discussion). GRs were not designed to adequately account for variability in water and grazing availability; boundaries often crossed seasonal migration lines and drought access, resulting in decreased mobility (Rutten 1992). The Land Group Representatives Act of 1968 also created a new governance structure for GRs, consisting of elected committee members who were tasked with implementing new range management, animal husbandry, and land use practices (Rutten 1992).

Following Amboseli National Park (ANP) being gazetted in 1974, in 1977 the Ilkisongo were excluded from settling within ANP to use swamps as a dry-season source of water and forage (Campbell 1981). The Ilkisongo were similarly excluded from Chyulu Hills National Park (CHNP) and Tsavo West National Park. Farming became a key livelihood strategy for many Ilkisongo following exclusion from ANP and a series of droughts (Campbell 1999). Inherent problems with GR design led to appropriation of land by elites, growing inequality, and their undermining by national prioritization of privatization and cash crop agriculture (Mwangi 2007; Galaty 1992; Galaty 1994; Rutten 1992). In Kajiado county, most GRs have been subdivided into private parcels; in the three GRs in Kajiado I considered here, land had been subdivided in high productivity swamps designated for cultivation, and other areas subdivided for towns, designated for construction of conservation lodges, and designated as conservancies (BurnSilver and Mwangi 2007; BurnSilver et al. 2008; Rutten 2002; Southgate and Hulme 2000). Formal subdivision processes of all GR land had begun at the time of writing. Small scale farming is practiced on Laikipia GRs, especially those that border Isiolo county (Ng'ang'a and Crane 2020) and has been attempted at Koija and other nearby GRs (King et al. 2018). However, farming is much more widespread in Kajiado, due to higher rainfall and lower annual variability in Kajiado, the subdivision and draining of swamps, and proximity and ease of export of cash crops such as tomatoes to Nairobi (Campbell 1999).

Following recognition of wildlife reliance on community lands (Western et al. 2009) and acknowledgement of the overlap in wildlife and pastoralist land use, community-based conservation (CBC) interventions have sought to secure delineated megafaunal corridors that pass through pastoralist lands. Numerous conservation NGOs and ecotourism operators are active today within Kajiado GRs and lease conservancies and wildlife corridors. While GR boundaries were delineated in the mid-1970s, current GRs and committees in Laikipia were not formally recognized until the 1990s or early 2000s, when CBC 'trusts' were formed. Private ranches, many of which shifted their primary focus from cattle ranching to wildlife conservation and research in recent decades, and a consortium of non-governmental organizations (e.g. African Wildlife Foundation), played key roles in obtaining title deeds, drafting GR constitutions, and implementing zoning of land uses into settlement, grazing, and conservation areas (Kaye-Zwiebel 2011). CBC practices in both study sites have been justified locally because of their ability to provide employment, as well as medical, educational, and infrastructural development. Overall monetary benefits from wildlife conservation on GR lands in both Laikipia and Kajiado has been low (Sumba et al. 2007; Roque de Pinho 2009), with the main benefits accruing to a subset of GR residents employed as rangers and scouts in Kajiado, and as herders, security, tour guides, and research assistants in Laikipia (Kaye-Zweibel 2011).

Note S9 Survey and interview questions focused on changes in herding ecology (including rainfall, vegetation dynamics, and long-term ecological changes), socio-political and economic constraints on livelihoods, and diversification strategies. These questions were designed to gain an understanding of changes in formal and informal rules and norms that mediated livelihood practices, including but not limited to: land use, access, authority structures, and labor relations. Additional information about livestock wealth, household assets, income type, herding labor, and seasonal herding locations was also collected. See the studies referenced in Note S6 above for greater detail on methodology and analysis.

Note S10 See work that has highlighted the complexity of spatio-temporal dimensions of pastoral mobility practices (e.g., Butt 2010, Turner et al. 2016, Turner and Schlecht 2019, Maru 2022).

Note S11 Land tenure patterns on this land today is a legacy of colonial era leases, and remain contested (Kantai 2007, Hughes 2006, Letai and Lind 2013).

Note S12 See Greiner (2013) for discussion of the political drivers of these conflicts and their relation to colonial-era boundaries, changes in administrative boundaries over time, and wider conflicts.

Note S13 See Greiner (2012), Pas Schrijver (2019), and Schetter et al. (2022) for discussion of ongoing conflicts in the area and their relationship to conservancy formation.

Note S14 See Wade (2016), Pas Schrijver (2019), Letai and Lind (2013), and Unks et al. (2019a, 2019b) for detailed discussion of access to land and mobility at the time of study.

Note S15 See Herren (1987, 1991), Hughes (2006), Kantai (2007), and Letai and Lind (2013), for historical discussion of the establishment of these private ranches and the long-term implications.

Note S16 See Unks (2017) for a more detailed discussion of elders' observations and explanations of ecological change.

Note S17 See Unks et al. (2019a) and German et al. (2017) for more discussion of paid grazing arrangements.

Note S18 See Unks et al. (2019b) for the source of these figures and a more detailed analysis of herd composition and access to land during drought.

Note S19 See Unks et al. (2019b) for a detailed analysis, see also Wade (2016) for a discussion of land tenure and access to these lands under different formal tenure categories.

Note S20 See Unks (2017) for discussion of changes in vegetation and relationship to livelihoods.

Note S21 See Unks (2017) and Unks et al. (2019a, 2019b) for a detailed analysis of access to these lands and their contribution to herding livelihoods.

Note S22 See Unks et al. (2019b) for a detailed analysis of how these factors impact livelihoods during drought.

Note S23 See Unks et al. (2019a) for a detailed analysis of changing labor, access, and mobility; see also Herren (1991).

Note S24 See Unks et al. (2019a) and German et al. (2017) for detailed discussions.

Note S25 See Volpato and King (2019) for a discussion of camel adoption.

Note S26 See Unks et al. (2019a), as well as Herren (1991) and Hauck (2013) for detailed discussions of increases in small stock.

Note S27 See Unks et al. (2019a, 2019b) for detailed analyses.

Note S28 See Unks (2017) for further discussion.

Note S29 See Unks (2017) for further discussion.

Note S30 See Unks (2022) for a detailed analysis of these new land use configurations**.**

Note S31 See also BurnSilver (2009).

Note S32 See Rutten (2002) for a discussion of these relocations and the politics of conservancy formation. See also Unks (2022) for a recent discussion of the politics of wildlife conservation.

Note S33 See also Southgate and Hulme (2000) and Unks et al. (2023) for discussions of clan politics.

Note S34 See Unks (2022) for a discussion of how reserve grazing areas have been designated as and prioritized for use as wildlife corridors.

Note S35 See Unks et al. (2023) for a detailed discussion of the factors underlying differentiated mobility practices in these remote grazing reserves.

Note S36 See BurnSilver (2009) and Unks et al. (2023) for detailed discussions of socio-economic differentiation.

Note S37 See BurnSilver (2009), Hemingway et al. (2022), and Unks et al. (2023) for discussions of livelihood diversification.

Note S38 See Muchiru et al. (2009) for further discussion of the ecological impacts of permanent settlements.

Note S39 Tomatoes grown for export to Nairobi were the most lucrative cash crop, but had prohibitive input costs, and high amounts of financial risk due to fluctuating market prices and disease prevalence. Success of farming was also highly dependent on plot characteristics, including soil, location with respect to water sources for irrigation, and distance to transit corridors. See BurnSilver (2009), Hemingway et al. (2022), and Unks et al. (2023) for detailed discussion of farming in relation to wider livelihood diversification and socio-economic differentiation.

Note S40 see Unks et al. (2023) for a detailed discussion of socio-economic differentiation and patterns of accumulation of benefits.

Note S41 See Unks et al. (2023) for the detailed discussion of market relations that informed the present analysis.

Note S42 Also reported by Campbell (1999) and in Unks et al. (2023).

Note S43 See also BurnSilver (2009), Unks (2022), and Unks et al. (2023) for discussion of changes in livestock breeds.

Note S44 An alternative framing focused on landscape pattern could ask: "What are the patterns of woody encroachment at broad scales in Kenya, and what is the relationship between encroachment and changing landscape process (e.g., changing fire regime, herbivory processes) and abiotic conditions (e.g., soil taxonomy, topography, climate) across landscapes?"

Note S45 As also suggested for land system science (McSweeney and Coomes 2020); attention to complex processes of capture of resources and land control (e.g., Peluso and Lund 2011) could help landscape ecologists to become more reflexive about their own positionality as knowledge producers and their relationships within international power asymmetries. See also Calderón-Contreras and White (2020) for further discussion of the relationship between Ribot and Peluso's 'Theory of Access' (2003) and SES frameworks.

2) Supplementary Figures

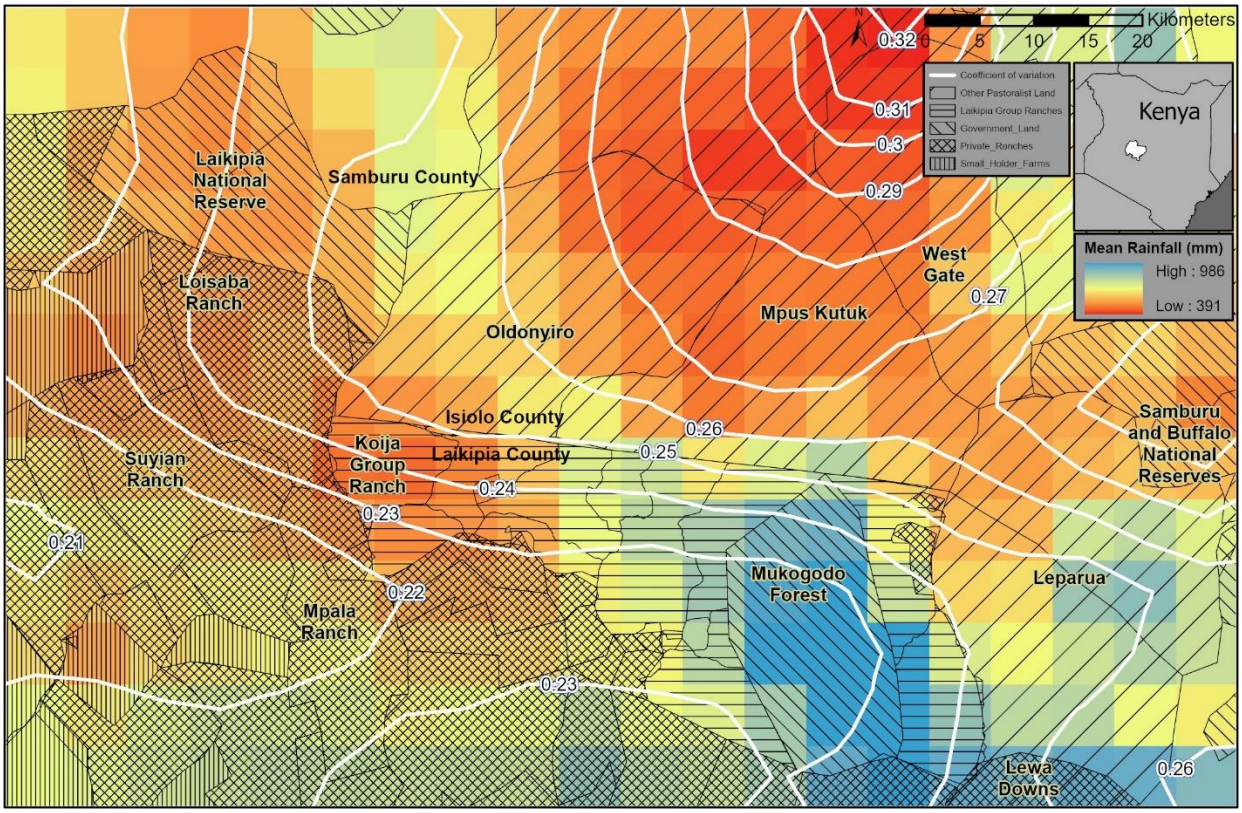

Figure S1 - Mean annual rainfall and coefficient of variation on the borders of northern Laikipia, Samburu, and Isiolo counties (matching the spatial extent of Figures 2 & 3 in the main text)

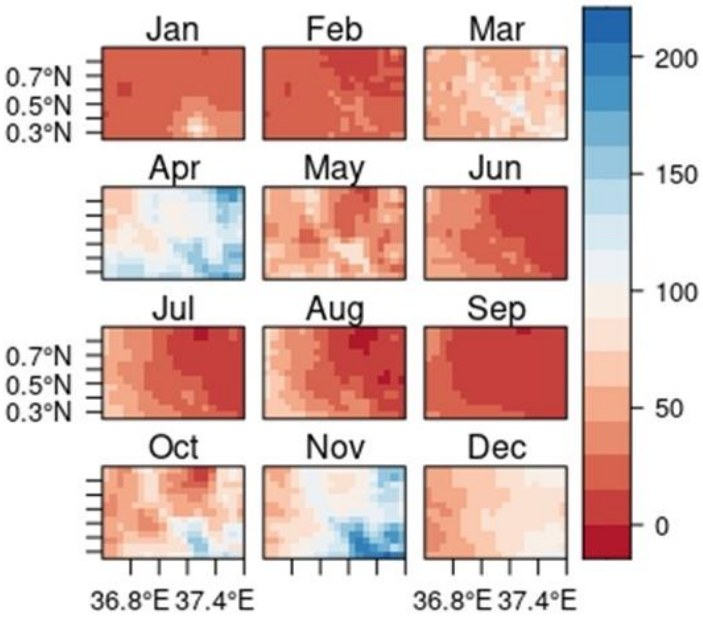

Figure S2 - Monthly mean rainfall (matching the spatial extent of Figures 2 & 3 in the main text)

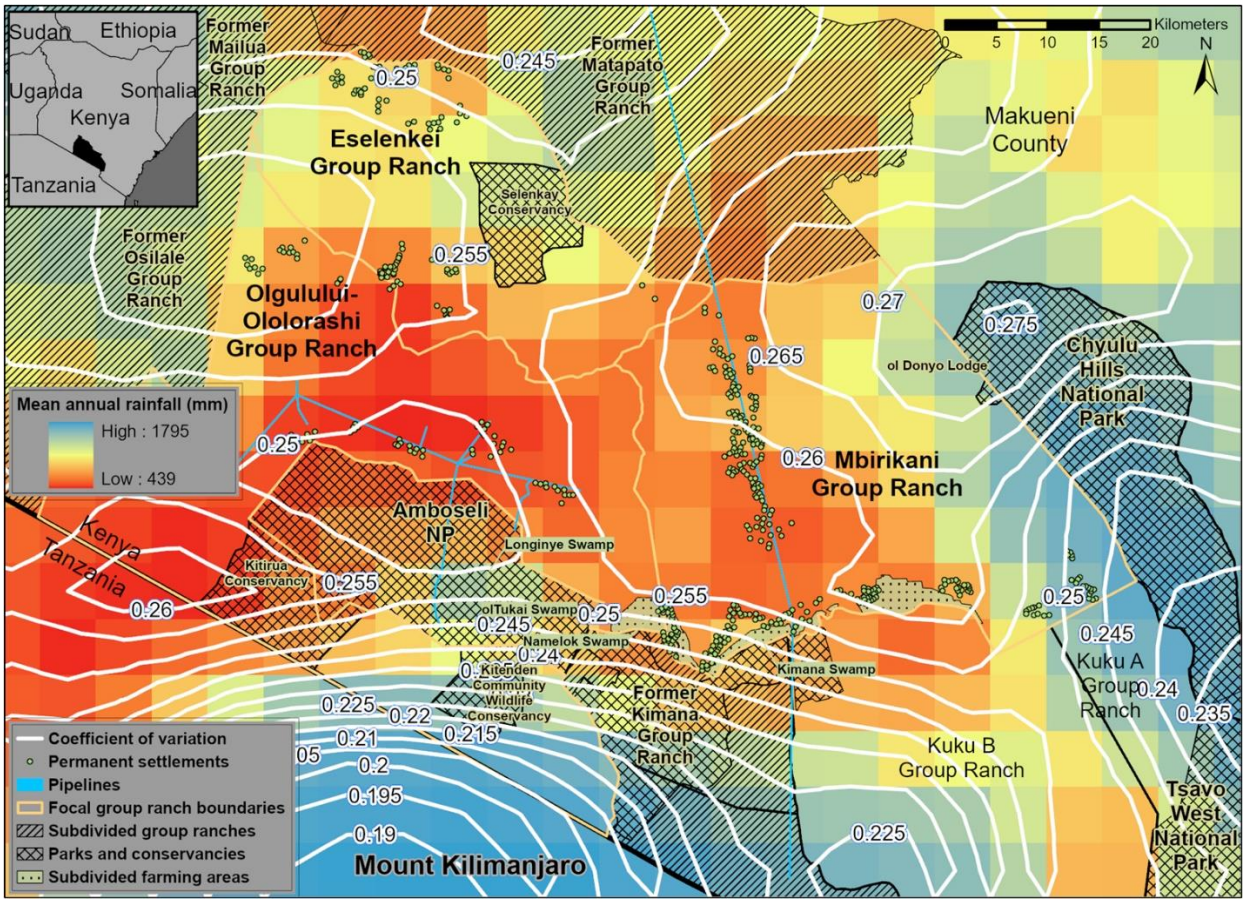

Figure S3– Mean annual rainfall and coefficient of variation across the Amboseli ecosystem (matching the spatial extent of Figures 6 & 7 in the main text)

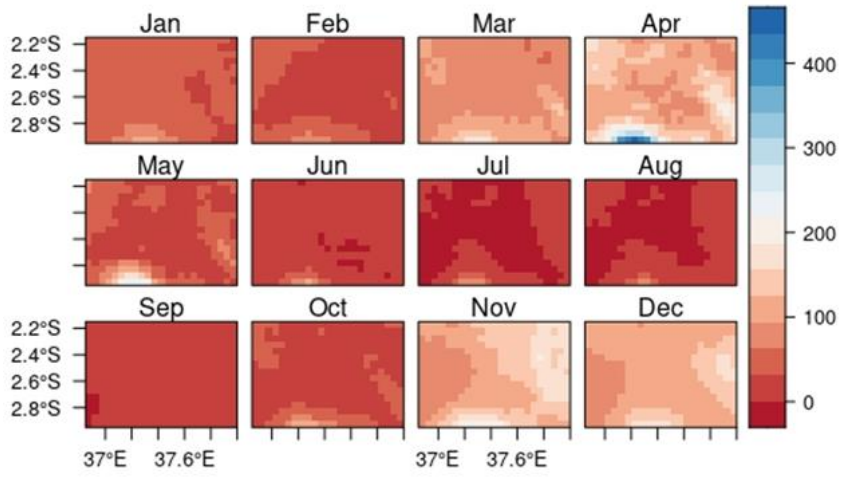

Figure S4 - Monthly mean rainfall across the Amboseli ecosystem (matching the spatial extent of Figures 6 & 7 in the main text)

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