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From crisis to opportunity: climate change benefits livestock production in Somalia

Jaabir Hussein[1,2,*], **Franco Bilotto**[3,4], **Jason Sircely**[2], **Damaris Mbui**[5], **Philip Omondi**[6], **Carla Sofia Santos Ferreira**[7,8], **Shah Fahad**[9], **Ke Liu**[3] and **Matthew Tom Harrison**[3,*]

[1] Institute for Climate Change and Adaptation (ICCA), Department of Earth and Climate Science, University of Nairobi, PO Box 30197, Nairobi 00100, Kenya
[2] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), 22 International Livestock Research Institute, PO Box 30709, Nairobi 00100, Kenya
[3] Tasmanian Institute of Agriculture, University of Tasmania, Newnham, Launceston, TAS 7248, Australia
[4] Department of Global Development, College of Agriculture and Life Science, Cornell University, Ithaca, NY 14853, United States of America
[5] Department of Chemistry, University of Nairobi, PO Box 30197-00100, Nairobi, Kenya
[6] IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, Kenya
[7] Coimbra, Applied Research Institute, Rua da Misericórdia, Lagar dos Cortiços—S. Martinho do Bispo, 3045-093 Coimbra, Portugal
[8] Research Centre for Natural Resources Environment and Society (CERNAS), Polytechnic Institute of Coimbra, Bencanta, 3045-601 Coimbra, Portugal
[9] Abdul Wali Khan University, Mardan, Khyber Pakhtunkhwa, Pakistan
[*] Authors to whom any correspondence should be addressed.

E-mail: Jiibka@yahoo.com and matthew.harrison@utas.edu.au

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Abstract

While livelihoods of Somalian livestock smallholders rely heavily on seasonal climate conditions, little is known of long-term implications of the changing climate for this nation. Here, we quantify implications of the changing climate on the productivity and profitability of livestock smallholders across a rainfall gradient in northwestern Somalia. Using the Sustainable Grazing Systems (SGS) model, we explore 80 future climate realisations, with global climate model projections including low- and high-impact socio-economic pathways (SSP245 and SSP585), two climate horizons (2040 and 2080) and four case study farm regions. In general, future seasonal and annual rainfall and temperature relative to the baseline period (1981–2020) increased for most regions. Mean annual temperatures increased by 9%–14%, while cumulative annual precipitation increased by 37%–57% from mid to late century, respectively. Grassland production increased with later climate horizons, as higher average annual rainfall together with elevated atmospheric carbon dioxide drove up growth rates in spring and autumn. Under the low emissions scenario (SSP245), changes in farm profit were modest or positive, ranging from negative 4% in Berbera–20% plus in Sheikh. Under the higher emissions scenario (SSP585), farm profits were higher, ranging from 23% to 42% above baseline profits, largely due to greater pasture production and lower requirements for supplementary feed. We conclude that future climates will benefit the productivity and profitability of smallholder farmers in Somalia, although more agile farm management will be required to cope with increased seasonal climate variability.

1. Introduction

In the African Sub-Saharan region, climate change has exacerbated food insecurity, poverty and conflict (Kaito *et al* 2000). Changing weather patterns have extended droughts and reduced agricultural productivity (Yunana *et al* 2017), leading to food shortages, malnutrition, poverty and widespread inequalities. Indeed, in many nations, climate change has increased the frequency and severity of floods and hurricanes, which have further devastating and cascading consequences for communities (FAO 2017, Harrison *et al* 2021, Emiru *et al* 2022). At the local level, Somalia has been grappling with a range of abiotic issues, including severe droughts that have led to crop failures and pasture scarcity (USAID 2020). While much work has been done on livestock systems internationally (Harrison *et al* 2014, Phelan *et al* 2018, Rawnsley *et al* 2019), less is known of how the changing climate may impact on pasture-livestock production systems in Somalia.

In many African countries, livestock contribute 60%–80% of rural household income and comprise a sole means of subsistence and nutrition (Knight-Jones *et al* 2014). Pastoral communities rely extensively on the natural resource base for prosperity (Guillaumont and Simonet 2011) and thus are heavily dependent on the climate, particularly rainfall, for livestock feed supply (Taylor *et al* 2016, Langworthy *et al* 2018). Livestock production in Somalia contributes more than 60% of gross domestic product (Knight-Jones *et al* 2014), and nearly 85% of total foreign exchange earnings (Godiah *et al* 2015). In 2015, 4.9 M sheep and goats, 294 000 cattle and 72 000 camels from Somalia were exported from horn of Africa to Gulf States, generating $380 M (FAO 2017) and wealth crucial for sustaining smallholder and marginal communities.

Grazing systems are highly susceptible to climate change, and there is a growing awareness of misuse and degradation (Cobon *et al* 2020, Harrison 2021). The availability and quality of grassland fodder are thus essential for food production, especially in production of meat, milk and wool (Cottle *et al* 2016, Taylor *et al* 2016, Meier *et al* 2020). However, climate change is amplifying challenges related to pasture quantity and quality (Cobon *et al* 2020), with pasture production challenged further by nutrient limitations (Singhal *et al* 2023). Simulation models are often used to examine how production may change under future climates or with various systemic interventions (Taylor *et al* 2016, Phelan *et al* 2018, Meier *et al* 2020). Models provide a valuable tool for gaining a better understanding and clarity, as relying solely on Meier *et al* (2020) experimental observations can offer limited information, especially when considering the temporal and spatial scales of processes in such systems (Liu *et al* 2021).

The aim of this study was to (1) assess the potential impact of climate change on pasture productivity by the mid and late century in Somalia, (2) examine effects of climate change on animal liveweight, supplementary feed requirements, farm productivity and profitability, and (3) explore how productivity and profitability vary across a rainfall gradient.

2. Methods

2.1. Study sites

Pasture production has been the cornerstone of many agricultural systems in Somalia, accounting for 55% of total land assets (Chaplin-Kramer *et al* 2022). Due to its high yield potential, pastures are cultivated year-round across a wide range of agro-ecological regions (AER) in northwestern Somalia. As such, we selected four case study farms, Berbera, Beer, Xaaxi, and Sheekh in northwest Somalia. Selection of these sites was based on several criteria, including predominance of livestock populations in the region. All case study farms were rainfed; further characteristics are provided in table 1.

Somalia climate varies from tropical arid to semi-arid. From 1981 to 2020, annual average rainfall across the four sites ranged from 297 to 574 mm, and the mean minimum and maximum temperatures ranged from 18 °C to 30 °C, respectively, with Berbera being the hottest and Sheikh being the coldest. The climate in Somaliland is characterised by four seasons: spring (Gu′), main rainy season which starts in late March with peak rainfall in May; a summer (Xagaa) dry season from late June to August; an autumn (Dayr) short rainy season starting in September with peak rainfall in October and November; and a **dry winter (Jiilaal)** season from December to mid–March.

3. Simulation workflow

3.1. Overview

Process-based crop models have been used extensively for understanding impact of climate change on grasslands and agriculture more broadly (Christie *et al* 2014, Rawnsley *et al* 2018, Bilotto *et al* 2021, Shahpari *et al* 2021), and can integrate physiological processes including weather, management, and paddock (Liu *et al* 2020, 2021). We invoked the Sustainable Grazing System (SGS) model here, because SGS contains biophysical processes and can account for seasonal and long-term impacts of climate change on pasture production, soil organic matter and carbon, and GHG emissions (Johnson 2016, Martel *et al* 2021). The model has been extensively calibrated and validated (Bell *et al* 2013) for simulation of pasture growth rates in many regions (Harrison *et al* 2017, Svinurai *et al* 2021) climate data obtained from meteorological archives from 1981 to 2020 were used as inputs to the model. Model calibration and evaluation was performed to ensure that the pasture parameters resulted in simulated outputs that captured the observed field data. Future climate data was downscaled using historical climate data including rainfall, maximum and minimum temperature, evapotranspiration, vapor pressure, and solar radiation (Räty *et al* 2014) for low

Table 1. Climate and soil characteristics of the case study farms (PAWC represents plant available water capacity).

Site	Coordinates (latitude, longitude)	Altitude (m above sea level)	Climate	Mean annual rainfall (mm)	Soil	Bulk density (g cm^{-3})	PAWC (mm)
Berbera	10.4348, 45.0140	3	Tropical with bimodal seasons (Long and short rainy season, and two dry seasons)	297	Haplic calcisols	1.42–1.45	238
Xaaxi	9.3501, 44.9661	1008		354	Haplic Calcisols	1.4–1.5	174
Beer	9.2701, 45.490	848		**345**	Calcic Vertisols	1.3–1.4	209
Sheekh	9.9375, 45.1822	1500		573	Lithic Leptosols	1.25–1.35	184

(SSP285) and high (SSP585) emissions scenarios. The impact of climate change on several parameters of interest (i.e. rainfall and temperature) was examined, followed by assessment of how the productivity and profitability of each livestock farm altered along a rainfall gradient (figure 1).

3.2. Farming systems simulation

The whole farm biophysical model SGS (Johnson *et al* 2003) simulates biomass production, pasture growth rate, supplementary feed requirement, animal metabolism, soil nitrogen and carbon cycling, and animal liveweight change on a daily-time-step. In the preliminary stage of the investigation, we selected four agricultural zones in northwestern Somalia, taking into account their heterogeneous rainfall levels and predominance of livestock production. Household heads provided detailed data on income, quantity of concentrate required, types of fertilisers used along with associated costs, available labour, productivity and profitability. The model was initialised with these data to establish a baseline for the study. Next, we simulated farm productivity per hectare and per year, with profitability then determined based on economic measures such as liveweight production per head per year and total liveweight production. We accounted for the cost of concentrates used to feed livestock, including the price of concentrates per kilogram and per hectare, concentrate intake per animal, workforce requirements and fertiliser costs. By deducting the total costs from total revenue, we obtained profitability per farm (gross margin).

3.3. SGS model description

Here we invoke the SGS model version 5.3.8 (Johnson *et al* 2003), a comprehensive, mechanistic, whole-farm system biophysical model. The model operates on a daily time step and includes modules for simulating pasture growth, soil water dynamics, soil nutrients, farm management, and animal metabolism, reproduction and production (Johnson *et al* 2003). The pasture module in SGS describes species-specific parameters for sunlight interception, photosynthesis, respiration, transpiration, nutrient uptake, partitioning of new growth and plant development, senescence, and turnover (Johnson *et al* 2003). The SGS model has default parameters for C4 (generic C4) and C3 (generic C3) plants, as well as legumes, which can be adapted when introducing new species to the model. The farm management module allows for representation of alternative pasture management strategies, including fertilizer application, irrigation regimes, cutting or grazing, and stock management.

3.4. Data collection and analysis

The model was initially run using default crop parameters, utilising daily meteorological data inputs comprising of daily minimum and maximum temperature (°C), rainfall (mm), solar radiation (MJ m^{-2}), evapotranspiration (mm), and vapor pressure (mm). Meteorological inputs from 1 January 1981 to 31 December 2020 were obtained from meteorological archives (https://power.larc.nasa.gov/data-access-viewer/). Livestock information, including the type of livestock raised, average animal liveweight, paddock size, number of grazing animals, and feed requirements, were incorporated into the model based on data collected from the field. For parameterisation, an experimental field dataset from four farms during growing seasons of 2021 and 2022 (comprising a long rainy period and a short rainy period) were utilized. Three samples were collected from each farm, resulting in a total of 12 samples. Quadrats covered an area of 1.5 m^2 by 1.5 m^2; all aboveground vegetation in the quadrat was cut, weighed to determine fresh mass, oven dried for 48 h, then weighed in a laboratory. We interpolated seasonal biomass as a function of rainfall, as follows:

$$X = Y \times \frac{Z}{W}$$

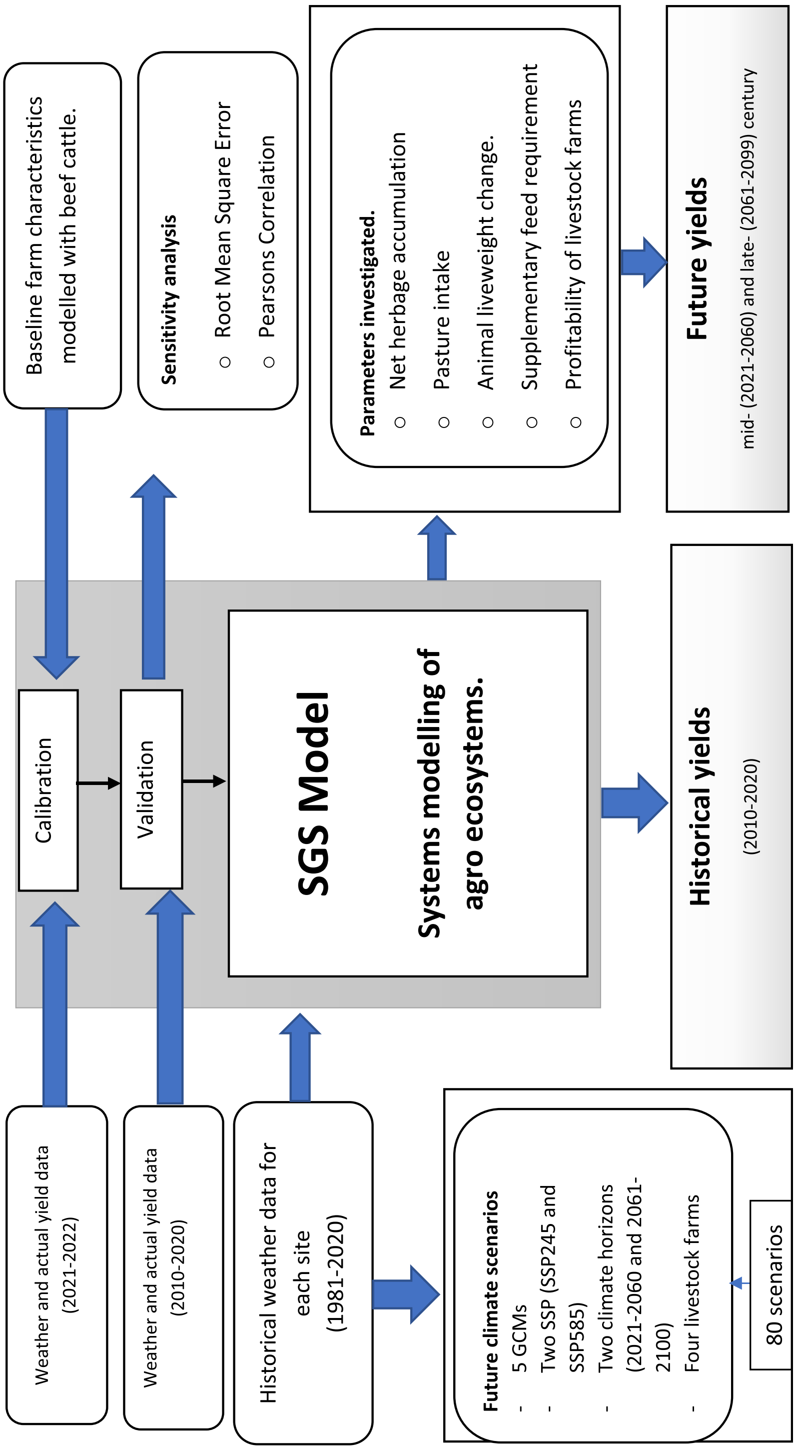

Figure 1. Conceptual framework of the study. SGS = Sustainable Grazing Systems model; GCM = global climate model' SSP = shared socioeconomic pathways.

Where:

X = biomass production of particular year to be interpolated

Y = mean annual rainfall of the year to be interpolated

Z = biomass production of the baseline year

W = mean annual rainfall of the baseline year

Field data collection was also performed to obtain information of the selected livestock farms. First, we deliberately selected four similar farms in terms of hectares, stocking rate, types of animals reared, production methods, herd size, household income, and grazing management in 2019. This was complemented with soil sampling tests conducted at the study sites and analysed in a laboratory. Pasture types and their background information were also collected from the selected household heads. Model evaluation was conducted using the coefficient of determination, root mean square error (RMSE), and Pearson's correlation coefficient following Harrison *et al* (2019). We also visually assessed the association between observed (Oi) and simulated (Si) values using R (www.r-project.org/) programming language, with ideal performance being all values falling on the 1:1 line.

3.5. Sensitivity analysis

Sensitivity analyses were conducted for many parameters in SGS (supplementary table S3) to gain insight into variables that were important/insignificant in determining the trajectory of pasture growth. Parameters pertained to antecedent shoot dry weight, initial root dry weight percentage of initial live weight, canopy structure, root distribution, photosynthesis, nitrogen dynamics, temperature stress, transpiration, grazing and other parameters. Each parameter was increased and decreased by 50% to observe any notable changes in biomass production. Parameters such as percentage of carbon allocated to shoots, optimal leaf nitrogen percentage, maximum leaf nitrogen percentage, effective minimum leaf area index, and high temperature stress parameters were found to be highly sensitive. Other parameters were either moderately sensitive or insensitive (further details are provided in table S3).

3.6. Calibration and validation

Experimental data collected from the farms in 2020/2021 was used to calibrate the model, with sensitive parameters being hinged upon literature values where available figure 2. Calibrated files were then used for validation with no further parameterisation. Dry matter (DM) yield from field data during 2020 and 2021 were used to validate the model. RMSE, and R^2 are used to assess model validity (Harrison *et al* 2016).

3.7. Statistical downscaling of global climate model (GCM) data

Simulations were conducted using historical period (1981–2020) and two future climate horizons. Future climate data were established using monthly gridded rainfall and climate data from GCMs downscaled to the meteorological sites at a daily time-step using a statistical downscaling model (Liu and Zuo 2012). Monthly gridded climate projections from GCMs were spatially interpolated to sites of interest using an inverse distance-weighted (IDW) interpolation method, followed by a bias correction to adjust for site-based monthly GCM simulations. Second, daily climatic variables (e.g. rainfall, Tmax and Tmin, radiation, evapotranspiration) were generated for each site from spatially downscaled projections using a modified version of the WGEN stochastic weather generator (Liu and Zuo 2012). The GCMs encompassed a range of climate conditions, from warm and wet (CNRM-CM6, CCSM4) to hot and dry (FGOALS-g2, MIROC-ESM) derived from the CMIP6 framework, using low (SSP245) and high emissions (SSP585) Shared Socio-economic Pathways (Frame *et al* 2018). The selection of the five GCMs for inclusion in the present study was based on the skill of the model hindcast simulations in reproducing various datasets or fields from the twentieth century; the quality of underlying physics represented by reasonable formulations of relevant physical processes; and finally, the consistency in producing similar simulations within the range of natural variability (Overland *et al* 2011). Two future scenarios were examined: mid-century (2021–2060) and late century (2061–2100).

4. Results

4.1. Model calibration and validation

We comprehensively calibrated and validated the model for two generic pasture species (C4 low-quality and C4 improved species). Both pasture ecotypes were well simulated by the calibrated model. For the C4 low-quality pasture, the model demonstrated a strong ability to simulate observed biomass production, with a high coefficient of determination ($R^2 = 0.92$) and close agreement between measured and simulated values. Average measured and simulated biomass production were similar, at 3470 kg ha^{-1} yr^{-1} and 3548 kg ha^{-1} yr^{-1}, respectively, with an RMSE of 728. For the improved C4 species, the calibration results

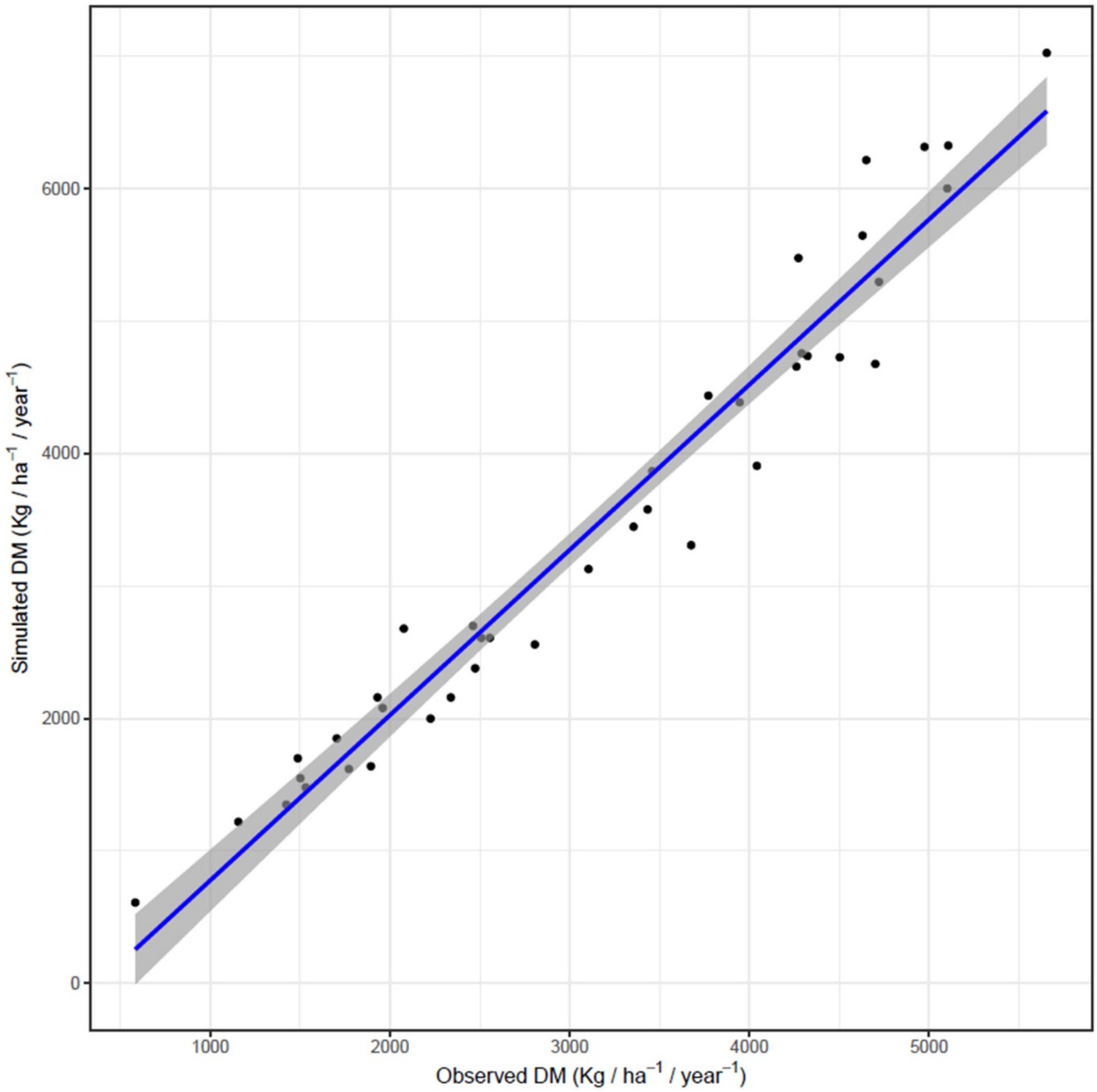

Figure 2. Simulated and observed pasture dry matter. Shaded region represents the 95% confidence interval associated with simulated dry matter values; points indicate measured data.

were stronger ($R^2 = 0.96$ and RMSE 686 kg DM ha^{-1}), indicating the model explained 91% of the variation in observed biomass production. Overall, the calibration demonstrates the model's ability to accurately simulate both low-quality and improved C4 species production. Further calibration results can be found in the supplementary material (table S4).

4.2. Analysis of historical and future climate

Effects of climate change on pasture production by mid-century (2021–2060) and late-century (2061–2099) are presented in table S1. All regions exhibited an increasing trend in annual and seasonal rainfall during the pasture growth period, with temperate increases of 9%–14%. Across sites, Berbera showed the highest increase in mean seasonal rainfall, ranging from 21% to 41%. Beer experienced a similar increase of 19%–39%. Sheikh and Xaaxi recorded a seasonal increase in rainfall of 8%–28% and 7%–27%, respectively, relative to historical rainfall. Figure 3 illustrates anticipated changes in rainfall, the number of wet and dry days, and maximum and minimum temperatures for the mid-century and late-century scenarios under SSP245 and SSP585.

Across sites, mean annual temperature increased by 9%–14%. The highest increase in mean maximum temperature was in Berbera, with a range of 5 °C–6.8 °C from mid- to late-century. Xaaxi exhibited the highest increase in mean minimum temperature, ranging from 1 °C to 3 °C from the mid-century to the late-century period, with a range of 2.5 °C–5 °C for SSP245 and SSP585, respectively. Changes in maximum temperature are expected to be like that of the minimum temperature, with a mean change of 2.0 °C and

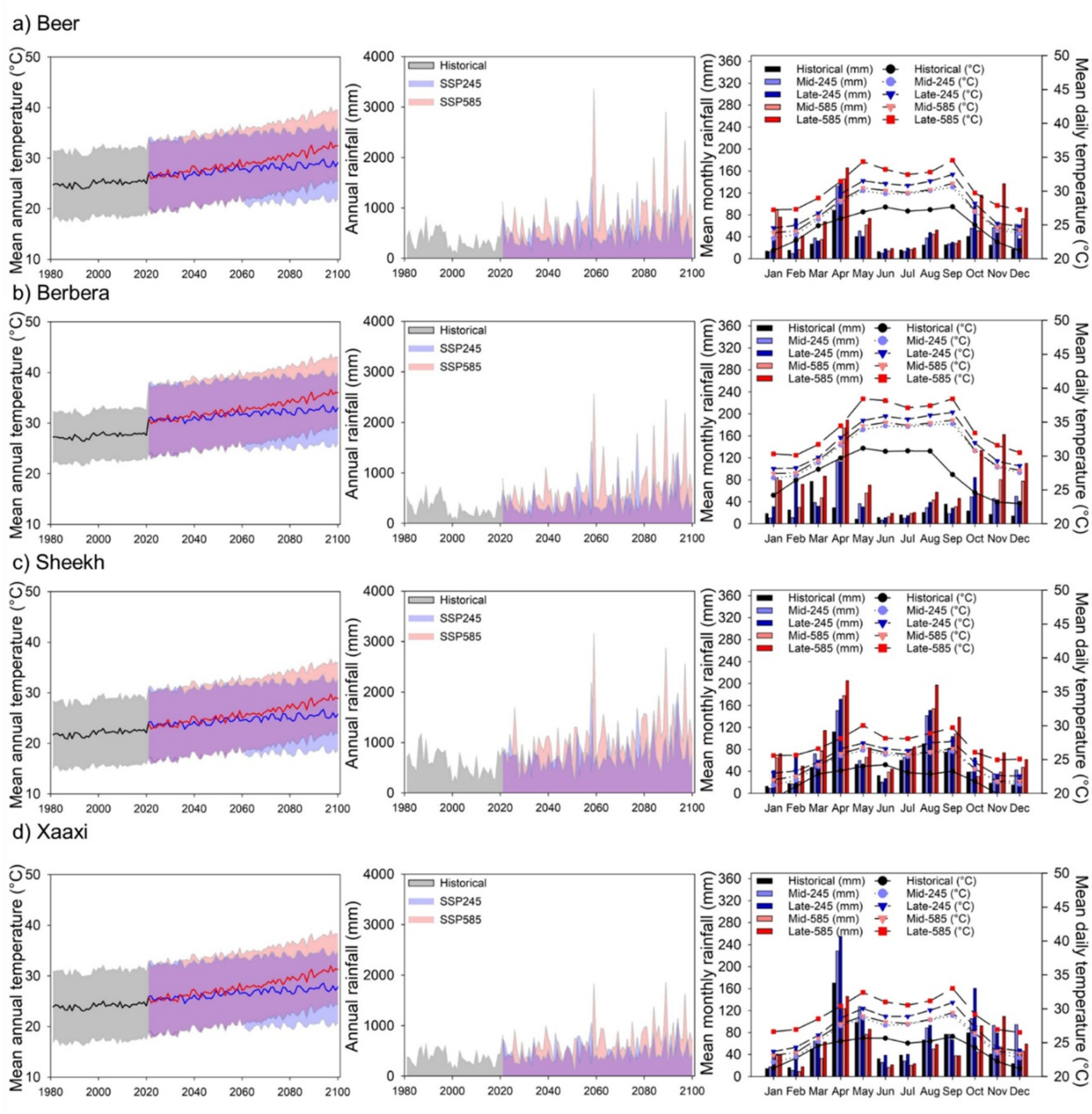

Figure 3. Historical and future monthly mean rainfall for each site and climate scenario. Statistics are expressed from computations using 40 years of climate data (avg. = average daily rainfall, st. dev. = standard deviation, and % increase).

2.0 °C, respectively. All scenarios resulted in more dry days and fewer wet days under future climates. Summary climate statistics are presented in table S1.

4.3. Impact of climate change on pasture production

We found large variability in pasture production across regions, emissions scenarios and future horizons. In general, biomass production will increase from mid to late century, mainly due to increased precipitation and temperature. At Berbera, annual average biomass increased by 36% and 66% relative to the historical baseline of 2 t DM ha^{-1} for the mid-century and late-century climate scenarios, respectively. At Beer and Xaaxi, biomass production increased by 57% and 85%, and 30% and 53% for the mid-century and late-century, respectively, relative to the historical baseline. In Sheikh, the modelled biomass production increased by 46% and 73% for the same climate scenarios compared with the baseline of 4.5 t DM ha^{-1}. The highest biomass production occurred in Beer, with an 85% increase by late-century. The highest mean annual biomass production occurred in Sheikh, with 6.6 t DM ha^{-1} and 7.8 t DM ha^{-1} for the mid-century and late-century periods, respectively, compared with the historical baseline of 3.0 t DM ha^{-1}. Mean annual and monthly DM production increased with each future climate scenario across sites, with higher DM production in spring and autumn compared with summer and winter. Berbera had the lowest summer growth rate compared with other sites. In Beer, a similar trend was observed in the average seasonal pasture biomass, with a significant increase in production during spring and autumn, but decreasing during summer. In general, we found higher growth rates during winter (December to February), where the combination of low prevailing rainfall and cold temperatures have historically constrained growth.

For each location, we assessed implications of multiple climate realisations, with corresponding pasture growth, variability, and percentage changes compared with the historical baseline. In Berbera, historical pasture production was 2994 kg DM ha^{-1}. As time progressed from mid-SSP245 to late-SSP585, biomass increased from 20% to 53% relative to the baseline. For Xaaxi, historical mean annual biomass production was 3505 kg DM ha^{-1}, again with future scenarios having higher growth rates at this site. At Beer, historical biomass production was 2916 kg DM ha^{-1}, with growth rates being 14%–85% above the baseline from mid to late century (figure 4). Similar trends were observed at Sheekh.

4.4. Supplementary feed requirements

Seasonal rainfall variability increased under future climates, although annual precipitation was generally greater than historical climates (figure 5). Monthly pasture growth variability generally increased; there were greater differences between future projections and each baseline than between emissions scenarios SSP245 and SSP585. Supplementary feed requirements diminished with increased pasture growth availability. During the historical period, average annual supplementary feed requirement was highest at Berbera (530 kg ha^{-1} yr^{-1}) and lowest in Sheekh (325 kg ha^{-1} yr^{-1}), with Xaaxi and Beer both requiring the same amount (387 kg ha^{-1} yr^{-1}). Projections suggested a lower need for supplementary feed across sites and future climate scenarios, except for Xaaxi, which had a 4% increase from the mid-century to the late-century under the SSP245 scenario. In Sheekh, supplementary feed requirement decreased by 17%–29% in the mid-century and late-century periods, compared with the historical period. However, future climates significantly increased supplementary requirement at Berbera due to lower biomass production at this site, with increased heat waves potentially also increasing incidence of livestock heat stress (Cottle *et al* 2016, Martel *et al* 2021).

4.5. Animal growth rates

Animal growth rates varied across regions, with animals gaining the highest liveweight during autumn (0.50 kg d^{-1}) and spring (0.43 kg d^{-1}), followed by summer (0.23 kg d^{-1}), and lowest in winter (0.026 kg d^{-1}). In January and February (winter), animals experienced significant weight loss due to the low pasture growth and lack of biomass. Liveweight gain was highest during April, May, September, corresponding to periods of higher rainfall and increased grass growth and higher biomass production (figure 6). The highest liveweight gain occurred at Shiekh, with mean daily animal liveweight gain of 0.33 kg d^{-1} averaged across the year.

4.6. Productivity and profitability of livestock farms across a rainfall gradient

Our study underscores significant variation in productivity and income across a rainfall gradient, and suggests that climate change heralds positive signals towards the end of the 21st century table 2. Under the SSP245 scenario, profit gains ranged from an 8% increase at Beer to a 20% increase at Sheekh, although the Berbera site experienced a 4% reduction in profit. In contrast, the SSP585 scenario saw all farms experience elevated profitability, with increases ranging from 23% at Beer to 42% at Sheekh. We revealed a strong positive relationship between livestock productivity, profitability, and increasing annual rainfall ($R^2 = 0.74$). While this may suggest that sites with higher rainfall levels tend to exhibit greater productivity and profitability, the statistical analysis was not statistically significant at the 5% level. This implies that while rainfall appears to be an influential factor, it may not be a reliable sole predictor of livestock performance across sites, suggesting that future analyses should use a range of climatic and economic metrics to determine potential changes in profitability and long-term prosperity (Harrison *et al* 2017, Ibrahim *et al* 2018, Langworthy *et al* 2018).

5. Discussion

In contrast to many other regions (Ara *et al* 2021, Harrison 2021, Liu *et al* 2022, Muleke *et al* 2022), we found that regions analysed here may benefit from the changing climate towards the end of the century, mainly due to increased precipatation and milder temperatures in winter, particularly in Beer, Berbera and Sheekh. These findings reflect field studies in Ethiopia, which found that increased rainfall improved pasture productivity (Brown *et al* 2017), and numerous studies have established connections between rainfall and productivity in arid and semi-arid regions (Noushahi *et al* 2022, Ali *et al* 2023). We do note however, that many other factors other than climate can dictate whether or not improvements in productivity benefit farmers. Some of these factors include knowledge and skills required to adapt (Bilotto *et al* 2021, Cullen *et al* 2021), access to capital required for infrastructure or animal husbandry needs (Ho *et al* 2014), market prices and supply chains (Muleke *et al* 2022), and changes in frequency and severity of extreme weather events (Kabir *et al* 2024).

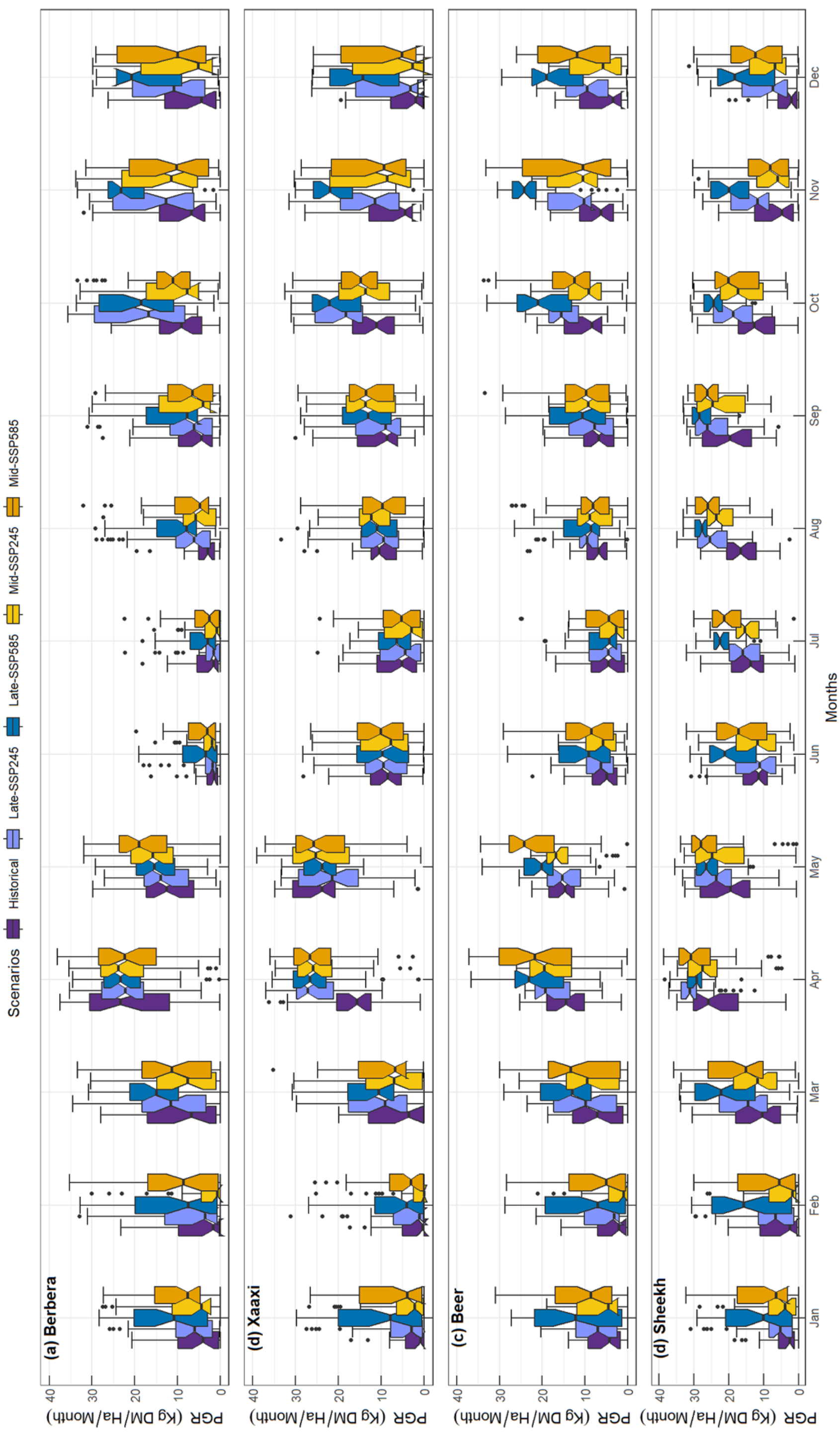

Figure 4. Pasture growth rates at (a) Berbera, (b) Xaaxi, (c) Beer, and (d) Sheekh. Boxplots show the median, 25th and 75th percentiles in the box, with the 10th and 90th percentiles in the whiskers and dots showing outliers beyond the 5th and 95th percentiles. Each boxplot represents 40 years of simulations, with each point showing an average daily pasture growth rate for that month.

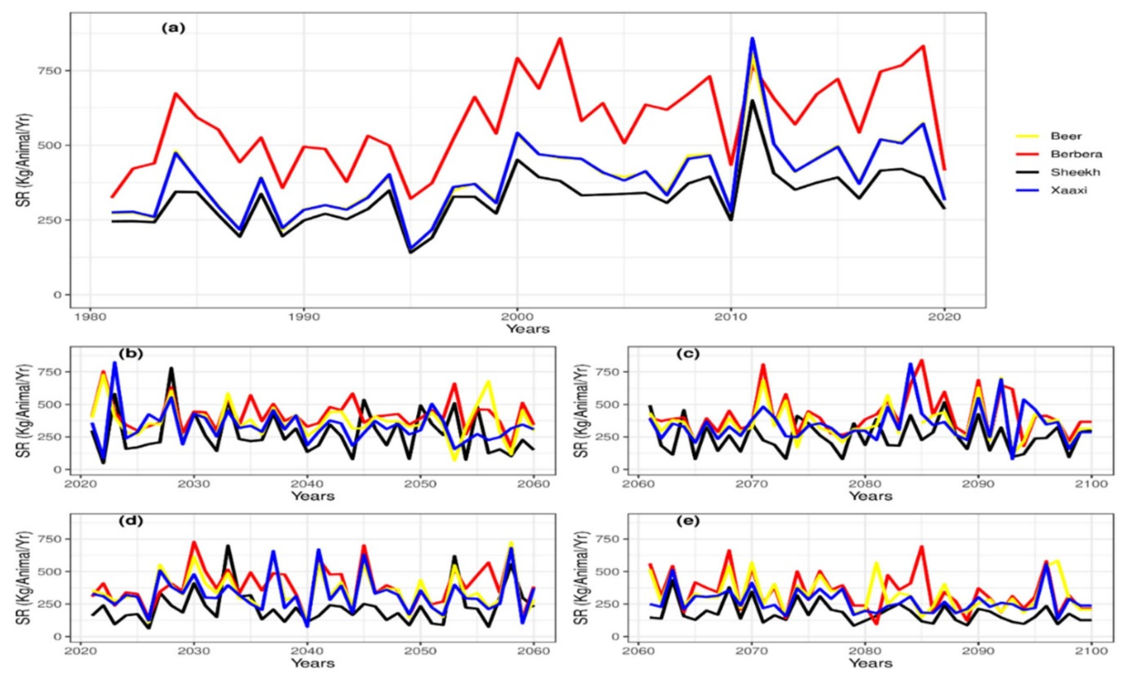

Figure 5. Supplementary feed requirement (SR) across sites for the (a) historical period (1981–2020), (b) mid-century SSP245 (2021–2061), (c) late-century SSP245 (2061–2100), (d) mid-century SSP585 (2021–2061), (e) late-century SSP585 (2061–2100).

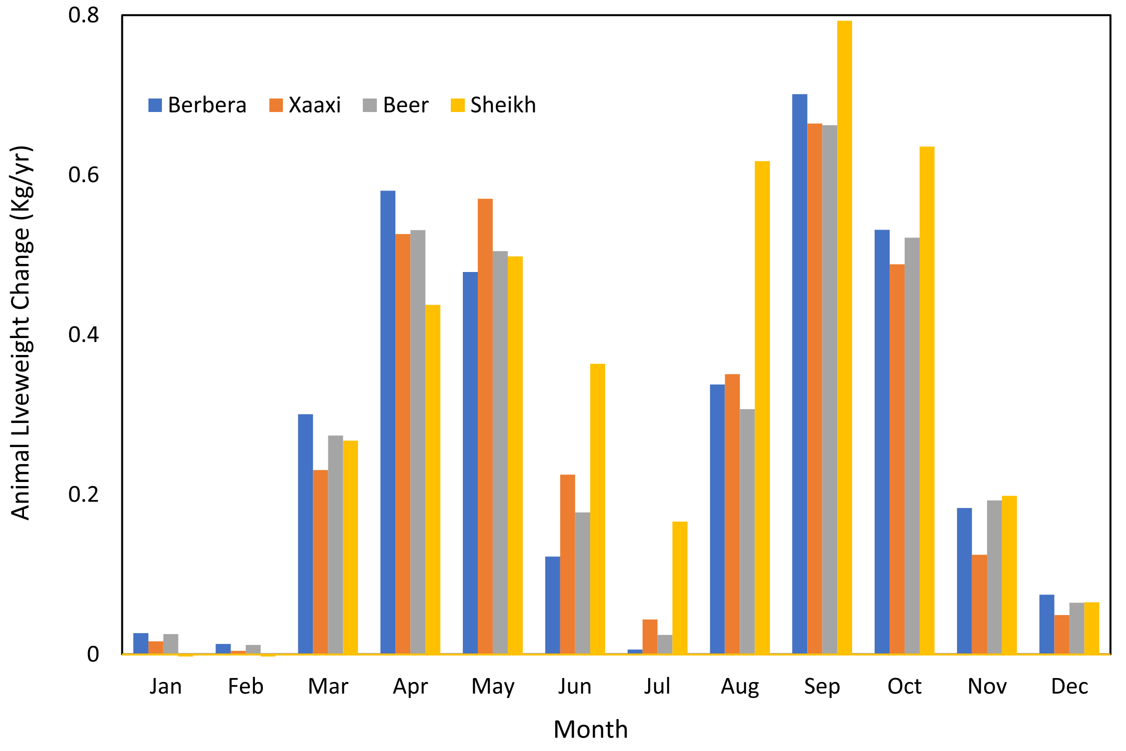

Figure 6. Liveweight gains of juvenile animals for four regions in Somalia (Berbera, Xaaxi, Beer and Sheekh). Values shown are averaged across 40 years.

Future climate projections consistently indicated increased maximum and minimum temperature across all study sites, SSP scenarios and climate horizons. Our results suggest that a 10% increase in annual rainfall and 1.7 °C warming would improve annual pasture growth by around 17%, larger than effects of climate change seen in other temperate agroecological regions (Zhang *et al* 2022). Such differences suggest that the tropical climes of the present study may be advantageous for achieving higher pasture productivity, although soil fertility, and ability to supply additional plant nutrient requirements as the climate changes, would need

Table 2. Historical, mid (2040) and late (2080) century impacts of climate change on profitability (gross margins) of Somalian livestock farms at Berbera, Xaaxi, Beer and Sheekh under low and high greenhouse gas emissions scenarios. Gross margins are shown in United Stated dollars (USD).

	Low emissions scenario (SSP245)				High emissions scenario (SSP585)			
Berbera	Gross margin ($)	STD ($)	Difference ($)	% change	Gross margin ($)	STD ($)	Difference ($)	% change
Historical	2187	1228		0	2187	1228		0
Mid-century	2124	970	1323		2386	1293	243	
Late century	2186	1350	61	−4	2825	1274	438	29
Xaaxi				0				
Historical	2412	1087			2412	1087		0
Mid-century	2894	1067	241		2934	1244	291	
Late-century	2769	1168	−124	15	3402	775	468	41
Beer								
Historical	2414	1049		0	2414	1049		0
Mid-century	2540	1113	−19		2765	1272	203	
Late-century	2608	1363	67	8	2985	1104	219	23
Sheekh								
Historical	2945	763		0	2945	763		0
Mid-century	3246	1491	172		3764	1194	301	
Late-century	3558	1037	311	20	4188	698	424	42

to be taken into account, Smith *et al* 2023). Our findings also imply that climate change will have significant impacts on pasture production, resulting in various perturbations in seasonal temperature and rainfall patterns across regions. While projected increases in rainfall may lead to increased pasture production, rising temperatures, particularly if coupled with increasingly frequent heat waves, could offset these gains. Thus, greater agility in farm management and adaptive potential will be required in future.

We found that supplementary feed requirement diminished with increased pasture biomass production and availability. Across locations, average annual supplementary feed requirement was highest in Berbera and lowest in Sheekh. We found that rainfall will increase most in the driest sites (Berbera 21%–41%) and least in the wettest sites (Sheekh; 7%–27%), clearly underlying the importance of assessing the impacts of the changing climate across a rainfall gradient. This observation has implications for any study purporting analyses of the impacts of climate change on the agricultural sector.

We showed that the highest liveweight gains occurred at Sheekh, with mean animal liveweight gain of 0.33 kg d^{-1}. These findings underscore the strategic potential of Sheekh among other locations for rearing livestock and becoming a commercial livestock transport route in Somaliland (Mahmoud *et al* 2010). Indeed, the high pasture growth and liveweight gains at this site, together with strategic proximity to Berbera port, position Sheekh as an ideal location for livestock production and sales. The highest liveweight gain was observed during the rainy seasons with highest biomass production in spring and autumn. Liveweight gain was lowest in Berbera, associated with the aridity of this region (Sejian *et al* 2018).

In the first comprehensive analysis for the livestock sector in this region, we showed that the calibrated SGS model accurately simulated pasture production (figure 2). The relationship between measured and modelled biomass indicates the model reasonably represented grassland biomass (annual mean aboveground biomass measured was 3470 kg DM ha^{-1}; modelled mean was 3365 kg DM ha^{-1}). Similar levels of agreement have been observed in simulations conducted in temperate regions (Svinurai *et al* 2021, Muleke *et al* 2022), suggesting that our analyses are robust. Some of the variability associated with our simulations could be attributed to downscaling and bias-correction of the climate data, as well as spatial differences in pasture persistence, soil parent materials, fertility and grazing behaviours. Nevertheless, outputs from the model align well with the observed trend in seasonal production of pasture, with minimal production during winter and maximum production during spring. This pattern corresponds to the main drought and rainy seasons in the observed farms and reflects the presence of adequate soil moisture and warmer temperatures.

Our comprehensive analysis of livestock enterprises has provided a compelling evidence-base for strategic prioritization of the Sheekh location for future fodder production development and investment. Considering manifold favourable indicators at this site, including high rates of pasture production, low supplementary feed requirements, high livestock growth potential, and high profit levels, Sheekh emerges as the most prospective location of those regions we examined here. The geographic positioning of Sheekh, with close proximity to the Berbera port and key livestock transport corridors, further enhances its suitability as a hub for the regional livestock industry. Our study provides clear evidence that should be used to inform contemporary policy with prospective interventions aimed at bolstering resilience, productivity, prosperity and social licence of the livestock sector to operate in Somaliland. By prioritizing development of Sheekh as a center for livestock production, quarantine and trade, regional stakeholders could leverage inherent advantages to drive sustainable growth, strengthen supply chain logistics, and position the nation as a competitive player in the global livestock marketplace.

Data availability statement

The dataset supporting the findings of this study is available in the Dropbox repository at the following link www.dropbox.com/scl/fo/28cdvncvw9rsq2pgspx37/h?rlkey=4ni7u6xfqj35176sxlo864sua&st=dofb12vb&dl=0. The dataset includes all the necessary files and materials required to reproduce the results presented in the study (Hussein *et al* 2024).

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ORCID iDs

Jaabir Hussein https://orcid.org/0000-0002-1566-2459
Carla Sofia Santos Ferreira https://orcid.org/0000-0003-3709-4103
Ke Liu https://orcid.org/0000-0002-8343-0449
Matthew Tom Harrison https://orcid.org/0000-0001-7425-452X

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