Feed biomass production may not be sufficient to support emerging livestock demand: Model projections to 2050 in Southern Africa

Dolapo Enahoro,^{1,*} Jason Sircely,² Randall B. Boone,³ Stephen Oloo,² Adam M. Komarek,^{4,5} Sirak Bahta,² Mario Herrero,⁶ Karl M. Rich⁷

*Corresponding author email: d.enahoro@cgiar.org

¹ International Livestock Research Institute, Accra, Ghana.

² International Livestock Research Institute, Nairobi, Kenya.

³ Department of Ecosystem Science and Sustainability Colorado State University, Colorado, USA.

⁴ The University of Queensland, School of Agriculture and Food Sciences, Gatton, Qld 4343, Australia.

⁵ The International Food Policy Research Institute, Washington DC, USA.

⁶ Commonwealth Scientific and Industrial Research, Brisbane, Australia.

⁷ International Livestock Research Institute, Dakar, Senegal.

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Abstract

The demand for livestock-derived foods has steadily grown over the past decades and rising incomes and human populations are expected to see demand further increase. It is unclear if current livestock feed resources are adequately prepared to meet future demand especially given the looming challenges of climate change. Many feeds such as grasses, crop by-products, and other biomass may not be widely grown commercially or sold in formal markets but are critical sources of livestock feed in many low-resource settings in which ruminant livestock production is important. The availability of these feed types can determine the extent to which the livestock sector can expand to meet growing, and sometimes critical, demand for animal-source foods. In this paper, we compare country-level projections of livestock demand from a global economic model to simulated data on feed biomass production. Our comparisons account separately for beef, lamb, and dairy demand. The data allow us to assess the future sufficiency of key sources of feed biomass, and hence aspects of the expansion capacity of livestock production in selected countries in Southern Africa. In a country and year, availability was calculated as total domestic production of a specific feed type divided by total domestic demand by livestock animals. Feed supply was considered relatively more or less sufficient in a future year compared to the relative availability calculations of the baseline or initial year of analysis. The role of feed biomass constraints is analyzed under different scenarios of changes in income per person and total human population, and of climate change conditions in the region in 2050. Our simulation results project that given the interacting effects of projected climate change and changes in income and population in the region, there will not be enough feed biomass produced domestically to meet growing demand for livestock products. For three types of feed biomass (feed crops including grains, grasses, and crop by-products) for which future livestock feed sufficiency was examined, our results showed feed sufficiency declines for all three feed types in Malawi

and Mozambique, for two out of three in South Africa and for one of three in Zambia, under intermediate and extreme scenarios of climate change in 2050. Grass production from rangelands was further projected to be more constrained than 2010 conditions, for all the countries in the study. Our results suggest an urgent need to improve feed biomass productivity to support future supply of animal protein in the study countries.

Keywords: Climate Change, Scenarios, IMPACT model, G-Range Model, Livestock Feeds

1. Introduction

Growing incomes are driving higher demand for livestock-derived foods in many low- and middle-income countries (1), raising prospects for the benefits of an expanded livestock sector to these countries (2). Potential benefits of expanding livestock production include *inter alia* rural and economic development (3), employment and incomes (4)(5), livestock-derived asset growth (6), and increased export earnings or import cost savings (7). In addition, there are economic, social, and ecological costs associated with the emergence of long food supply chains that more localized livestock production could potentially address (8). At the same time, these benefits may be in conflict with calls to limit growth of consumption and production of livestock derived products globally (9), given their potentially harmful impacts on public health and the natural environment (10). Nonetheless, there may be a strong case for increasing, rather than decreasing, animal source food consumption in some regions such as Southeast Asia and sub-Saharan Africa where access and consumption are low and increased supply of animal protein is expected to improve nutritional outcomes (11)(12)(13). Natural resource constraints, however, limit the expansion of livestock production in such areas (14), with scarcity of feed sources being a foremost constraint to production (15).

Risks of global climate change exacerbate natural resource and related constraints on livestock production (16)(17). For example, climate projections for Southern Africa to 2050 indicate the coverage of arid regions expanding, while sub-humid zones shrink towards the equator (18). Crop and livestock production systems in the region could see major shifts in response to the climate-induced changes (19). Being dependent on seasonal rainfall distributions and rainfall amounts, Africa's smallholder cropping systems may be particularly vulnerable to increased variability in crop cover and crop yields (18). Livestock producers in dry and marginal areas are in addition vulnerable to climate effects on animal performance; water availability for household, agricultural and other use; and the quantity and quality of feeds (19). The impacts of climate change on livestock feeds include changes in herbage growth of forages, pasture

composition and the quality of herbage, greater incidences of drought, and increased intensity of rainfall (20). Studies suggest that while opportunities may exist for some households in more conducive rangeland and cropping conditions resulting from climate change, the vagaries of these systems could pose real challenges for many other households (20)(21)(16). Other studies, however, suggest that economic changes not related to climate are the more ominous threat to agricultural related outcomes in low-and middle-income countries in the future (22).

Quantitative simulation models could improve our understanding of the trade-offs and complementarities associated with socio-economic and biophysical interactions under climate threats as well as inform policy to appropriately anticipate and address future opportunities and challenges in livestock-related food systems. Application of a dynamic framework of integrated climate, crop, pasture and livestock models to a population of dry area farms in Zimbabwe for example showed that reliance on rangeland residues and crop residues, which were of low quality in the dry season, will lead to feed gaps, constrained livestock productivity and reduced revenues for some categories of farms (23). Evidence from household-to-landscape level analyses are sometimes not readily elevated to higher level decision-making. Other tools and analyses are needed that can quantify the interactions of socioeconomics, livestock, and climate across countries in a continental region and in relation to the global agricultural and food system. Recent studies that have incorporated aspects of the biophysical realities of agricultural and livestock production and climate change into models of global livestock production have not explicitly accounted for rangelands or the grasses they supply as livestock feeds (24)(5). Others may have incorporated interactions of climate, feed biomass and livestock production at levels of analyses aggregated well beyond what would typically be applicable for national-level policy and planning (17), or do not account for and the potential influences of economic change (25).

There is potential to bridge current knowledge gaps in livestock feed biomass accounting within market-based models of the global agricultural and food system (26). Such advancements will aid in providing more precise projections of the impact of climate and other global change on local livestock systems and in assessing the potential of the livestock sector to contribute to development objectives such as food security and income generation. A recent study used a novel ecosystem model to quantify vegetation of global rangelands for a suite of plausible future climates, showing small to large changes in rangelands productivity for regions across the world (27). That study's projections for Southern Africa indicate major vegetative losses to 2050. Unlike other locations such as West Africa where rangeland productivity is projected to decline without substantial loss of plants, the projections for Southern Africa show increased bare ground following whole plant deaths of herbs, shrubs, and trees. This suggests more serious implications of climate change for future livestock production in the region.

In this study, we emphasize the importance of accounting for future feed biomass production in the economic modeling of the livestock system, focusing on four countries in Southern Africa. We investigate the future availability and use of grasses, crop residues and fed feed crops, with the aim of quantifying the extent to which the supply and use of feeds limit or enhance growth of livestock production in the region. We do this by linking a global economic model that projects the demand for animal source foods and production-side responses to this demand, to an ecosystem model quantifying expected changes in biomass production in rangelands. Our integrated assessment framework investigates the potential of the region's livestock production to maintain the status quo, looking at the role of livestock feed biomass under different scenarios of global economic and climate change in 2050. Our current study asks two main questions, given the current importance of different feed types to livestock production in the study region: (1) what are the anticipated impacts of economic and climate change on feed biomass supplies to 2050; and (2) what implications do the changes in feed availability have for livestock development and the production of livestock-derived foods. We do not offer a normative goal for feed availability but explore

what sufficiency would look like for the different feed categories under a range of what-if scenarios for income, population, and climate change. The study focuses on a four-country sub region comprising Malawi, Mozambique, South Africa, and Zambia. These selected countries were the focus of Southern Africa- Towards Inclusive Economic Development (SA-TIED), a trans-disciplinary research program with thematic focuses on enterprise development, public revenue, inequality, climate and energy, macro-modelling, and regional growth (<https://sa-tied.wider.unu.edu/>, accessed March 12, 2021).

2. Methodology

To assess current and future national demand for animal-source foods (meat and milk) against national livestock production and availability and use of grasses and other feeds in the selected countries, our study analyzed model projections from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), a multi-market model of the global agricultural and food system; and G-Range, a spatial ecosystem model quantifying global changes expected in rangelands under future climates. Both models have been previously used and are well documented (28)(29)(30)(25). Here, we highlight their applications to the specific context of projected changes in (animal source) food demand and the production of feed biomass (crops, crop residues and grasses). The focus is on the treatment of livestock and feed demand and production in both models, the linkages between the two models, and plausible scenarios of the future on which assessments of future feed sufficiency are based. The analysis is applied to Malawi, Mozambique, South Africa, and Zambia (S1 Figure).

2.1 IMPACT Model

The IMPACT model is a system of linked models of global agriculture used to analyze long-term challenges and opportunities for food, agriculture and natural resources (31). IMPACT has at its core a global, partial equilibrium model of the agricultural sector that interlinks information from climate models, crop simulation models and hydrology models. The model's economic, climate, hydrology and agricultural components interact through national and international markets for (62 total) agricultural commodities, six of which are livestock. The model solves supply and demand of agricultural commodities at the country scale. IMPACT calculates livestock numbers as a function of livestock's own output prices and the prices of feed and includes a component that maintains livestock herd size growth rates consistent with historical trends. Livestock numbers in the model's initial year correspond to national statistics published by the Food and Agricultural Organization of the United Nations (32). Livestock output per animal (yields) also track historical trends, while meat and milk production are the products of related animal numbers and yields. Model solution animal numbers are a function of initial numbers, an exogenous trend in numbers, prices of the animal and prices of the feed (equation 10, (31)). Feed demand is calculated as a function of livestock's own prices, the price of feed inputs, and growth in livestock herd numbers. IMPACT's accounting of feed demand incorporates feed crops having alternative use as human food. These crops are either fed directly to livestock or used in formulation of concentrate feeds. They include typical feed grain cereals (e.g., corn, sorghum) and legumes (e.g., soybean), as well as root and tuber (e.g., cassava, sweet potato), oil (e.g., oil palm) and seed (e.g., rapeseed, sunflower) crops.

Crop production is similarly structured as livestock, having numbers (acreage) and yield (productivity) components. Crop production is in addition affected by technological change (e.g., change in crop variety), water availability, and climate. Demand for crop and livestock commodities is mainly driven by prices, incomes per capita, and total population. Total domestic demand for a commodity includes its use as food, livestock feeds, intermediate product (e.g., oilseeds in seed oil production), biofuel stock or other. In the

case of a crop commodity such as maize, total demand for it will include both food and livestock feed components. In combination with country level net trade, the amounts of a commodity produced, consumed, or otherwise used, imported or exported or reserved in stock in any one year are fully accounted for through an equilibrium condition that total global demand for a commodity equals its total global supply.

Alternative scenarios of the future can be simulated that represent differences in climate, income, and human population. The model simulates annual outputs from 2005 to 2050. Output data are generated as solutions to a global market equilibrium condition on prices, demand quantities, production, supply and trade of the different primary and processed commodities. The core multi-market model and many of the modules in IMPACT are written in the General Algebraic Modeling System (GAMS) environment. IMPACT has previously been applied to livestock sector simulations, including for assessing the impacts of higher demand for animal source foods globally (33)(34)(22). For the four study countries, i.e., Malawi, Mozambique, South Africa and Zambia, country- and regional- level results from the IMPACT model are simulated for a given start (2010) and final (2050) year for selected model scenarios that are presented in Section 2.4. The choice of simulation years allowed for streamlining of the analysis in IMPACT to G-Range, and for aligning of the model start and end years to what has commonly been used for such studies (31).

The relevant livestock (commodities) included in our study are dairy (milk), bovines (beef), and small ruminants (mutton/lamb). Model projections are collated on demand, production, and trade of the commodities and on live animal numbers associated with livestock production. For the climate scenarios we include in our analysis, the IMPACT model simulations already incorporate the impacts of climate change on crops, previously quantified for the model using the DSSAT crop models (35). These results are useful for accounting for impacts of climate change on livestock feed available from crop sources.

2.2 G-Range Model

G-Range is a spatial ecosystem model that allows to quantify global changes expected in rangeland productivity (e.g., annual net primary production of herbaceous biomass in grams per square meter) under future climates (30). It is used in the simulation of biogeochemical processes and vegetation structure in rangelands. Rangelands here refer to grasslands, drylands, and other extensively grazed ecosystems. Biomes are the unit at which parameter sets are specified. These are defined according to potential vegetation, with potential application to global or any other area where trivial modification of map layers is possible. The spatial scale of the G-Range model used in our study is half degree (0.5°) grid cell resolution. Non-rangeland areas based on the United States' Geological Survey, USGS (36) land cover types are not simulated. Market factors affecting forage production are also not taken into consideration.

The primary driver of rangeland productivity change in G-Range is climate (monthly precipitation, minimum and maximum temperatures, CO₂: carbon dioxide). These parameters are the basis on which climate change impacts on grass production can be measured. G-Range has been calibrated to run scenarios of climate by CO₂ to 2070. The model runs in monthly time-steps, with future simulations running forward from 1957–2070. Historical weather data from 1901–1999 are used in simulations to allow equilibration of soil organic carbon and vegetation populations. The model runs forward from the configuration saved in 1957. The biogeochemical processes simulated are the primary production of grazing and browse forages decomposition, and cycling of carbon, nitrogen, and water, while the vegetation structures simulated include herbs, shrubs, trees, and bare ground. Outputs can be analyzed up to regional and global levels. G-Range is coded in FORTRAN 95 and distributed as compiled executable files.

For the four countries in the study, country-level outputs and regional aggregates from G-Range were simulated for a 2010 start and 2050 final year for selected [climate X CO₂] scenarios reported in the

scenarios Section 2. In our study we used G-range to compare net primary productivity (npp) projections for 2050 under the different scenarios with simulations of npp in 2010.

2.3 Linking the IMPACT and G-RANGE models

The IMPACT model was used to generate projections of the demand for animal-source foods in 2050 in the selected countries. At the same time, the model generates market-responsive levels of livestock production associated with each of these commodities. Its focus is on food production from livestock animals, i.e., dairy milk, beef, and lamb, and on the demand from these animals for three types of feeds: feed crops, crop residues and grasses. Model outputs on the numbers of producing animals inform the calculation of feed use. G-Range was used to simulate production of the grass component of livestock feed use.

2.3.1 *Feed demand*

Feed demand was derived as the product of animal numbers and feed use per animal. Animal numbers are generated from IMPACT as country-level numbers of animals producing each livestock food product type (i.e., beef, milk, and lamb). Annual feed use per animal follows production system-specific livestock feed baskets previously estimated for different global regions (37). Global livestock feed use can be classified into four commonly observed types: grains and other feed crops which may have both human food and livestock feed purposes, grasses for direct grazing and fed as silage, crop residues, and occasional feeds that include planted (cut-and-carry) forages and legumes (37). Future supply of the occasional feed category is challenging to quantify in the current context (explained below) and its demand has not been included in the analysis.

To apply the feed use quantities from the literature (37), country-level livestock numbers generated from IMPACT were re-distributed to underlying livestock production systems, as has been proposed for livestock sector quantification in the IMPACT model (26). Livestock production in the region was

distributed into rangelands (i.e., extensive systems of livestock production), mixed (crop-livestock), peri-urban (smallholder) and urban (intensive) systems. Ruminant livestock types identified for these systems include dairy and beef cattle, and dairy and meat sheep and goats. For each livestock production system and product type there is an annual per animal demand in kilograms dry matter for each category of feeds. The feed demand variable is then summed over livestock animals and products for each country.

This method of redistributing country-level estimates based on current knowledge of the different livestock systems (animal types, breeds, environment and management conditions, including feeding) has been used previously (38). The method allows to reasonably disaggregate the IMPACT model's calculation of animal numbers in such a way that we project future feed demand totals that account for production system differences. The disaggregation is necessary for assessing the capacity of the countries' livestock sectors to meet future demand (26). On the other hand, the estimate of total feed crop demand is generated as a primary output from IMPACT. This variable sums up the demand for grain, oilseed and crop-derived concentrates used in the production of ruminant meat and milk in the study countries. We use the methods described above to disaggregate the total demand for feed crops, crop residues and grasses into component livestock production systems, and by species. Our calculations rely on historical observations of feed demand quantities in the region rather than on feed demand quantities that can be calculated based on animal nutrient requirements (39). Due to the lack of appropriate vegetative cover for the occasional feed category, there is currently no consistent way to simulate its supply under future scenarios. Consequently, we exclude its demand and supply from the analysis.

2.3.2 Feed production

Feed crop quantities come from the IMPACT model outputs, where supply grows through changes in area (influenced by marginal revenues, land costs, and the impacts of external factors such as government programs to expand crop areas) and yield changes (influenced by product and input prices, climate trends,

and factors such as seed technology investments and management practices)(31). In the assessment of feed availability, we maintain the model's projections of national crop production and its allocation to livestock feed use. The national estimate can be disaggregated into livestock production systems as described above for feed demand. This disaggregation will make it possible to assess feed crop availability for any single livestock production system in a country, and thus the potential for production-based livestock sector expansion.

To calculate crop residue production, we apply harvest index values to feed crop (yield X area) generated in IMPACT. The harvest indexed values, taken from existing studies, have been estimated for different crop commodities used as livestock feeds globally. We used the grain production quantity and harvest index value to estimate of amount of crop residue feeds produced. We do not simulate the determinants, pressures or trade-offs associated with alternative crop residue uses (40). Simulated data on grasses, i.e., grassland area and production come from G-Range. Using spatial mapping techniques, the model's spatially explicit output data are spliced into livestock production systems (for system-level assessments of feed availability) and then aggregated for country-level assessments.

2.3.3 Measures of feed sufficiency

The demand for feed crops, crop residues and grasses associated with IMPACT model projections of the demand and production of livestock food products, is compared to estimates of biomass production of the various feed types, as informed by both IMPACT and G-Range. Calculated ratios of feed sufficiency in 2050 are compared to what was obtained in 2010. Our estimates of feed availability are thus in relation to the historical status only, i.e., no presumptions are made about optimum levels of feed availability or use. Issues of feed accessibility (e.g., based on seasonality, distances, or mobility) or usability (e.g. based on feed quality), and how these potentially change from 2010 to 2050, are not considered (25). Instead, we assess the extent to which feed is available relative to the livestock numbers and how this is more constrained (or loosened) in the year 2050 compared to the year 2010. As feed constraints are already

considered binding for many countries and production systems in the region (15), this may be a reasonable criterion. A simple ‘feed sufficiency’ indicator was thus developed that measures in any year the ratio of the amounts of feed produced to the amounts of feed needed, calculated based on the total numbers of livestock animals (summed up by species). This measure was calculated for each of three feed types, i.e., grasses, feed crops, and residues, by country and for the region made up of four countries. We calculated relative changes to biomass and other feed production and to feed demand under different scenarios of global change in 2050.

2.4 Scenarios in 2050

Economic factors play a key role in the demand for livestock-derived foods (1); while technological and climate factors are expected to have major direct influences on livestock production and thus on local livestock feed demand (20). We used the shared socioeconomic pathways (41) to study how different income and population pathways out to 2050 may influence demand for livestock-derived food. These scenarios are the SSP2, representing moderate economic and population growth to 2050; SSP1, an alternative socio-economic pathway of “global sustainability” characterized by medium to high economic growth and low population growth; and SSP3, a “global economic fragmentation” pathway characterized by slow economic and high population growth. We model the income and population trajectories in the SSPs, not the full SSP narrative, using IMPACT. Two of the scenarios, SSP1 and SSP3 were simulated under conditions of constant (year 2005) or no climate change to 2050.

Our baseline scenario in IMPACT was for the SSP2 scenario and with no climate change. We also simulated two greenhouse gas emissions trajectories in addition to the no climate change scenario. These climate scenarios, known as representative concentration pathways (RCP) 4.5 and 8.5 represent intermediate and extreme climate change, respectively. Given inherent uncertainties in the quantification of the effects

(e.g., on temperature and precipitation) of the various climate change trajectories, a standard approach in climate modelling has been to adopt a range of impacts as have been calculated using different earth system or general circulation models (27). For our study, we adopt climate scenarios modelled in IMPACT and G-Range to simulate the two climate change trajectories using general circulation models developed by different global communities of climate modelers (**Table 1**).

Table 1: Selected global scenarios affecting livestock production in Southern Africa in 2050.

	Economic change	Climate change	GCM
Economic Growth, no climate change scenarios	Medium (SSP2) (Baseline)	No climate change	none
	Slow (SSP3)	No climate change	none
	Fast (SSP1)	No climate change	none
Climate change, moderate economic growth scenarios	Medium (SSP2)	Intermediate (RCP 4.5)	HADGEM
	Medium (SSP2)	Intermediate (RCP 4.5)	IPSL
	Medium (SSP2)	Intermediate (RCP 4.5)	MIROC
	Medium (SSP2)	Intermediate (RCP 4.5)	GFDL
	Medium (SSP2)	Extreme (RCP 8.5)	HADGEM
	Medium (SSP2)	Extreme (RCP 8.5)	IPSL
	Medium (SSP2)	Extreme (RCP 8.5)	MIROC
	Medium (SSP2)	Extreme (RCP 8.5)	GFDL

Source: Authors. The economic growth scenarios were run only in IMPACT. SSP = Shared Socioeconomic Pathway. Climate scenarios were simulated using both IMPACT and G-Range. HADGEM represents the General Circulation Model (GCM) developed at the Hadley Center in the UK; IPSL is from *Institut IPSL* in France; MIROC originates from Japan's community of climate modelers, and the GFDL from Princeton, USA (31).

The final mix of 11 scenarios represents a plausible intersect of economic and climate scenarios, and global climate models applicable to Southern Africa in 2050. The individual scenarios have all been previously

quantified for use in IMPACT (31) and G-Range (27). We compare changes brought on by economic and climate change in 2050 to baseline scenarios for 2010 and/or 2050.

3 Model initial conditions

3.1 Income and human population

The economies of the study are currently categorized as low income (Malawi, Mozambique), lower-middle income (Zambia) and upper middle income (South Africa) (42). In the initial simulation year, annual income per person was US\$ 796 in Malawi, US\$ 823 in Mozambique, US\$ 1,383 in Zambia, and US\$9,470 in South Africa (**Table 2**). South Africa in 2010 accounted for roughly half (49%) of the four-country region's population, and 91% of its total income measured as gross domestic product (GDP).

Under the baseline scenario of medium economic growth and no climate change (**Table 1**), South Africa accounts for 36% of the human population of the four country-region in 2050, and 73% of its GDP (**Table 2**). Per capita income of South Africa in 2050 is projected at more than twice (at 105% of) the regional average. Income per capita however grows faster in the other countries of the region, projected to grow by 578% in Mozambique, 467% in Zambia 467% and 385% in Malawi. The largest expansion in human population and aggregate national income terms to 2050 occurs in Malawi. Under the scenario of high economic growth, Malawi is projected to grow the fastest in the region on a per capita income basis. Mozambique fares the worst in the region under simulated conditions of a global economic slowdown.

Table 2: Key socioeconomic indicators in 2010 and 2050

Economic growth	Baseline *	Medium (SSP2)	Slow (SSP3)	Fast (SSP1)
Year	2010	2050	2050	2050
<i>Human Population</i>	Millions USD	<u>Percent change from Baseline 2010 (%)</u>		
Malawi	14.90	1.72	2.22	1.25
Mozambique	23.39	0.81	1.00	0.61
South Africa	50.13	0.26	0.23	0.24
Zambia	13.09	1.30	1.90	0.94
Region	101.51	0.73	0.91	0.57
<i>GDP</i>	Billions USD	<u>Percent change from Baseline 2010 (%)</u>		
Malawi	11.85	12.21	8.14	20.78
Mozambique	19.24	11.26	6.46	19.84
South Africa	474.76	2.66	1.71	3.37
Zambia	18.11	12.04	8.62	17.49
Region	523.97	3.51	2.27	4.86
<i>GDP per capita</i>	USD	<u>Percent change from Baseline 2010 (%)</u>		
Malawi	795.53	3.85	1.84	8.66
Mozambique	822.72	5.78	2.73	11.96
South Africa	9470.06	1.91	1.21	2.51
Zambia	1383.80	4.67	2.32	8.51
Region	5161.62	1.60	0.71	2.74

Source: Authors' calculations, based on IMPACT (Robinson et al. 2015) and G-Range (27) models. *Socio-economic projections for 2050 are presented as percent change (%) from initial values of 2010, which are reported in value terms. USD is United States Dollars, with values standardized to 2005 equivalents. Socio-economic indicators for the climate scenarios were assumed to be same as those of the medium growth scenario in 2050 and are omitted from the table.

3.2 Livestock Herds

According to Herrero et al. (2013), around 10% of dairy and beef cattle stocks in Malawi are raised in rangeland systems. This proportion is 33% in Mozambique, 41% in South Africa and 65% in Zambia. Ranging from 52% in Mozambique to 91% in South Africa, beef cattle makes up the greater proportion (87%) of the region stock of cattle, with dairy cattle accounting for the remaining 13%. Small ruminant animals are mostly kept for meat within the region and are found mainly in the rangeland and mixed crop-livestock systems. Mozambique is the only one of the selected countries where small ruminants are used for milk production. Around 40% of these dairy animals are in the rangeland system. The data support

that rangelands are an important system for meat and milk production in the study region. Mixed crop-livestock systems (which also have a high demand for grasses) are also important in the region, holding 43% of regional cattle stocks. The information on livestock distributions was used in the analysis to disaggregate country-level projections of livestock production and feed demand to the region's livestock production systems.

3.3 Feed demand

Total demand for livestock feeds by ruminant animals generally follows the patterns of cattle and small ruminant animal stocks. Grasses are a major component of the aggregate feed basket of ruminant animals across the region, making up 60 to 96% of all feed biomass demand in the different systems, including in urban/peri-urban production. In Malawi, 65% of the demand for grass and nearly 90% of the demand for other feed types is from the mixed crop livestock system (where up to 73% of large ruminants and 68% of sheep and goat in the country are found). However, grasses make up more than 82% of the demand for livestock feed biomass within all of Malawi's production systems. These results reinforce the need to assess the future supply of grasses for livestock feed use in the region. **Table 3** presents per head estimates of livestock feed consumption used to calculate current and future feed demand totals.

Data are available on the use of grasses as feeds by dairy and beef cattle in the region, and by small ruminant animals kept for meat production; but not of use by small ruminants for dairy purposes (which are uncommon in the region), or of other feed sources. There were limited data on the use of occasional feeds such as non-grass fodder and household wastes that may be fed to livestock. For the different countries, dry matter feed intake by cattle is lowest in Malawi and highest in South Africa. Feed intake by small ruminant animals is lowest in Mozambique (for dairy) and highest in South Africa (for meat). Whereas recommended amounts of biomass dry matter fed to cattle is 2% to 3.4% of the animal's weight

(39), the daily amount we obtain from disaggregating the databases is around 1.6% to 2.9% of average cattle body weight (assuming 250kg). These would suggest baseline conditions of somewhat constrained nutrition.

Table 3: Estimated use of feed biomass types, by animal type (kg/head/year)

	Malawi	Mozambique	South Africa	Zambia	Region
Grasses					
Dairy cattle	871.9	1526.3	982.7	1448.7	1173.7
Beef cattle	1406.4	1902.9	2165.7	1442.6	1993.3
Dairy sheep/goats	n/a	156.9	n/a	n/a	24.6
Meat sheep/goats	197.6	323.1	35.4	262.1	89.7
Crop Residues					
Dairy cattle	543.7	384.7	386.9	216.7	366.8
Beef cattle	n/a	n/a	425.4	n/a	311.4
Dairy sheep/goats	n/a	5.9	n/a	n/a	0.9
Meat sheep/goats	51.6	39.7	27.8	22.1	30.4
Feed Crops					
Dairy cattle	62.1	55.2	466.0	25.0	280.5
Beef cattle	20.6	28.4	n/a	6.0	3.6
Dairy sheep/goats	n/a	13.1	n/a	n/a	2.1
Meat sheep/goats	31.5	42.8	33.4	29.9	34.0

* Source: Author adaptations (37). n/a is used where use of feed type by specific animal type is not observed, or data is unavailable. The estimates have been derived in consistence with the published statistics on animal numbers and aggregate feed demand.

4 Results

4.1 Meat and milk demand

Baseline model calculations of demand from the four countries in 2010 were computed at around 930,000 metric tons (MT) of beef, 247,000 MT of lamb and 3.5 million MT of dairy (**Table 4**). Although South Africa accounted for only around 50% of the regional population in 2010, the country contributed 86%, 78% and 91%, of regional totals for beef, lamb, and dairy demand, respectively. Under the baseline scenario in 2050, total demand from the region increased to 2 million MT of beef (116% change from 2010), 787,000 MT of lamb (219% increase) and around 7 million MT of dairy (97% increase). At the country level, demand grows the most for beef and for milk in Malawi (604% and 520%, respectively), and for lamb in Zambia (701%). The regional projections were compared with data from published national statistics (32) to assess the extent to which projections mirror, or deviate from, historical observations. According to the national statistics, total beef demand from the four countries increased by 106% from 1970 to 2010. Lamb demand increased by 20% and milk demand by 58% over the same period. These results show that the projections of growth in demand for small ruminant meat and milk from 2010 to 2050 are much more optimistic than the published data from the 40 years prior will indicate. However, the projections of growth in beef demand, a major driver of the demand for grass biomass in the region, are close to historical trends.

Alternative growth (fast and slow economic growth, respectively) and climate scenarios were also simulated with IMPACT. Regional demand for beef, lamb and milk was projected to be between 6.1% and 14.7% higher under the fast-economic growth scenario compared to the medium growth scenario in 2050. By contrast, 2050 demand for beef, lamb and milk under a slow growth scenario was estimated to be between 6.7% and 14.4% lower than demand in the baseline scenario. Meat and milk demand were projected to be only slightly affected by climate change, with the change in demand between the medium growth and climate change scenarios in 2050 less than 0.2%. The effects of climate change are expected to be more pronounced for livestock production than they are for the demand for livestock products. This holds because the impacts of a changing climate (e.g., temperature and precipitation change) have more

direct effects on the factors affecting production (e.g., feed availability) than they do on drivers of food demand (e.g., population and income).

4.3 Animal numbers

Around 2.5 million beef cattle and 13.5 million sheep and goats were slaughtered for meat in the region in the base year of 2010. A further 1.8 million dairy cattle produced milk. South Africa contributed 83% of meat cattle, 70% of small ruminant and 46% of the dairy cow numbers (**Table 5**). South Africa accounts for only 46% of the regional dairy cow numbers but 94% of the milk produced. Although it has more production animals than in the rest of the region, these numbers also suggest a slight technological advantage. Under the baseline scenario in 2050, (producing/slaughtered) beef animals increased 12% over year 2010 estimates, lamb animal numbers 77% and dairy cows 26%. At the country level, animal numbers increased the most for lamb in South Africa (79%), beef in Mozambique (47%), and milk in Zambia (38%). The growth in animal numbers was slower than the growth in production in the different countries, indicating some animal yield increases to 2050.

Animal numbers (offtakes) increase between 1.67% and 4.4% more under the fast growth scenario compared to the medium growth scenario in 2050. Under slow economic growth, animal numbers are between 3.3% and 6% less than the estimates for the 2050 baseline. The number of ruminant meat and milk animals only change slightly (<0.1%) under a climate change scenario. The animal numbers are not projected to change dramatically, partly because IMPACT does not account for any direct impacts of climate on livestock production (e.g., animal performance). All climate impacts on livestock are accounted for through changes in feed crop availability.

422 **Table 4:** Total demand for (ruminant) meat and dairy in 2010 and 2050, in 1000 MTs

Climate Scenarios:		No Climate Change			Intermediate Climate	Extreme Climate
		Baseline	Medium (SSP2)	Slow (SSP3)	Fast (SSP1)	Medium (SSP2)
Economic Growth Scenarios:	Year	2010	2050	2050	2050	2050
<i>Malawi</i>						
	Beef	28.78	202.70	180.34	250.48	202.71
	Lamb	15.43	108.83	96.92	131.94	108.89
	Dairy	71.15	441.78	394.76	534.41	441.96
<i>Mozambique</i>						
	Beef	27.48	119.36	104.49	139.83	119.37
	Lamb	29.23	175.08	138.67	225.15	175.18
	Dairy	115.13	265.23	272.39	258.94	265.33
<i>South Africa</i>						
	Beef	798.83	1349.29	1238.41	1393.65	1350.60
	Lamb	191.91	423.32	367.27	450.93	423.72
	Dairy	3224.36	5676.80	5107.22	5964.64	5682.07
<i>Zambia</i>						
	Beef	73.27	332.04	346.16	341.58	332.13
	Lamb	9.98	79.98	71.31	94.59	80.03
	Dairy	116.94	575.30	574.09	615.81	575.53
<i>Region</i>						
	Beef	928.36	2003.39	1869.40	2125.53	2004.80
	Lamb	246.56	787.21	674.17	902.62	787.82
	Dairy	3527.58	6959.10	6348.46	7373.80	6964.90

423 Source: Authors' calculations, based on IMPACT (31). Intermediate and extreme climate are the average estimates for four (4) global climate model
424 models simulating RCP 4.5 and RCP 8.5 climate change scenarios, respectively. Economic growth is based on income trajectories in the Shared
425 Socioeconomic Pathways (41).

426

427 **Table 5:** Number of producing (milk) and slaughtered (meat) animals, in 1000 Heads

Climate scenarios:		No climate change			Intermediate climate	Extreme climate
Economic growth scenarios:	Medium	Medium	Slow	Fast	Medium	Medium
Year:	2010	2050	2050	2050	2050	2050
<i>Malawi</i>						
Beef	114.22	166.05	158.04	171.74	165.86	165.95
Lamb	1115.90	1944.82	1879.04	2002.34	1949.26	1954.98
Dairy	80.25	105.71	103.96	106.51	105.62	105.01
<i>Mozambique</i>						
Beef	122.67	181.17	172.43	187.39	180.97	181.06
Lamb	2192.65	3763.62	3636.32	3874.93	3772.21	3783.29
Dairy	621.38	805.14	791.75	811.23	804.40	799.76
<i>South Africa</i>						
Beef	2928.04	3071.51	2878.91	3212.66	3079.89	3068.58
Lamb	9496.75	16965.55	16277.33	17611.56	16946.56	16959.16
Dairy	840.62	1003.83	958.49	1027.76	1003.76	1007.96
<i>Zambia</i>						
Beef	383.92	548.78	521.02	568.26	548.19	548.75
Lamb	733.09	1263.17	1220.45	1300.53	1266.06	1269.78
Dairy	294.19	407.39	390.88	415.35	407.33	406.97
<i>Region</i>						
Beef	3548.84	3967.51	3730.41	4140.05	3974.91	3964.33
Lamb	13538.38	23937.15	23013.14	24789.37	23934.09	23967.22
Dairy	1836.44	2322.07	2245.07	2360.86	2321.10	2319.70

428 *Base 2010 are level estimates for year 2010 under the baseline scenario. Base 2050, Slow, Fast and
 429 Climate (moderate and extreme) represent the level estimates for the baseline, slow economic growth,
 430 fast economic growth, and two climate change scenarios, RCP 4.5, and RCP 8.5, respectively.

431

432

433 4.4 Feed production and productivity

434 Compared to 2010, crop grain production in the region was projected to be 60% more on average in 2050
 435 under the assumption of constant climate or no climate change conditions. The projected increase in feed
 436 crop production was 32% in Mozambique, 62% in South Africa, 82% in Zambia, and 87% in Malawi. As
 437 crop residue production is derived directly from crop grain, its production increases by similar proportions.

438 Country-level production of grasses under moderate economic growth and constant climate to 2050
439 remains relatively unchanged in Malawi, Mozambique, and Zambia, and increases by 20% in South Africa.
440 Regional supply of all three feed types was shown to be more constrained under climate change.
441 Compared to the constant climate scenario, crop production in the region was projected at 9% lower on
442 average given an intermediate climate change scenario and 17% lower under an extreme climate change
443 scenario. Grass production in 2050 was projected to be 16% lower under the intermediate climate
444 scenario and 17% lower under the extreme climate scenario, compared to the scenario with no climate.

445 The impacts of climate change were projected to be more on yields (i.e., production per unit area) than
446 on area of grass production (**Table 6**). Compared to 2010, the yields of grasses with potential use as
447 livestock feeds were projected to decline across different livestock production systems in the four
448 countries in 2050. Table 5 shows the average changes in grass area under the intermediate (RCP 4.5) and
449 extreme (RCP 8.5) climate change scenarios. Both rangeland and mixed crop-livestock systems were
450 shown to be adversely affected.

451

452 **Table 6:** Impacts of climate change on grasses areas and productivity in 2050, by livestock production system

Country	Scenarios	Grass- Arid/semi- Arid	Grass - Humid	Grass - Temperate	Mixed – Arid/semi- Arid	Mixed- Humid	Mixed - Temperate	Other	Urban / peri- urban
<u>Average annual % change in pasture productivity under climate change, 2010 to 2050</u>									
Intermediate climate	Malawi	-0.1444	0.3274	0.0061	-0.2310	-0.2739	0.0144	-0.4757	-0.1228
	Mozambique	-0.1587	-0.0580	0.2276	-0.1524	-0.3136	-0.0982	-0.0049	-0.0726
	South Africa	-0.0593	-0.5292	-0.1592	-0.1811	-0.4576	-0.1468	-0.1873	-0.0668
	Zambia	-0.1108	0.0046	-0.1200	-0.1959	0.1869	-1.2934	-0.0088	-0.2295
Extreme Climate	Malawi	0.1211	0.4006	0.0907	0.0313	0.2072	0.1675	0.0896	0.0542
	Mozambique	-0.1455	0.0200	0.1626	-0.1314	-0.1613	-0.0221	0.0413	-0.1792
	South Africa	-0.3730	-0.6240	-0.2401	-0.4447	-0.5169	-0.2431	-0.2886	-0.2413
	Zambia	-0.0307	0.1116	0.1370	-0.0644	0.2069	-0.9962	0.1866	0.0170
<u>Average annual % change in pasture areas under climate change, 2010 to 2050</u>									
Intermediate climate	Malawi	0.0000	0.0000	0.0000	0.0000	0.0096	0.0000	0.0000	-0.0106
	Mozambique	0.0008	0.0022	0.0000	-0.0006	0.0000	0.0000	0.0000	-0.0014
	South Africa	0.0002	-0.0061	-0.0018	0.0000	0.0072	0.0043	-0.0031	0.0000
	Zambia	0.0000	0.0022	-0.0080	0.0000	0.0000	0.0000	0.0189	-0.0005
Extreme Climate	Malawi	0.0000	0.0000	0.0000	0.0000	0.0096	0.0000	0.0000	-0.0106
	Mozambique	0.0008	0.0022	0.0000	-0.0006	0.0000	0.0000	0.0000	-0.0014
	South Africa	0.0002	-0.0061	-0.0018	0.0000	0.0072	0.0043	-0.0031	0.0000
	Zambia	0.0000	0.0022	-0.0080	0.0000	0.0000	0.0000	0.0189	-0.0005

453 Source: Authors' calculations using G-Range. Positive values (**bold**) indicate improved production (areas) or productivity (i.e., production per
454 area) in 2050 compared to 2010 levels. Negative values indicate declines compared to 2010.

455

456

Climate change in 2050 was also projected to lead to yield increases in some areas. Whereas grass yield is reduced (compared to 2010 values) for most of the countries and production systems, the model projects increases in some temperate agro-ecological zones in Malawi and Mozambique, and humid zones in Malawi and Zambia (**Table 6**). Climate-related changes in rainfall likely drive these results. In Malawi, the climate-induced yield increases lead to higher production of grasses in total nationally under the extreme climate scenario. The projections of increased livestock production (section 4.3), driven by higher demand for animal source foods in the countries, however, mean that the projections of grass production, even when increased in 2050, do not translate to sufficiency of produced grasses in any of the study countries under climate change.

4.5 Feed crop, crop residue and pasture sufficiency in 2050

The production of feed crop and crop residues useful as livestock feeds are projected to be in sufficient amounts (meaning supply exceeds demand) for ruminant livestock use in Malawi, South Africa, and Zambia, under the slow economic growth scenario with no climate change (**Table 7**). This result, which is consistent with earlier findings (43), is in comparison to the initial conditions and not based on a normative prescription about feed biomass availability. As the assumption on economic growth becomes more optimistic, i.e., under the medium and fast growth scenarios, feed crop production in South Africa is no longer projected to be sufficient. The introduction of climate change scenarios further leads to major changes. Projections of feed crop and crop residue production are sufficient in Zambia; feed residue (and not feed crop) production is sufficient in South Africa; and neither feed crop nor residue production is enough in Malawi. Calculated on a per animal demand bases, the relative supply of grasses from rangelands was projected to be less than half what was obtained in 2010, for some countries (**Figure 1**).

Table 7: Indication of relative feed sufficiency under scenarios of climatic and economic change in 2050

	Malawi	Mozambique	South Africa	Zambia	Region
Slow economic growth, no climate change					
Grasses	0.668	0.634	1.180	0.705	0.867
Feed crops	1.172	0.838	1.009	1.149	1.002
Crop residues	1.225	0.875	1.441	1.250	1.352
Fast economic growth, no climate change					
Grasses	0.642	0.612	1.109	0.674	0.824
Feed crops	1.131	0.791	0.977	1.101	0.962
Crop residues	1.189	0.828	1.374	1.195	1.287
Medium economic growth, no climate change (Baseline scenario)					
Grasses	0.624	0.596	1.062	0.654	0.794
Feed crops	1.094	0.755	0.950	1.059	0.928
Crop residues	1.156	0.793	1.326	1.154	1.239
Medium economic growth, intermediate climate					
Grasses	0.510	0.530	0.843	0.587	0.694
Feed crops	0.987	0.770	0.936	1.061	0.907
Crop residues	0.989	0.782	1.311	1.127	1.222
Medium economic growth, extreme climate					
Grasses	0.450	0.714	0.582	0.658	0.745
Feed crops	0.563	0.913	0.929	1.024	0.874
Crop residues	0.963	0.692	1.308	1.110	1.302

Source: Authors' calculations based on IMPACT (31) and G-Range (27). *Relative sufficiency is the ratio of 'feed production to feed demand' in the 2050 scenario relative to the same variable in 2010. Relative sufficiency is improved if it measures greater than 1, meaning that feed availability is less constrained than in 2010. The situation is improved if relative sufficiency is greater than 1, (**bold** numbers in the table) meaning that feed availability is less constrained compared to the situation in the initial simulation year, 2010. Numbers closer to 1 indicate conditions in 2050 that are closer to what obtained in 2010.

Figure 1: Projections of change in grasses supply calculated on a per animal (MT/Cattle head) bases for the Southern Africa region under extreme climate change in 2050 vs 2010. Data shown are in comparison to starting values of grass MT/head/year under the moderate economic growth scenario with no climate change in 2010. Extreme climate is the average value of four general circulation models' representation of the representative concentration pathway 8.5 (41). Source: Authors.

Two key results from the sufficiency calculations are that, according to the analysis, none of the (three) feed types are projected to be produced in sufficient quantities in Mozambique, and grass production is insufficient at the country level in all the study countries, under climate change (**Table 7**). These results could be consequential for future feed use and livestock production in the region.

The results suggest that the availability of grasses for feed will be substantially reduced in the region in 2050 compared to the initial conditions, assuming no major changes are introduced in rangeland management. The rate of this decline could mean a reduced capacity of livestock production systems to support the expansion of (especially) ruminant livestock production to meet future demand. Climate change is projected to be an important factor in exacerbating eminent constraints on feed resources and does so much more than economic pressures. This result differs from an earlier study using IMPACT (22), but which did not account for non-crop sources of livestock feeds or include the Southern Africa countries that are the focus of the current study. In that study, global economic changes posed more serious constraints to the future of ASF demand and supply than did the impacts of climate change.

4.5 Imports of livestock-derived foods

Other outputs generated from the integrated modeling have implications for the region. Per capita supply of beef, lamb, and milk were projected to reduce substantially under the scenario of a potential downturn in the global economy but were maintained under the moderate economic growth and climate change scenarios of 2050. Increased imports of livestock derived products are projected to play an important role in meeting supply of animal source foods. This result suggests that there are options for mitigating the potential effects of higher feed availability constraints on livestock production and the supply of animal source food in the study region. In addition to beef and lamb obtained from local ruminant

production that is intricately linked to rangelands and grasses production, countries in the study can access beef, lamb, and milk, as well as pig meat, poultry, and eggs through international markets.

4.6 Discussion of results and their implications

This study projects declining availability of grasses biomass for livestock use in some parts of the study region under different assumptions of economic growth, and with or without climate change. This projection occurs alongside projections of increased relative abundance of feed sources such as crop residues and (to a smaller extent) feed crop. For example, **Table 7** indicates insufficiency of grasses in Malawi, Mozambique, and Zambia under the slow economic growth scenario in 2050, occurring simultaneously with improved relative availability of feed crops and crop residue in both Malawi and Zambia. While there is some degree of substitutability between the different feed sources that we have not accounted for in the analysis, i.e., an animal's direct requirement for nutrients could be fulfilled to varying degree with intakes of grasses, feed crops, or crop residues, the fact that the study projects diminished prospects for production of grasses is of high relevance.

Grasses are the most important livestock feed in southern Africa but are bulky and difficult to move, especially over long distances, making issues of localized availability quite important. Further, there may be reasons to assume limited prospects for the future development and use of feed crops and crop residues in support of livestock production. Both feed sources are known to have important non-livestock uses not fully accounted for within this analysis, with feed crops being directly in competition for use as human food and industrial input (40)(16). The known importance of grass as ruminant livestock feed in the study countries (Table 2) makes somewhat untenable the result that all study countries are projected to see declines in the sufficiency of grasses under climate change. Reduced pasture availability in the region could place additional stress on feed systems throughout the region, including through effects on

546 the prices of livestock products and the opportunity costs of developing alternative feed sources. The case
547 of Mozambique calls for particular attention, where all three feed sources analyzed are projected to be in
548 supply that is insufficient to meet demand in the country in 2050.

549 The options to meet higher demand for meat or milk in the region through imports holds in general
550 because markets are assumed open, i.e., there is potential for the countries to trade freely with outside
551 regions. Import options also suggest that there are locations outside of the region that either do not face
552 natural resource or feed constraints like those identified for the study region or have some capacity to
553 overcome them. These may not necessarily hold in practice. Additional studies are needed that can
554 expand the current feed availability analysis to explicitly account for regions that the Southern Africa
555 countries trade livestock and related products with. If supply of livestock-derived foods in the region is
556 not as readily met through imports as unrestricted trade models will predict, and feed-related constraints
557 seriously hamper livestock production in the future, it will be reasonable to assume that the production-
558 related disruptions will have their most profound effects on economically vulnerable populations (11).

559 Earlier studies estimated that more than 19 million people in Southern Africa can be placed in the category
560 of ‘poor livestock keepers’— a term depicting poverty thresholds amongst producers who derive at least
561 part of their livelihood from livestock (2)(44). Around 16% of so-called poor livestock keepers in the region
562 live on rangelands (44), underscoring the importance of rangelands management to the overall discussion
563 on poverty reduction and food security in the region. In turn, the efficient management of anticipated
564 expansions of the livestock sector needs to be part of the discussion on rangeland management in the
565 region. At least one study (45) has indicated that while strategies such as conservative stocking will lead
566 to the most favorable outcomes from social and ecological perspectives in the region, such are unlikely to
567 be enforced based on past legacies of the region. New strategies are needed that can objectively consider
568 current realities (such as the influence of legacies in land management) while anticipating the impacts of

alternative futures (such as those defined by economic change and climate change) on livestock production.

Events such as the COVID-19 pandemic have disrupted global agricultural and food supply systems in ways that our standard models fail to capture. Similarities that have been suggested between the causes, effects and impact management of COVID-19 and climate change (46) however make the global health emergency a relevant factor to include in follow-up analysis to this study. In particular, issues of feed resource management may need to be included as a matter of high urgency in post COVID-19 recovery strategies for the region, where attainment of possibly conflicting goals of fast economic growth and sustainable use of the region's natural resources need to be co-managed.

5 Conclusions and next steps

This study provided a quantification of the impacts of climate change and changing income and population on the ability of feed biomass resources to meet growing demand for livestock production, with a spotlight on rangeland geographies in Southern Africa. It does this by comparing IMPACT model projections of the demand for animal-source food of four Southern Africa countries under a range of what-if scenarios for per person income and population growth; and grassland productivity projections obtained from a compatible ecosystem model called G-Range. The demand for animal-source foods is linked to measures of livestock feed sufficiency through model simulations of livestock production. The results show appreciable reduction in feed biomass, particularly grass availability for livestock feed use in 2050, compared to initial conditions. Given the intricate links between the availability of this type of feed and livestock production in the study region, declines in grass availability are a concern given expected increases in the demand for ruminant livestock food products. In this study, we have shown, even under assumptions of future economic trends that are like what occurred historically, that feed resources will

likely pare down in a future under climate change. As the status of livestock feeds availability is already considered dire in the region (as it is for many other developing regions where livestock is important), it stands to reason that feed resource management should be a key tenet for building climate resilience in Southern Africa. The results suggest that investments in feed development may need to be prioritized for rangeland areas within the study countries. The relevance of production to livestock productivity in the region makes this an important regional priority. Unless (self-initiated or policy-induced) out-migration from vulnerable rangelands are anticipated (and acceptable) outcomes, the results could suggest that investments in better land management, such as the conversion of land to other uses, or the re-grassing of rangeland areas, as well as technologies to improve feeds, e.g., crop residue and grass yield enhancements, will need to be prioritized regionally.

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