CGIAR Research Initiative on Livestock and Climate

Climate outlook for rangelands in Tanzania

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Executive summary

By the year 2050, changes in climate are likely to affect rangelands and agriculture and livestock production in East Africa. Global weather patterns are expected to shift under climate change, causing rainfall to decline in some areas, while rainfall in other areas may remain similar to the present.

In the United Republic of Tanzania, climate change is projected to have moderate though often negative effects on annual rainfall and the production of rangeland biomass and livestock. Changes in rainfall may be minor, and potentially positive, in drier rangelands (current average annual rainfall < 700 mm/yr) of the Eastern Branch of the Rift Valley. These drier, semi-arid rangelands at lower elevations are projected to maintain their current rangeland and livestock productivity through 2050, demonstrating consistent, long-term livestock production potential.

In most wetter rangelands with higher rainfall at present (> 700 mm/yr), moderate negative impacts are projected. Rainfall is forecasted to decline moderately alongside increases in temperature and aridity, causing an average projected loss of approximately 13% of current rangeland biomass production. These higher-rainfall rangelands of Tanzania (semi-arid to sub-humid savanna woodlands of the western and southern miombo, and coastal and lake region savannas) are productive for both livestock and crops, and some are globally significant to conservation. The costs of climate change in terms of economics, livelihoods, and the environment may be significant, though feasible to counteract through effective land use and management.

Increasing severity and frequency of droughts and flooding will continue to cause disruption. The projections presented in this brief do not include changes in these or other extreme weather events, nor changes in land use or management. Drought- and flood-proofing, and sound land and livestock management, will become increasingly important to maintain the productivity of livestock and agriculture in Tanzania.

Rangelands and livestock appear set to play significant roles in enabling smallholder producers and rural communities in Tanzania to adapt to the impacts of climate change on livelihoods and economic activity. Projected changes in rangeland productivity in response to shifting rainfall can help guide initiatives to plan and achieve sustainable intensification of management in rangelands and the larger agricultural sector, toward further gains in rural livelihoods and economy in Tanzania in spite of ongoing climate change.

Background

Most of the United Republic of Tanzania can be considered rangelands populated with livestock and wildlife. Livestock contribute 20% of agricultural gross domestic product (GDP) while employing 60% of the rural population (1). Rangeland livestock systems make large contributions to rural livelihoods, nutrition, economy, and environmental goods in Tanzania (1), and may become more important under climate change (2). Overall, East Africa is less likely to be severely affected by climate change than many other regions of the world. However, even modest changes in climate (3) in terms of decreasing annual rainfall and increasing aridity may combine with increasingly frequent droughts and other shocks to disrupt agricultural and livestock production.

Climate impacts on rangeland ecosystems and livestock, and the ripple effects of these impacts throughout the agricultural sector, may negatively affect the livelihoods of smallholder producers and the national economy. Ecosystem simulation models can project rangeland ecosystem functioning under forecasted future climate conditions. Here, the G-RANGE global rangeland model (4,5) provides projections of rangeland biomass production and other ecosystem functions, as a result of changes in annual rainfall and aridity up to the year 2050. Simulation model projections (4) are useful to better understand and prepare for relatively likely changes in agriculture and livestock systems over coming decades.

The G-RANGE global rangelands model is run forward from a long-term equilibrium (2000 years) in the year 1951, through the year 2050. Projected changes in rangeland ecosystems are primarily caused by rainfall and temperature forecasts from seven different climate models: BCC (China), CSIRO (Australia), GFDL and GISS (USA), HadGEM2 (UK), IPSL-CM5 (France), and MIR-CGCM3 (Japan) (6-12). Here, the seven CMIP5 climate models are run under a relatively positive scenario for global greenhouse gas (GHG) emissions (RCP 4.5), and run again under a negative scenario (RCP 8.5), creating a total of 14 simulations of future climate and ecosystems. Changes in above-ground rangeland biomass production (net primary productivity; NPP) and other ecosystem outcomes produced by the 14 simulations are averaged to provide the projections presented in this brief.

Since each climate model forecasts somewhat different rainfall and temperature, each simulation produces somewhat different changes in rangeland ecosystems. The projections reflect the best of our scientific understanding, but are unlikely to be perfectly accurate. Extreme droughts, flooding events, and other system shocks are likely to become more frequent, but since no predictions are available for these unpredictable events, they cannot be represented. Changes in land use and land management are not included either, as it is unclear how these factors will change along with social and economic systems and values.

About this brief

The projections presented here can be used first to better understand what major changes in rangelands, livestock, and agriculture are relatively likely in certain rangeland regions or areas by 2050, as a result of climate change. Other appropriate uses include strategic planning of land use; identifying management practices that may improve productivity and sustainability in these areas; and setting policy and programmatic priorities for sustainable development. Where no major changes are expected, that information is also highly useful. Projected values for any local area may have high uncertainty, and the projections for a certain local area should never be used at local level, for any purpose. The most appropriate scale for interpreting and using these projections is at national or sub-national level such as the administrative regions of Tanzania or broad eco-regions.

The rangeland projections focus first on trends in above-ground rangeland biomass production through 2050, which result directly from changes in annual rainfall, temperature, aridity, and the concentration of carbon dioxide (CO_2) in the air (aridity is the combined effects of rainfall and temperature). These factors

can also cause changes in vegetation structure and composition, bare ground, and soil carbon stocks and dynamics. Changes in rangeland ecosystems may significantly influence agricultural and livestock systems, with impacts on feed supply rates, long-term livestock production potential, agro-climatic suitability for livestock and rainfed crops, the sustainability of rangeland production, and the ability to store carbon in soils, land, and ecosystems. Suitability for livestock production is defined here in terms of the productivity of livestock compared to rainfed crops, as well as the sustainability of livestock production in terms of land degradation. Climate impacts in rangelands can help identify the most appropriate and feasible sources of rural livelihoods and relevant management practices under climate change. As a result, projected impacts can help inform policies and initiatives in support of the sustainable intensification of agriculture and livestock production in Tanzania.

Year 2050: Climate change effects on rangelands and their larger impacts

By 2050, rangelands in Tanzania are projected to change in the following ways in response to shifts in climate, rainfall, temperature, aridity, and atmospheric CO_2:

Rangeland biomass production

- In drier rangelands (current rainfall < 700 mm/yr; semi-arid Rift Valley), rangeland biomass production is projected to remain similar to current levels.
- In wetter rangelands (current rainfall > 700 mm/yr; semi-arid to sub-humid miombo, coast and lake areas) production is projected to decline moderately, losing approximately 13% of current biomass production.
- These trends do not include the negative impacts of droughts and floods, nor positive or negative changes in land use or management.

Livestock feed supply

- The total local feed supply should remain consistent in the drier rangelands (< 700 mm/yr).
- The total local feed supply may contract moderately in wetter rangelands (> 700 mm/yr).

Potential and suitability for livestock production

- In drier rangelands (< 700 mm/yr) the potential and suitability for livestock production should remain similar to the present.
- In the wetter rangelands (> 700 mm/yr) livestock production may moderately decline with lost biomass production; however, the suitability, sustainability, and importance of these rangelands for livestock production might increase.

Rangeland vegetation structure and cover

- In the drier rangelands (< 700 mm/yr) no major changes in vegetation cover are projected, such as expansion of bare ground or large invasions of woody shrubs and trees, though ongoing woody invasions in some areas may continue.
- In wetter rangelands (> 700 mm/yr) no major changes in vegetation or bare ground cover are projected, although ongoing conversion of savanna woodlands to crops may be likely to continue, along with ongoing woody invasions in some savanna rangelands.

Soil and ecosystem carbon storage potentials

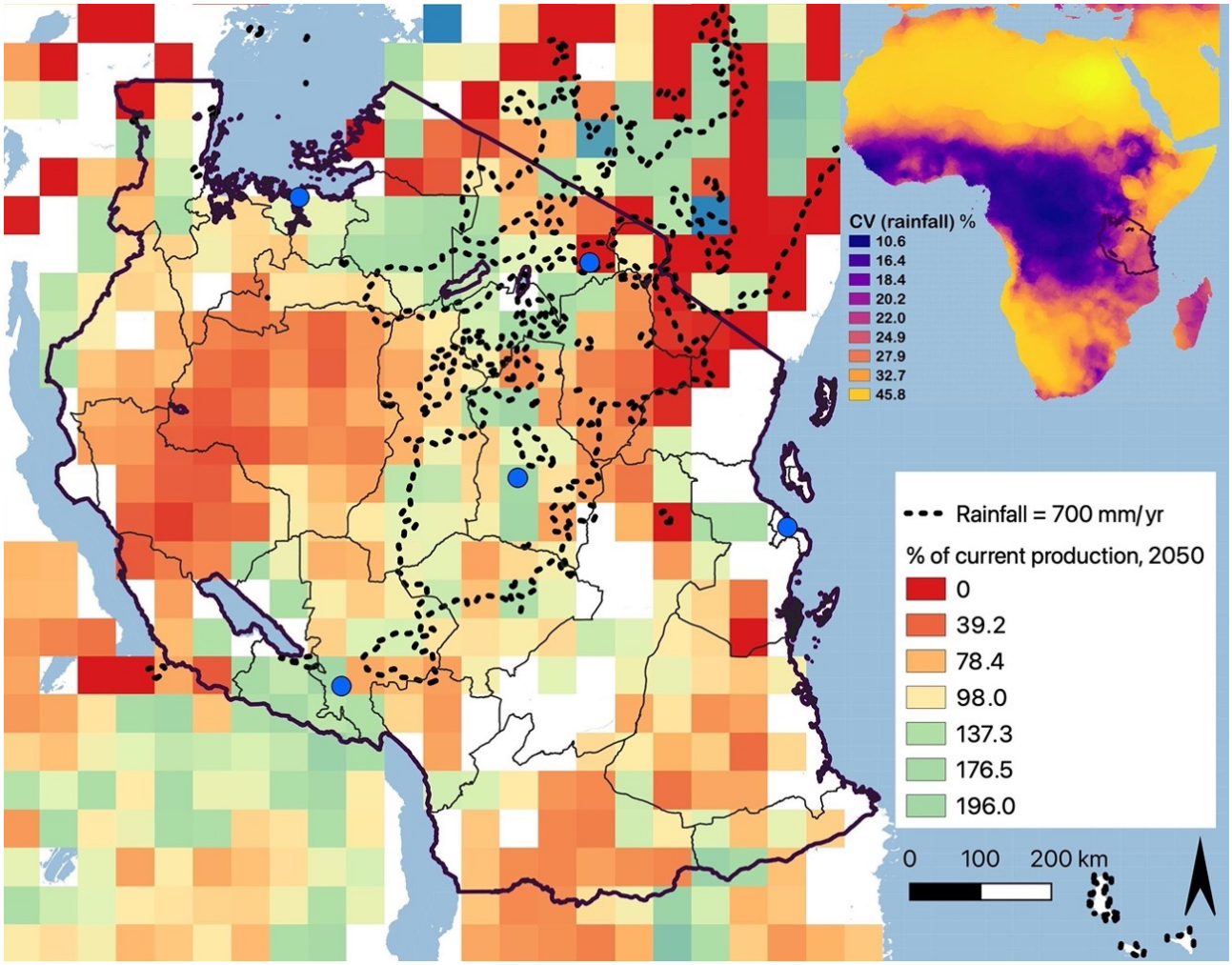
- Soil organic carbon and ecosystem carbon storage potential are projected to increase from the current, modest levels in drier rangelands (< 700 mm/yr), a hopeful trend for climate change mitigation strategies, especially in the Rift Valley.
- Soil organic carbon is projected to decline moderately in roughly half of wetter rangelands (> 700 mm/yr), together with rangeland productivity and the carbon storage potential of soils and ecosystems. Lower productivity and soil carbon indicate a moderate decline in the ability to store carbon in soils or ecosystems in the miombo, coastal, and lake regions.

Projected changes in rangeland ecosystems

In most drier semi-arid rangelands in Tanzania (current rainfall < 700 mm/yr), rangeland biomass production is projected to remain similar to current levels through the year 2050 (Table 1, Figure 1), especially where the Rift Valley (Eastern Branch) cuts through the centre of the country, including some landscapes significant to biodiversity conservation. Biomass production may increase in certain localities, or on average. These drier, lower elevation portions of Tanzania will likely have a similar livestock feed supply in 2050 as they have currently. The potential and suitability of the drier rangelands for livestock production will likely remain similar to the present, as should cropping suitability and yields. No major changes in woody cover or bare ground are projected (4). Soil organic carbon is projected to increase in these drier semi-arid rangelands (4), partly on account of consistent productivity, increasing the potential to store carbon in soils and ecosystems above present levels. Degraded rangelands in these areas may be good candidates for soil carbon storage especially through restorative grazing, along with other relevant mitigation options such as veterinary care.

In cntrast, in wetter, semi-arid to sub-humid rangelands (current rainfall > 700 mm/yr), biomass production is projected to decline moderately, losing approximately 13% of current productivity by the year 2050 (Table 1, Figure 1). These rangelands in the western and southern miombo savanna woodlands, and the coastal and Lake Victoria region savannas, are most of the rangelands in Tanzania, and include two global biodiversity hotspots. The livestock feed supply and livestock production potential might decline modestly as a result of lost biomass production. However, the suitability of these rangelands for livestock production might increase, if these areas become drier and therefore more important and sustainable for rangeland production. Woody cover and bare ground are not projected to change (4) in response to the modest aridification projected, and in some areas ongoing crop expansion and excessive burning may continue to threaten savanna woodlands. In other areas, ongoing woody invasions into formerly grassy savanna rangelands may accelerate. Partly due to lower rangeland productivity, soil carbon is projected to decline in roughly half of these wetter rangelands (4), along with the carbon storage potential of soils and ecosystems in affected areas. Land management practices to achieve global carbon mitigation through soil or ecosystem sequestration may vary from feasible to unrealistic in various areas, depending on actual changes in rainfall patterns over coming decades. Ecosystem carbon storage can be coupled or replaced with other relevant mitigation options.

Figure 1. Projected changes in rangeland biomass production through 2050, shown as the percentage of current biomass production remaining in the year 2050 ('current' production and rainfall are for the year 2000).



The dashed line (---) at rainfall of 700 mm/yr roughly shows the elevation contours of the Rift Valley Eastern Branch, as well as highlands scattered throughout the Rift Valley. Solid lines are the regional boundaries. Inset map shows the coefficient of variation (CV; in %) of annual rainfall; the most arid rangelands have CV > 33% (13).

Table 1. Climate change projections for rangelands in Tanzania, and their implications for livestock production and management. Impacts are separated for drier rangelands (current rainfall < 700 mm/yr) and wetter rangelands (> 700 mm/yr) in Tanzania.

		Current rainfall	
		Rainfall < 700 mm/yr (semi-arid)	Rainfall > 700 mm/yr (semi-arid to sub-humid)
Rangeland biomass production (total net primary production [NPP])			
	Average % of current* biomass production in 2050	104.62%	87.42%
	Average change from current* to 2050	+4.62%	–12.58%
Implications for livestock production and management			
	Biomass production (total NPP)	Similar to currently	Loss
	Livestock feed supply (local, total)	Similar to currently	Loss
	Livestock production potential**	Similar to currently	Loss
	Livestock suitability	Similar to currently	Gain
	Crop productivity (rainfed)***	Similar to currently	Small loss
	Woody cover	Similar to currently	Similar to currently
	Soil organic carbon (SOC)	Gain	Loss
	C storage potential (total = ΔNPP + ΔSOC)	Gain	Loss

* 'current' biomass production (total NPP) is for the year 2000

** livestock production potential = livestock feed supply + suitability for livestock (as compared to rainfed crops)

*** for crops currently grown—does not include switching to drought-tolerant crops

Climate change impacts and their implications for rangelands

Drier rangelands (semi-arid Rift Valley Eastern Branch)

In the drier, semi-arid rangelands (current average annual rainfall < 700 mm/yr) of the Rift Valley Eastern Branch, no major changes in climate or rangelands are projected. The productivity of the present mix of livestock and crops may not change fundamentally through 2050, although droughts, floods, and management will continue to have their impacts. Rainfed crops are an important aspect of livelihoods in the area, and are likely to have similar feasibility in 2050 as at present (14). Over coming decades livestock and their products should remain key sources of income and livelihoods.

On average throughout the entire Rift Valley, the low chance of large losses in rainfall indicates that more direct climate change impacts may be modest, with minor effects on rangeland biomass production and the larger livestock and agriculture sectors (Table 1). These drier rangelands may benefit from 'CO2 fertilization', the direct positive effect of rising atmospheric CO2, which increases water use efficiency and drought tolerance, benefitting production of rangeland and crop biomass. This positive effect of CO2 helps counteract the effects of increased temperature and aridity.

The projected trends indicate that the overall livestock production potential of the lower, drier rangelands of Tanzania is more likely than not to remain similar to the present. Rangeland biomass production, the feed supply, and appropriate stocking rates may not change much if at all from the present. As they are not projected to become more or less arid, these dry rangelands should remain well-suited to relatively sustainable livestock production.

In these drier rangelands, stocks of soil organic carbon and the carbon storage potentials of soils and ecosystems are projected to increase, while no changes in vegetation structure or bare ground are projected (4). Semi-arid rangelands produce biomass at modest rates over very large areas, and degraded portions have strong potential to rebuild soil carbon (15). In addition, a wide variety of effective non-land-based mitigation measures are available for agriculture and livestock systems including rangelands throughout Tanzania.

Wetter rangelands (semi-arid to sub-humid western and southern miombo savanna woodlands, and coast and lake region savannas)

A modest projected decline in rangeland biomass production in wetter semi-arid and sub-humid rangelands of Tanzania (current average annual rainfall > 700 mm/yr) would be disruptive to the livestock sector, and the larger agricultural sector. These rangelands include the western and southern miombo savanna woodlands, and the coastal and Lake Victoria region savannas. Producers might feel the greatest impacts from somewhat more difficult rainfed cropping, although these impacts are projected to be modest overall and possible to address through improved management (14). Lower crop yields in combination with reduced rangeland production, feed supplies, and livestock density may cause negative economic and livelihood impacts. However, no extreme changes in livestock or agricultural production may be expected by 2050. More likely changes may include switching to more drought-tolerant rainfed crops (14,16), increasing use of irrigation (16), more efficient use of fertilizers and water (16,17), and greater emphasis on livestock or alternative livelihoods (2,16).

The moderate projected loss of rangeland biomass production in the wetter rangelands of Tanzania is primarily the result of declining rainfall and increasing temperature. This increase in aridity is the result of shifts in global weather currents forecasted under climate change (3). Drying of these rangelands due to climate change might resemble degradation to the casual observer at ground level, but more precisely

this would be modest aridification, a change in the climate of the area, as opposed to degradation caused by land management. Woody cover is not projected to change in these wetter rangelands, although in some areas savanna woodland tree cover is threatened by unsustainable conversion to crops, while in other areas woody invasions into formerly grassy rangelands are ongoing. Changes in climate may be more difficult to forecast in some of the wetter rangelands, especially where different climate models disagree on how weather currents and rainfall will change through 2050. Disagreements among climate models (here, seven models) may contribute to the patchwork of projections varying from positive to negative (Figure 1). This local uncertainty means that local values may not be accurate for any exact local area. Projections for specific individual localities should not be used directly in calculations, formulation of recommendations, or otherwise. Rather, the average projection for all wetter rangelands with rainfall over 700 mm/yr (Table 1), or regional patterns (Figure 1), are the best estimates of future changes.

Given these projections, the long-term overall livestock production potential of the wetter rangelands of Tanzania will most likely decline modestly from the present. Lower rangeland biomass production would limit feed supplies from local sources, and might reduce livestock density, affecting rural livelihoods negatively. Meanwhile, if these rangelands become slightly more arid due to climate change, their suitability to livestock production may increase slightly, as more arid lands are generally better suited to livestock than to rainfed crops (2), and can be more sustainable in terms of land degradation (13). Rainfed cropping may become less efficient and less sustainable as 2050 approaches, more due to droughts and flooding than to changes in annual rainfall. A moderate loss of rainfall caused by climate change might suggest that the wetter rangelands could become more important, suitable, and sustainable for livestock production in coming decades as a result of becoming slightly drier.

Climate change through 2050 may reduce soil carbon stocks and the carbon storage potentials of wetter rangelands of Tanzania, although any decline in livestock density would imply reduced GHG emissions from livestock. These wetter rangelands have multiple opportunities for carbon sequestration, including soil storage in savanna rangelands (18) and storage in savanna woodland tree biomass. However, declining biomass production means declining inputs of carbon to the ecosystem, and declining soil carbon stocks (Table 1). Land management would need to supersede or override the negative effects of climate change in terms of declining rainfall to provide global carbon mitigation through ecosystem carbon sequestration, which may be very challenging in some areas. A variety of other mitigation measures available could be more feasible and effective in reducing GHG emissions from livestock systems in the wetter rangelands of Tanzania.

Other factors likely to influence actual future changes

The projections presented in this brief do not include some factors that may have strong effects on the eventual, actual impacts of climate change. Among the most important factors are increasingly frequent extreme droughts and flooding events, which make the projections seem relatively optimistic—that is, real trends could be more negative than the projections here. Invasive species could bring unforeseen difficulties in rangelands, crops, and elsewhere. Climate change may also reduce forage quality in rangelands with low soil nitrogen and cause shifts in rangeland vegetation (19) (for example, perennial to annual grasses, or grasses to shrubs), while more variable rainfall within each season can slow production (20). More positively, as the climate changes, rangeland vegetation could expand rapidly into newly appropriate habitats, helping to maintain biomass and ecosystem productivity. If rangeland vegetation can keep pace with changes in climate, the projections would be relatively pessimistic, and rangelands could see weaker impacts than projected. However, the greatest uncertainty is the human element. Land use change (rangelands to crops, crops to rangelands, etc.) and land management could further degrade rangelands and create inefficient production systems. Alternatively, planning of appropriate land use and effective land management can greatly help toward achieving climate-resilient crops and livestock, and preserving their contributions to local and national economies.

Management, planning and policy for rangelands in response to climate change

Changes in production systems

Nearly all of the rural population of Tanzania engages in agriculture (97%) and most engage in livestock keeping (60%) (1). Livestock and their products are among the livelihoods sources that many Tanzanian producers are shifting toward as a result of climate change (16), and livestock may greatly assist producers to adapt to a changing climate throughout Tanzania. Climate impacts, however, will likely differ between the drier Rift Valley savanna rangelands and the more humid miombo and other rangelands of Tanzania. In coming decades, livestock will likely have an expanded role in livelihoods and the economy as compared to the present.

In the wetter rangelands (> 700 mm/yr) found mostly in western, eastern, and southern Tanzania, changes in agricultural systems in coming decades may include growing more drought-tolerant and diversified rainfed crops than at present, more irrigation, and greater reliance on livestock (2) and their products among other livelihood sources (16). Most crops currently grown are projected to remain feasible for rainfed production throughout Tanzania by 2050, yet can benefit from climate-adapted management practices (14) and especially more efficient use of fertilizers and water (17). Livestock and their products are taking on a stronger emphasis in the household mix of livelihoods in the wetter rangelands of Tanzania (16), which may seem counterintuitive since rangeland biomass and livestock productivity are projected to decline. If these wetter rangelands become drier by 2050, greater future suitability of these areas to livestock relative to rainfed crops is likely. If they do become drier, less severe rangeland degradation from livestock production (13) could lead to relatively more sustainable rangeland production. Livestock help drive crop agriculture as well (21), and manure and draft power can assist climate change adaptation by increasing crop yields (17). Livestock may become more important to the larger agricultural sector and local and national economies over coming decades, along with emerging livelihoods for rural residents, such as intensive small-scale poultry, other more commercialized agricultural value chains, solar power generation, and beyond.

In contrast, in drier rangelands (< 700 mm/yr) in the Rift Valley, no major shift in rainfall can be expected, if any at all. However, both drought and flooding events appear likely to become increasingly severe and frequent. Still, these rangelands appear likely to maintain present levels of biomass and livestock production. Livestock are the ‘backbone’ of pastoralism (22), agro-pastoralism, and even mixed farming (21), especially in many drylands. In the semi-arid Rift Valley, livestock appear likely to continue their present critical roles in supporting livelihoods, economy, nutrition, and environmental goods including the benefits of pastoralism and livestock to conservation and ecosystem services (15,18,22).

No major transformations of agro-livestock systems are anticipated as a result of changes in annual rainfall in Tanzania. In both the drier rangelands of the Rift Valley, and the wetter rangelands that cover most of Tanzania, ongoing efforts to improve livestock production, crop yields, and sustainability may be just as relevant in 2050 as today. Agricultural development programs and the use of improved management practices can continue largely uninterrupted on their present course toward sustainable intensification (23). Existing policies, extension, research, information systems, and other sectors that support livestock and agriculture throughout Tanzania will likely be equally relevant, applicable, and strategic as at present. It is somewhat concerning that the region around Mt. Kilimanjaro and parts of the western miombo show sharp projected declines in rainfall and rangeland biomass production, losing 60% of production or more in some localities (Figure 1). If these trends came to pass, they would have severe negative consequences for multiple major conservation priority areas. However, these projected declines cover only small areas, which together with uncertainty in future rainfall forecasts suggests that only a low level of confidence should be

placed in these trends. Overall, conservation areas including major global biodiversity hotspots are likely to largely retain their present ecological capacity to support wildlife populations and ecotourism and other wildlife-based income streams.

Land, livestock, and policy options for productive and resilient rangelands

Adaptation to climate change at societal level in Tanzania can benefit substantially from rangeland livestock production, and several strategic options for producers and policymakers may enhance these benefits. Land management will be more important than ever, and practical strategies are needed, especially in pastoralist drylands and communal lands in farming zones. New options are emerging for management of communal grazing lands, which focus on building the capacity of local producer institutions to manage lands for mutual benefit.

Building upon traditional and local range management approaches, such as the Maasai and ngitili systems in Tanzania (24), recently developed institutional approaches include community-based rangeland management (22), communal grassland management in farming areas (25), and Participatory Rangeland Management (26), which has been piloted in Tanzania since 2014 (27). Building local institutions provides a means to develop alternative incomes, manage land, livestock, and crops more efficiently, and achieve large-scale rangeland restoration. Low-cost approaches for rangeland restoration are being developed (28,29), while even simply monitoring for degradation can be a management and policy tool in certain contexts (30). At the same time, though, some rangelands in Tanzania are undergoing rapid and often unproductive land use changes—such as clearing of savanna woodland tree cover, unsustainable temporary cropping of poor soils, unsanctioned privatization of communal lands, and ill-advised forestry plantation (31). To prevent these and other negative outcomes, land use planning for zoning land uses where most appropriate and sustainable (32) is a critical step. Further, a clear sense of access to land and resources for herders is key to the management of communal grazing lands, as is codified access in, for example, communal fisheries and forests. Clear and durable recognition of rights for communal use of rangelands significantly enhances management and sustainability (27,33) and benefits the preservation and restoration of rangelands for sustained productivity. As the National Land Use Planning Commission (NLUPC) rolls out integrated and participatory village land use planning, management and administration throughout Tanzania (32), and given sufficient funding, clear land use rights and regulations could soon be in place effectively nationwide. Under this process, the mechanism for joint village land use planning has proven practical for improving management of pastoralist rangelands (27) and can significantly improve the efficiency and sustainability of agricultural and livestock production. Step-wise intensification of rangeland livestock production under climate change will further benefit from policies and investments in support of information needs of producers, and the legal, financial, and infrastructural (livestock routes, abattoirs, markets, etc.) conditions that can accelerate rural development (23).

Improving production efficiency and adaptation to climate change can significantly benefit from a variety of livestock management options. Dual-purpose crops (34) that produce both food grain and quality feed as well as planted fodders can be crucial supports in times of poor rainfall, though they also rely on rainfall (or irrigation) and face challenges similar to rainfed crops. Like crops, private fodder plots can fragment communal rangelands into small fractions, often diminishing natural resources and communal well-being (22). Veterinary care and surveillance for disease pathogens and vectors can limit livestock mortality and help detect outbreaks (35), and can be merged with rangeland management for joint improvement in One Health (36). Shifting livestock herd composition enables a better fit of livestock feed demand to available feed resources and management needs. Browsing livestock such as goats and camels largely prefer woody browse to grassy forages, making them more drought-resilient than grazers like cattle and sheep. Browsers can productively utilize excessive woody vegetation and promote recovery of grassy or mixed pastures, also controlling wildfire risk. Small ruminants (goats and sheep) are more drought-resilient than cattle, given their lighter feed and water needs, greater mobility, and lower risk of mortality, most especially for goats (37). Breeding of climate- and disease-adapted livestock is important, though breeders face challenges in anticipating changes in climate, disease risk, and production systems, including the feed base and access to

veterinary services. Manure management techniques such as regular movement of mobile livestock corrals (38) can fertilize the land and boost rangeland productivity (a technique long practiced by pastoralists in Africa), while efficient use of manure can support climate adaptation of crops (17). All of these options are equally relevant throughout all of Tanzania, although their implementation would often vary. A significant outstanding question relates to the possible scenarios that could follow large-scale control of livestock disease and vectors, especially tsetse flies (Glossina spp.) and animal trypanosomiasis disease. At present, over 50% of rangelands in Tanzania are little utilized for livestock due to tsetse and trypanosomiasis (23). A reduced threat from tsetse would likely increase the use of especially miombo savanna woodlands for livestock raising, and allow changes in herd composition toward more sensitive cattle and camels. It is possible that expanded use of miombo would cause degradation primarily from clearing of trees for cropping, alongside unregulated grazing. Yet as long as uncontrolled cropping can be prevented, expanded use of miombo for rangeland livestock could incentivize the conservation of savanna woodland tree cover and the globally significant biodiversity found in the western and southern miombo.

In contrast, direct control of stocking rates may not be the most useful tool for improving land and livestock management. Climate-induced aridification and a possible decline in stocking rates in the wetter rangelands of Tanzania, and existing aridity in the Rift Valley, make the use of stocking rates at carrying capacity a weak management tool. High stocking rates can reduce rangeland condition over the long term. However, stocking rates and rotations often have little effect on rangeland quality (39,40), and stocking rates are practically difficult to reduce in communal lands for multiple reasons. In the wetter rangelands of Tanzania, droughts and moderate losses of rainfall and biomass might cause stocking rates to decline and stabilize at a slightly lower livestock density. Further reduction of stocking rates would likely be socially and economically unacceptable. Lower densities would limit economies of scale (in dairy, for example) and lessen fertilizer and draft power inputs to crops. In contrast, in the drier rangelands of the Rift Valley, stocking rates may remain similar to the present. In these drylands, producers often struggle to predict appropriate stocking rates in advance of a certain season, since rainfall varies dramatically (sometimes over short distances). A rangeland can be understocked one year; then overstocked as a drought hits the next; and then again understocked the following year due to livestock deaths (41). If rainfall in the coming season cannot be reliably predicted at local scales, the ideal stocking rate is not predictable either. For these among other reasons, the United States Bureau of Land Management (BLM) is currently testing with a pilot group of private ranchers (30) whether the BLM might alter or possibly end the use of carrying capacity for setting federal grazing permits in dry rangelands.

Implications for mitigation of GHG emissions

As in any region of the world negatively impacted by climate change, efforts to sequester carbon in rangeland soils, lands, or ecosystems in Tanzania should proceed with due diligence. In the wetter rangelands of Tanzania, the forecasted moderate decline in rainfall due to climate change poses a constraint to carbon sequestration. If current climate forecasts prove accurate, the wetter rangelands of Tanzania would lose carbon due to declines in annual rainfall, biomass production (Figure 1), soil organic carbon stocks, and total ecosystem carbon stocks (Table 1). These losses of carbon may threaten the feasibility of carbon storage in rangelands in western, eastern, and southern Tanzania, a threat that may be challenging to overcome wherever rainfall decreases (Figure 1). On the other hand, semi-arid rangelands in the Rift Valley have stable and appreciable soil carbon storage potential in rangelands facing some degree of prior degradation. Efforts to sequester carbon in rangeland soils, land, or ecosystems should identify and prioritize locations and management practices more likely to successfully store carbon through 2050 in light of forecasted rainfall declines in some areas.

In semi-arid Rift Valley rangelands, carbon storage is technically feasible (18) and will likely remain feasible under climate change through 2050. Soil carbon storage potential can be significant in rangelands that have become degraded over the past few decades. In rangelands that are not degraded, soil carbon may already be maximized, reducing the ability to ‘pack’ more carbon into the soil (15,18). Three challenges

face carbon storage in these semi-arid rangelands. First, semi-arid rangeland vegetation grows relatively slowly on account of modest rainfall, meaning relatively low and slow inputs of carbon to the ecosystem as compared to forests, for example. Second, scientific prediction of carbon storage requires attention to low effect sizes, high variance, long time periods to measure change in soils (up to 10 years), and the weak availability of information describing rangeland management practices and their impacts on carbon stocks across major ecological and management gradients (42). Soil carbon storage is methodologically and technically feasible in semi-arid rangelands (18), yet work remains on demonstrating links to specific management practices, most particularly communal pastoralist systems. The final major challenge also relates to communal pastoralist lands, since land tenure policy formulation and implementation is an important precondition for productive, appropriate and ethical dedication of carbon revenues to designated beneficiaries in a durable legal framework. The NLUPC integrated and participatory village land use planning, management and administration process (32) provides the type of legal recognition for land use rights that are needed for clear and appropriate carbon revenue arrangements. The process is not yet fully financed or implemented, and carbon projects should confirm the status of land use planning in any specific area of Tanzania before proceeding with project implementation.

In addition, there are multiple alternatives to ecosystem carbon storage for reducing GHG emissions and emissions intensity in livestock systems. These options are viable across pastoralist rangelands, agro-pastoral areas, and mixed crop-livestock farming. Mitigation measures available for livestock include improved feeds and veterinary care to enhance production efficiency, manure management to reduce GHG emissions from manure and exploit this key fertilizer resource, and attention to emissions hotspots such as corrals and water bodies (43). Protecting surface water and using mobile corrals (38) would directly reduce GHG emissions. The mitigation benefits from these and most other viable approaches are poorly documented for the African continent (44), with communal pastoralism most poorly represented, and more empirical data are needed to accurately assess GHG emissions baselines and likely reductions.

Conclusion

Climate change in Tanzania is projected to cause generally moderate impacts nationwide, as a result of shifting global weather patterns causing changes in annual rainfall, temperature, and aridity. These impacts will most likely be light or non-existent in drier semi-arid Rift Valley rangelands. Moderate impacts are projected in wetter rangelands of the western and southern miombo savanna woodlands, and savannas of the coast and Lake Victoria areas. On average, moderate declines in rainfall, rangeland biomass production, soil carbon, and carbon storage potentials are projected. Some wetter rangelands may see increases in rainfall and production, however, and there is some uncertainty regarding precisely where annual rainfall may increase or decrease, and by how much. The projected changes in rangelands do not include the impacts of increasingly frequent yet unpredictable droughts and floods, nor do they account for good or poor land use and management leading to degradation or rehabilitation of rangelands.

Overall no major transformations of agriculture or livestock systems can be expected as a result of projected changes in rangelands. However, in wetter rangelands in the western, eastern, and southern portions of the country, moderate declines in rainfall and rangeland biomass production might cause a reduction in livestock stocking rates, which would negatively affect rural livelihoods and economy. Crops are generally not projected to be heavily impacted by changes in annual rainfall in Tanzania, although livestock and other livelihood alternatives may become increasingly important as droughts and heavy rains make cropping more challenging. In doing so, livestock and their products may provide significant avenues for productive adaptation to climate change, including the roles of livestock in supporting crop agriculture. The effects of aridification due to climate change, droughts, and flooding in wetter rangelands should be feasible to counteract through land use planning and land management. In contrast, semi-arid Rift Valley rangelands appear set to maintain their current biomass and livestock production levels through 2050, although droughts and floods will have their impacts.

Over coming decades, the current importance of rangelands and livestock for economy, livelihoods, nutrition, and environmental goods is not likely to change dramatically in Tanzania. However, especially in wetter rangelands facing increasing aridity as a result of climate change, the importance of livestock is expected to increase, along with alternative livelihood sources. Projected moderate negative changes in wetter rangelands can guide producers and policymakers to identify appropriate and strategic climate adaptation options such as those outlined herein. In contrast, the absence of strong climate impacts in the drier semi-arid rangelands of the Rift Valley indicate few changes if any. Throughout Tanzania, current efforts toward sustainable intensification of crop and livestock production may proceed largely on their present course. Projected changes in rangeland productivity and agriculture and livestock systems can help guide the development of initiatives and management techniques to sustainably intensify rangelands and the larger agricultural sector, toward further gains in rural livelihoods and economy in Tanzania in spite of ongoing climate change.

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