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

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November 20, 2023

Abstract

While the livelihoods of Somalian livestock smallholders are rely heavily on seasonal climate conditions, little is known of long-term implications of the changing climate for this nation. Here, we quantify climate change impacts on pasture 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 models 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 to 20% 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 adaptive farm management will be required to cope with increased seasonal climate variability.

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

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Key Points:

- The Sustainable Grazing Systems (SGS) Model was tested in tropical areas and used to project future scenarios in the mid and late century.
- The assessment examines pasture production, feed requirements, animal liveweight changes, and livestock farm profitability.
- Future climates benefit smallholder farmers in Somalia, but adaptive farm management is vital to cope with increased climate variability.

Abstract

While the livelihoods of Somalian livestock smallholders are rely heavily on seasonal climate conditions, little is known of long-term implications of the changing climate for this nation. Here, we quantify climate change impacts on pasture 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 models 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 to 20% 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 adaptive farm management will be required to cope with increased seasonal climate variability.

Keywords: Grassland, climate crisis, adaptation, profit, beef cattle, dairy, sheep, hay, forage, grain

Plain Language Summary

This study investigates the impact of climate change on pasture productivity and profitability for livestock smallholders in northwestern Somalia. The research reveals that future climates in the region will experience increased rainfall and higher temperatures. These changes are expected to enhance grassland production and subsequently have positive effects on farm profits. Under a low emissions scenario, farm profits show modest improvements, ranging from a 4% decrease in Berbera to a 20% increase in Sheikh. In contrast, a higher emissions scenario leads to even higher profits, with ranges between 23% and 42% above the baseline. This outcome is primarily attributed to increased pasture production and reduced reliance on supplementary feed. However, it is important to note that adapting farm management practices will be crucial to effectively cope with the anticipated seasonal climate variability resulting from these changes. Ultimately, this study highlights that, while future climates bring benefits in terms of productivity and profitability for smallholder farmers in Somalia, proactive measures and adaptive strategies are essential to navigate the challenges posed by climate change.

Introduction

In Africa, particularly the 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 in Sub-Saharan countries (Yunana, et al., 2017), leading to food shortages and malnutrition. Climate change has also increased the frequency and severity of floods and hurricanes, which can have devastating impacts on agricultural systems and long-lasting consequences for communities (Emiru et al., 2022; FAO, 2017). 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 (Rawnsley et al. 2019; Harrison et al. 2014; Phelan et al. 2015), less is known of how the changing climate may impact on livestock production in Somalia.

In many African countries, livestock contribute 60-80% of rural household income and may comprise a sole means of subsistence and nutrition (Knight-Jones, Njeumi, Elsawalhy, Wabacha, & Rushton, 2014). Pastoral communities rely on natural resources to make a living (Guillaumont & Simonet, 2011) and are heavily dependent on rainfed grazing for livestock feed supply (Langworthy et al., 2018) . In particular, one third of the total number of cattle in the world are located in Sub Saharan African countries (Ayal, 2022). Livestock production in Somalia contributes more than 60% of the total gross domestic product (Knight-Jones et al., 2014), and nearly 85% of total foreign exchange earnings (Godiah et al., 2015). In 2015, 4.9 million sheep and goats, 294,000 cattle and 72,000 camels from Somalia were exported from horn of Africa to Gulf States, and generated $380 million (FAO, 2017).

Grazing systems are highly susceptible to climate change, and there is a growing risk of misuse and degradation (Cobon et al., 2020a; Harrison, 2021). The availability and quality of grazed rangelands are essential for food production, especially in the production of meat and milk (Meier, Thorburn, Bell, Harrison, & Biggs, 2020; Taylor, Harrison, Telfer, & Eckard, 2016). However, the impact of climate change exacerbates the challenges related to pasture quantity and quality (Cobon et al., 2020b) and is challenged further by inherent nutrient limitations (Singhal et al., 2023). As such changes need to be examined holistically, simulation models are often used to examine how production may change under future climates or with various emissions mitigation interventions (Meier et al., 2020; Phelan et al., 2018; Taylor et al., 2016). 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 goals of this study were as follows: (1) to assess the potential impact of climate change on pasture productivity by the mid and late century, (2) to examine the effects of climate change on animal live weight, supplementary feed requirements, and livestock farm productivity and profitability, and (3) to explore potential variation in productivity and profitability along a rainfall gradient.

Methods

Study sites

Pasture production for dairy and livestock farming has been the cornerstone of agricultural systems in Somalia, accounting for 55% of its 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 the northwestern part of Somalia. In this study, we selected four case study farms, Berbera, Beer, Xaaxi, and Sheekh, located in the northwest of Somalia, which experiences diverse climatic conditions. The selection of these sites was based on specific criteria, including whether the region was a primary fodder production site and accessibility to livestock transport routes in the Gulf states. All case study farms rely on rainfed agriculture, and their baseline characteristics are provided in Table 1.

Table 1: Climate and soils of the case study farms (PAWC: plant available water capacity).

Sites	Coordinates	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		34	Calcic Vertisols	1.3 – 1.4	209
Sheekh	9.9375, 45.1822	1,500		573	Lithic Leptosols	1.25 – 1.35	184

Somalian climate varies from tropical arid to semi-arid. The eastern regions (Sool, Sanaag, and Togdheer) experience more frequent drought waves and lower annual average rainfall compared with the western regions (Awdal, Waqoyi Galbed), which receive more rainfall and have higher temperatures. 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 to 28^{o}C, respectively, with Berbera being the hottest and Sheikh being the coldest. The climate in Somaliland is characterised by four seasons: spring, which starts in late March with peak rainfall in May; a summer dry season from late June to August; an autumn rainy season starting in September with peak rainfall in October and November; and a winter season from December to February.

Simulation framework

Overview

Process-based crop models have been used extensively for understanding impact of climate change on grasslands and on agriculture more broadly (Bilotto et al., 2021; Christie et al., 2014; Rawnsley et al., 2018; Shahpari et al., 2021), and can integrate physiological processes including weather, management, and paddock (Liu et al., 2021, 2020). For the current study, the Sustainable Grazing System (SGS) model was used because it includes a biophysical pasture simulation model with common underlaying structures (Chang-Fung-Martel et al., 2021; Johnson, 2016). SGS has been validated (Bell, Eckard, Harrison, Neal, & Cullen, 2013) for simulation of pasture growth rates (Svinurai, Hassen, Tesfamariam, Ramoelo, & Cullen, 2021). Historical climate data obtained from meteorological archives ranging from 1981-2020 were used as inputs to SGS. 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 using delta bias correction (Räty, Räisänen, & Ylhäisi, 2014). The impact of climate change on several parameters of interest (i.e. rainfall and temperature) was conducted, followed by assessment of how the profitability of each livestock farm altered along a rainfall gradient (Figure 1).

Farming systems simulation

The whole farm model SGS (Johnson et al., 2003) simulates biomass production, pasture growth rate, grazing animal pasture intake, supplementary feed requirement, and animal liveweight change. All variables are simulated on a daily-time-step. We examined the profitability of the four farms by manipulating economic variables. In the preliminary stage of the investigation, we selected four agricultural zones of Somalia, taking into account their heterogeneous rainfall levels and predominance of livestock production. Household heads provided background data on income, quantity of concentrate required, types of fertilisers used along with associated costs, available labour, productivity, and profitability. This data was collected to establish a baseline for the study and ensure that selected farms shared similar characteristics. Next, we simulated the livestock farm productivity per hectare and per year, followed by determining the profitability based on economic output measures such as liveweight production per head per year and total liveweight production. We also considered the total cost of concentrate requirements per farm, including the price of concentrates per kilogram and per hectare, as well as concentrate intake per animal. We calculated the combined workforce requirements and fertilizer costs. By deducting the total output cost of the farm, cost of concentrates, workforce expenses, and fertilizer expenses, we obtained the gross margin.

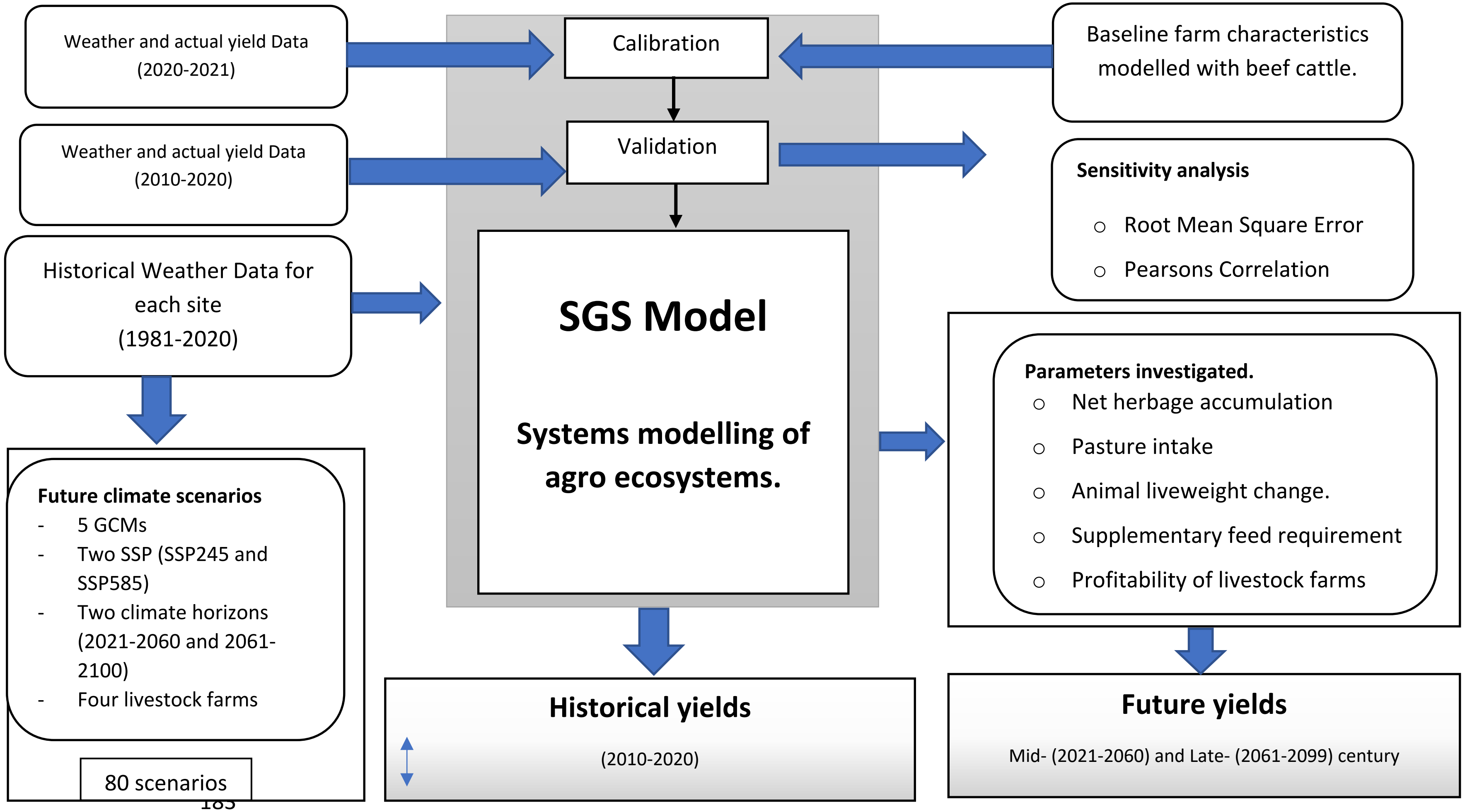


Figure 1: Conceptual framework of the study

The model was initially ran 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 covering the period from January 1, 1981, to December 31, 2020 were obtained from meteorological archives available at (https://power.larc.nasa.gov/data-access-viewer/). Livestock information, including the type of livestock being raised, average animal liveweight, paddock size, number of grazing animals, and their feed requirements, were incorporated into the model based on data collected from the field. For the parameterisation of the Soil and Water Assessment Tool (SWAT) model, an experimental field dataset from Sheikh farm during the bimodal growing seasons of 2021 and 2022 (comprising a long rainy period and a short rainy period) was utilized. Based on the two-year field data, the remaining observed data were extrapolated using a weighted method. This method employs a logic-based approach that cross-calculates yearly variation relative to their corresponding rainfall amounts, as described by the equation below:

$$X = y * z / w$$

X = The missing biomass production of particular year

Y = The mean annual rainfall of the missing year

Z = The biomass production of the baseline year

W = The mean annual rainfall of the baseline year

The performance of the pasture model was evaluated using the coefficient of determination, root mean square error, and Pearson's correlation coefficient following (Harrison et al., 2019). A graphical display between observed (Oi) and simulated (Si) values was also considered to check model performance using R (https://www.r-project.org/) programming language.

Climate Scenarios

Simulation modelling was conducted using historical and future climate data spanning a period of 40 years (1981-2020). The study developed 80 scenarios with the aim of investigating the potential impact of climate on the future of four livestock farms. These scenarios consisted of combinations of five global climate models (GCMs) and two shared socio-economic pathways (SSP245 and SSP585) for two future time periods: 2040 (2021-2060) and 2080 (2061-2100). The objective was to gain a deeper understanding of how these scenarios could influence the productivity and profitability of the farms. To establish future climatic predictions for the four sites, historical data from five GCMs were downscaled. These GCMs encompassed a range of climate conditions, from warmer and wetter

(CNRM-CM6, CCSM4) to hotter and drier (FGOALS-g2, MIROC-ESM), as part of the CMIP6 framework, under the SSP245 and SSP585 Shared Socio-economic Pathway (Frame, Lawrence, Ausseil, Reisinger, & Daigneault, 2018). The selection of the five GCMs for evaluation and inclusion in the study was based on three primary considerations: first, the skill of the models' hindcast simulations in reproducing various datasets or fields from the twentieth century; second, the quality of the 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 prediction scenarios were utilized: Mid-century (2021-2060) and Late century (2061-2100).

Results

Model Performance

The SGS model effectively captured the variability in pasture dry matter production during the 2021/2022 period, as depicted in Figure 2. The average aboveground biomass of *Cynodon Dactylone* grass measured for model calibration was 3470 kg DM ha^{-1}, while the simulated average was 3365 kg DM ha-1. Minimum measured biomass was 609 kg DM ha^{-1}, whereas minimum simulated biomass was 1,281 kg DM ha^{-1}. Maximum measured biomass reached 6,823 kg DM ha^{-1}, while the simulated maximum biomass was 8,232 kg DM ha^{-1}. The comparison between measured and modelled grass biomass demonstrated that the SGS model adequately represented the biomass, accounting for up to 90% of the variation in grass (R^2 = 0.95; $p < 0.01$), as depicted in Figure 3a. The root means square error (RMSE) calculated from the study indicated that model outputs deviated from the corresponding field-measured herbage biomass by 688 kg DM ha^{-1}.

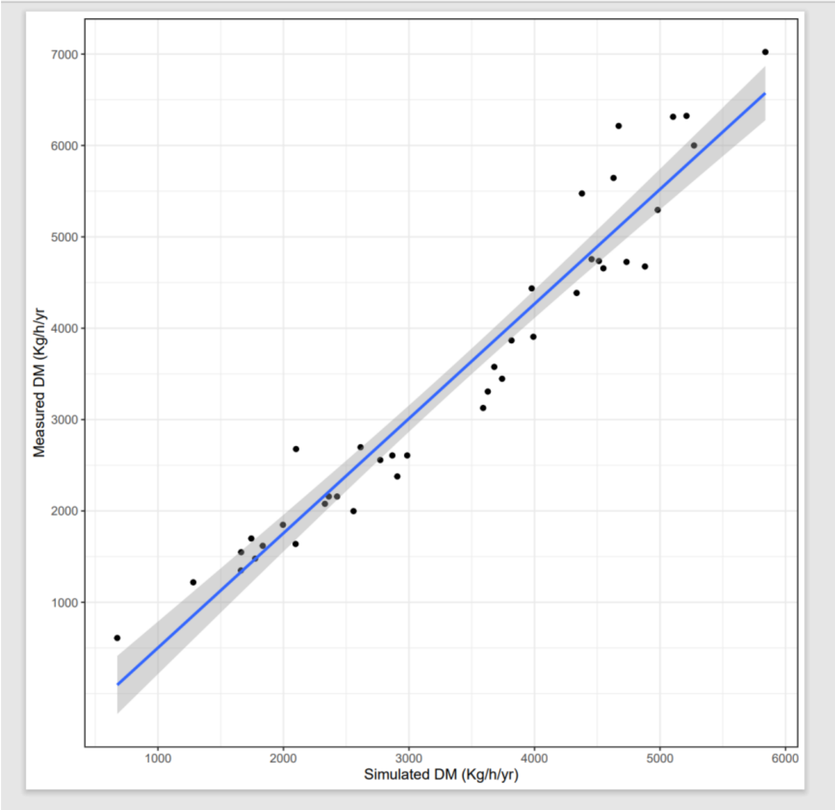


Figure 2: Comparison between simulated and observed biomass production. The observed data were obtained from two-year field data and authors calculations.

Projected Changes in Climate

The effects of climate change on pasture production for mid-century (2021-2060) and late-century (2061-2099) climate scenarios, compared to a baseline period (1981-2020) are presented in Table 2. All the farms exhibited an increasing trend in annual and seasonal rainfall (during the pasture growth period) for both study periods and under the SSP scenarios. The study revealed a significant projected increase in mean annual temperatures, ranging from 9% to 14%. Cumulative annual precipitation under future climates increased by 37-57%. Across sites, Berbera showed the highest projected increase in mean seasonal rainfall, ranging from 21% to 41% compared to the mean observed rainfall. Beer experienced a similar increase of 19% to 39%. Sheikh and Xaaxi recorded a seasonal increase in rainfall of 8% to 28% and 7% to 27%, respectively, relative to the mean historical rainfall. Figure 1 illustrates the 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, relative to the baseline period. The projections suggested increased mean maximum and minimum temperatures across all study sites under future climates.

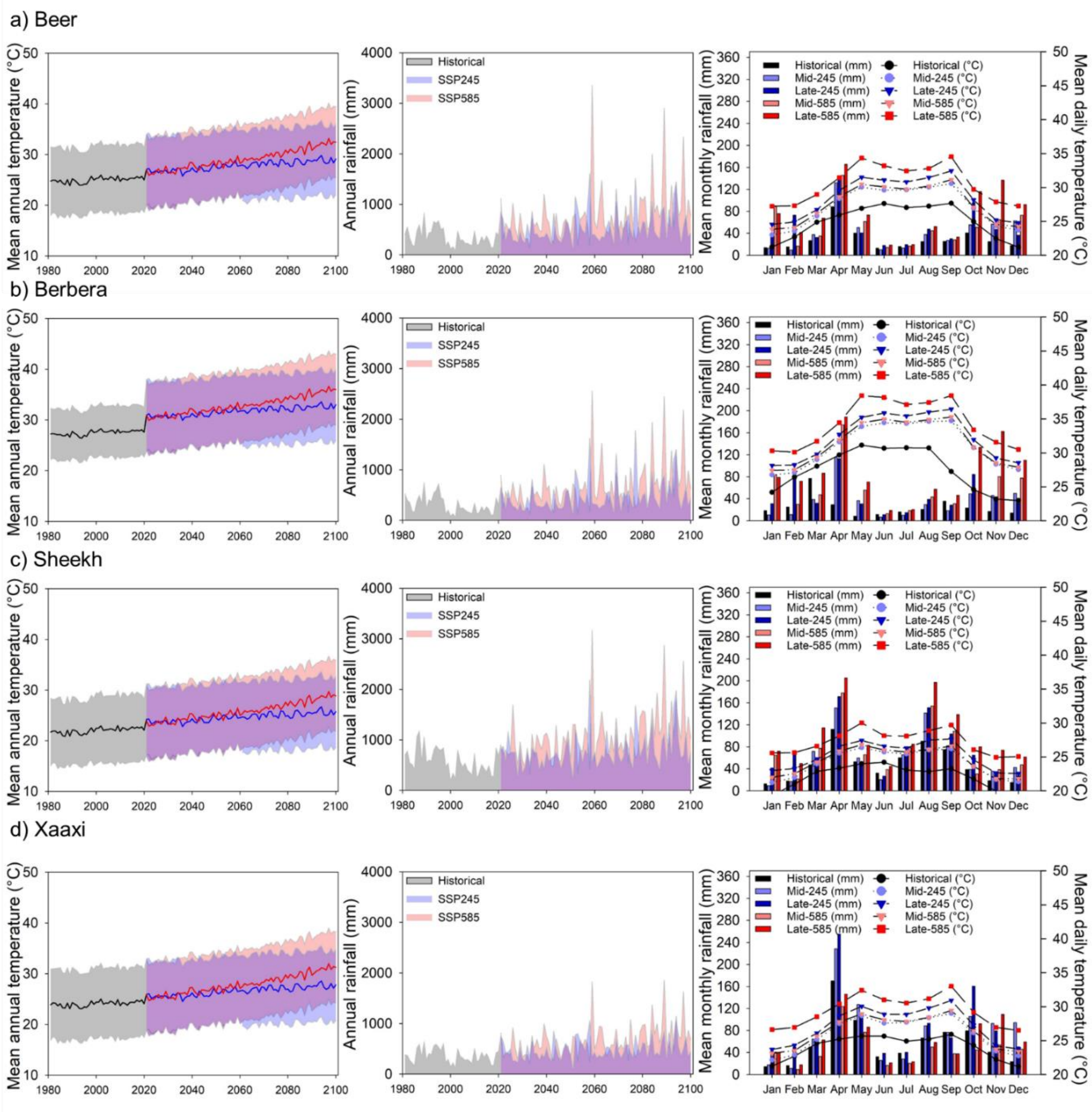


Figure 3: Historical and future monthly mean rainfall for each site and climate scenario. Statistics are expressed from computations using 40 years of climate data (avg. = average daily rainfall, st. dev. = standard deviation, and % increase).

Mean annual temperature increased by 9% to 14%. The highest increase in mean maximum temperature was in Berbera with a range of 5°C to 6.8°C from the mid-century to the 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 to 5°C for SSP245 and SSP585, respectively. Changes in maximum temperature are expected to be similar to that of the minimum temperature, with a mean change of 2.0°C and 2.0°C, respectively. All scenarios showed an increase in the number of dry days and a decrease in the number of wet days under future climates.

Table 2. Summary climate statistics for four sites (Berbera, Xaaxi, Beer and Sheekh), three climate horizons (historical, mid and late century) and two emissions scenarios (SSP245 and SSP585).

	Historical		Mid-century					Late-century				
Parameters	**Mean**	**STD**	**Mean**	**STD**	**Difference**	**% Increase**	**Seasonal**	**Mean**	**STD**	**Difference**	**% Increase**	**Seasonal**
Berbera- SSP_245												
Tmax	32	0.53	38	0.5	5.	17		39	0.5	6	21	
Tmin	22.	0.44	24	0.5	1.	7		25	0.5	2	12	
Mean Rainfall	297	172	425	273	128.	43	10	551	352	254	85	21
Avg. no. dry days	101		180					182				
Avg. no. wet days	265		185					184				
Berbera - SSP_585												
Tmax	32	0.5	38	0.8	5	18		41	1	8	27	41
Tmin	22	0.4	24	0.8	2	8		27	1	4	21	
Mean Rainfall	297	172	540	395	243	81	20	695	510	498	167	
Avg. no. dry days	101		178					187				
Avg. no. wet days	265		187					185				
Xaaxi - SSP245												
Tmax	30	0.6	32	0.6	1.	6		34	0.5	3	1	
Tmin	17	0.4	18	0.6	1	10		20	0.5	3	17	
Rainfall	354	141	480	20	126	35	8	523	188	169	47	11
Avg. no. dry days	150		164					165				

Avg. no. wet days	214		201					200				
Xaaxi - SSP_585												
Tmax	30	0.6	33	0.9	2			36	1	5	17	28
Tmin	17	0.4	19	0.9	2	12		22	1	5	30	
Mean Rainfall	354	141	554	282	200	56	14	754	332	400	112	
Avg. no. dry days	150		165					170				
Avg. no. wet days	214		199					196				
Beer_SSP245												
Tmax	31	0.6	34	0.6	2	7		35	0.6	3	12	19
Tmin	18	0.4	20	0.6	1	9		21	0.6	3	16	
Mean Rainfall	347	178	507	288	159	45	11	613	324	266	76	
Avg. no. dry days	165		195					194				
Avg. no. wet days	201		170					172				
Beer_SSP585												
Tmax	31	0.6	34	0.9		9		37	1	5	18	
Tmin	18	0.4	20	0.9	2.	11		23	1	5	28	
Mean Rainfall	34	178	640	507	293	84	21	893.	545	545	157	39
Avg. no. dry days	165		195					200				
Avg. no. wet days	201		170					165				
Sheekh_SSP245												
Tmax	28	0	31	0	2	8		32	0	3	12	12

Tmin	15	0.4	17	0.5	1	10		18	0.5	2	17	
Mean Rainfall	574	244	736	315	162	28	7	870	368	296	51	
Avg. no. dry days	207		231					235				
Avg. no. wet days	158		134					130				
Sheekh_SSP585												
Tmax	28	0.7	31	0.8	2	9		34	1	5	19	
Tmin	15	0.4	17	0.8	1	12		20	1	4	30	
Mean Rainfall	574	244	904	479	330	57	14	1207	487	633	110	27
Avg. no. dry days	208		236					235				
Avg. no. wet days	157		130					130				

Model calibration and validation

The calibrated model demonstrated good simulation of the long-term average monthly and annual pasture production across all sites, with a correlation coefficient (r) of 0.98 ($p < 0.005$) and a root mean square error (RMSE) of 728 kg DM/ha annually. Overall, the model effectively captures the trends in pasture production at each site. At Berbera, the annual average predicted production increased by 36% and 66% compared to the historical baseline of 2 t DM/ha for the mid-century and late-century climate scenarios, respectively. At Beer and Xaaxi, the simulated pasture growth rate increased by 57% and 85%, and 30% and 53% for the mid-century and late-century scenarios, respectively, relative to the historical baseline of 2 t DM/ha. In Sheikh, the predicted pasture growth rate increased by 46% and 73% for the same climate scenarios compared to the historical baseline of 4.5 t DM/ha. The highest pasture growth rate, with an 85% increase, was simulated in Beer during the late-century period. At Beer, the mean predicted annual pasture production was considerably higher than the baseline (2.99 t DM/ha) for the mid-century and late-century climate scenarios, reaching 4.5 t DM/ha and 5.4 t DM/ha, respectively. The highest mean annual pasture growth rate was simulated in Sheikh, with 6.6 t DM/ha and 7.8 t DM/ha for the mid-century and late-century periods, respectively, compared to the historical baseline of 2.99 t DM/ha. Beer also exhibited the highest percentage mean annual pasture growth rate, with 57% and 85% for the mid-century and late-century climate scenarios, respectively. The predicted mean annual and monthly dry matter (DM) production increased progressively with each future climate scenario across the sites, with higher pasture growth in spring and autumn compared to summer and winter seasons. The driest farm, Berbera, recorded the lowest summer growth rate compared to the other sites. In Beer, a similar trend was observed in the average seasonal pasture growth rate, with a significant increase in production during spring and autumn, but a decrease during summer. The simulation also indicated an increase in pasture growth rate during the winter (December to February) cold season, which is typically considered a drought period.

Table 3. Mean, coefficient of variation (CV), and percentage increase for annual and seasonal predicted pasture production (kg (DM)/ha), during the baseline years (1981–2020) for a Cynodon Dactylon pasture at Berbera, Xaaxi, Beer, and Sheikh.

MEAN ANNUAL PASTURE GROWTH RATE

Berbera				Xaaxi		
Scenarios	**PGR Kg DM/ha**	**Coefficient of Variation Kg DM/ha**	**CV %**	**PGR Kg DM/ha**	**Coefficient of Variation Kg DM/ha**	**% Increase Kg DM/ha**
Historical	2, 994			3505		
Mid-SSP245	3, 525	530	**17**	4,194	689	**20**
Late-SSP245	4, 086	1, 091	**36**	4,377	872	**25**
Mid-SSP585	4, 090	1, 09	**36**	4,589	1,084	**31**
Late-SSP585	4, 982	1, 987	**66**	5,368	1,863	**53**

Beer				Sheekh		
Scenarios	**PGR Kg DM/ha**	**Coefficient of variation**	**% Increase**	**PGR Kg DM/ha**	**Coefficient of variation**	**% Increase**
Historical	2,916			4,544		
Mid-SSP245	3,408	492	**17**	5,169	624	**14**
Late-SSP245	3,815	898	**31**	5,448	903	**20**
Mid-SSP585	4,591	1674	**57**	6,678	2,133	**47**
Late-SSP585	5,417	2501	**85**	7,863	3,318	**73**

Berbera				Xaaxi		
Scenarios	**PGR Kg DM/ha**	**Coefficient of variation**	**% Increase**	**PGR Kg DM/ha**	**Coefficient of variation**	**% Increase**
Historical	8			9.		
Mid-SSP245	9	1	**17**	11	1	**20**
Late-SSP245	11	2	**36**	12	2	**27**
Mid-SSP585	11	2	**36**	12	2	**31**
Late-SSP585	13	5	**66**	14	5	**53**

Beer				Sheekh		
Scenarios	**PGR Kg DM/ha**	**Coefficient of variation**	**% Increase**	**PGR Kg DM/ha**	**Coefficient of variation**	**% Increase**
Historical	7			12		
Mid-SSP245	9	1	**17**	15	2	**19**
Late-SSP245	10	2	**31**	16	4	**34**
Mid-SSP585	12	4	**5**	18	5	**44**
Late-SSP585	14	6	**86**	21	8	**70**

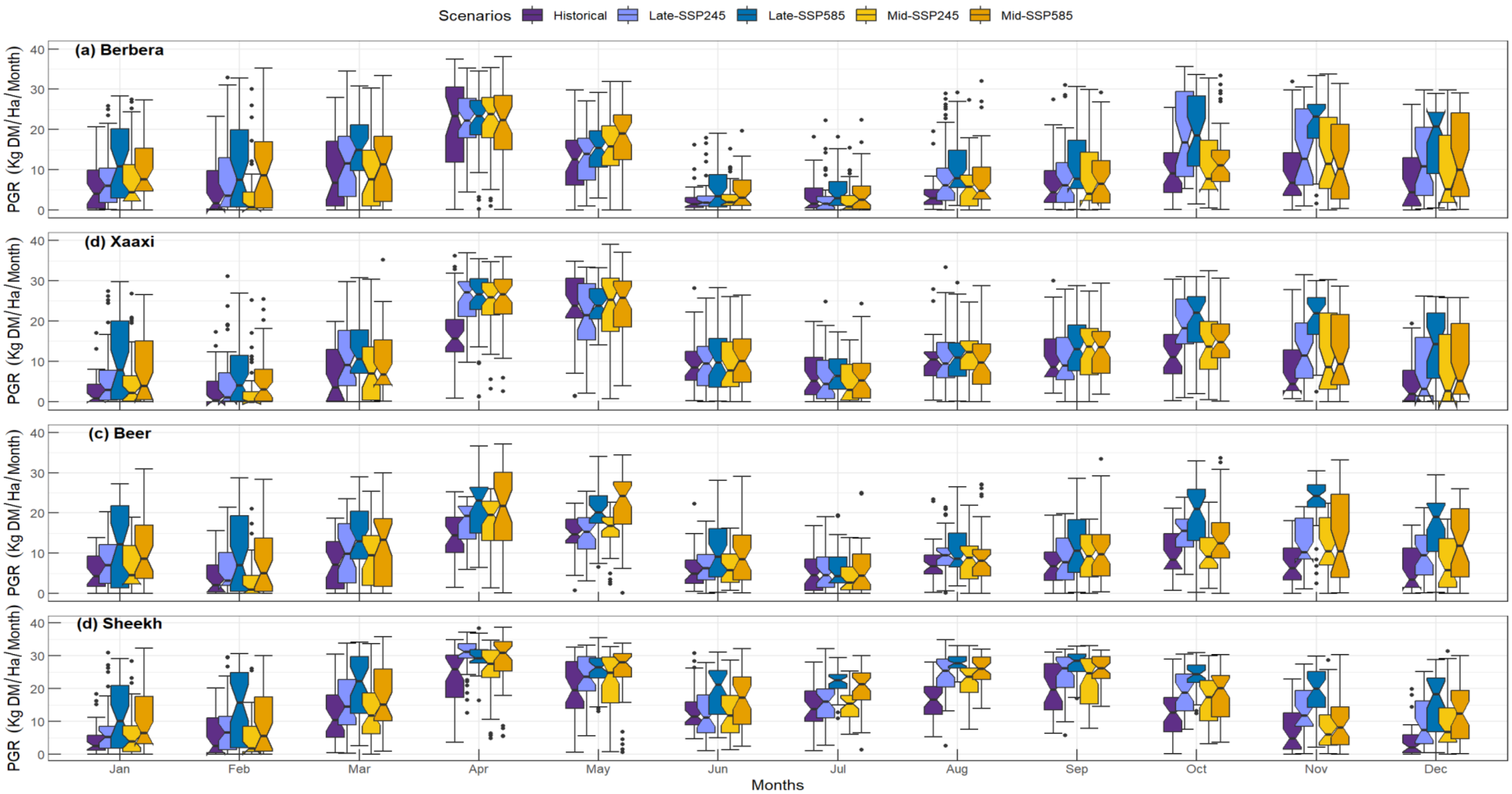


Fig. 4. Boxplots of pasture growth rates at (a) Berbera, (b) Xaaxi, (c) Beer, and (d) Sheekh. Plots show the median, 25th and 75th percentiles in the box, with the 10th and 90th percentiles in the whiskers and dots showing outlier values beyond the 5th and 95th percentiles. Each boxplot represents 40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

Seasonal rainfall variability increased under future climates, although annual precipitation was generally greater than historical climates. 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/yr) and lowest in Sheikh (325 kg/ha/yr), with Xaaxi and Beer both requiring the same amount (387 kg/ha/yr). Projections suggested a reduce 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 Sheikh, which has the highest supplementary feed requirement, the reduction in supplementary feed was between 17% and 29% in the mid-century and late-century periods, respectively, compared with the baseline period.

Supplementary feed requirements

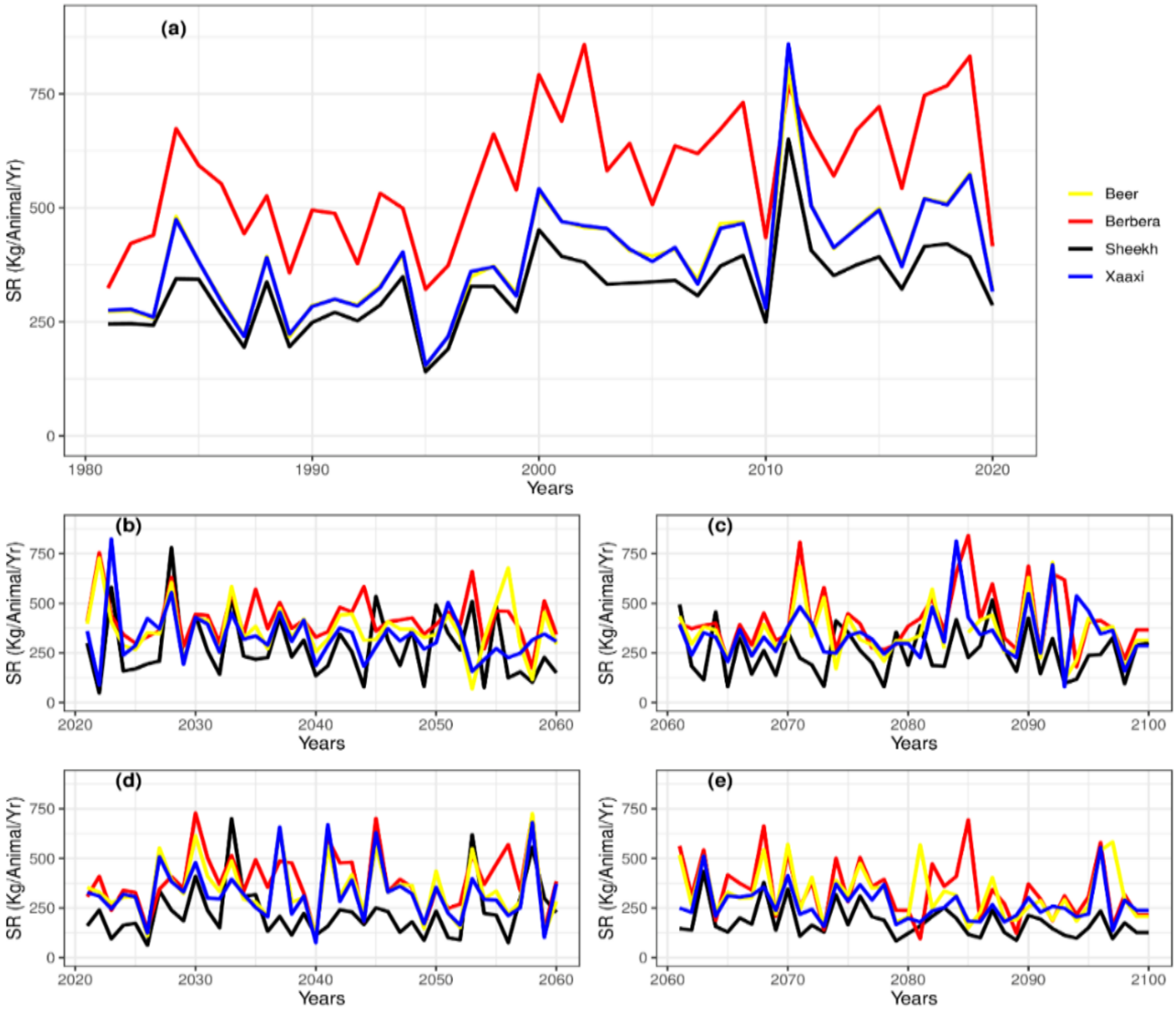
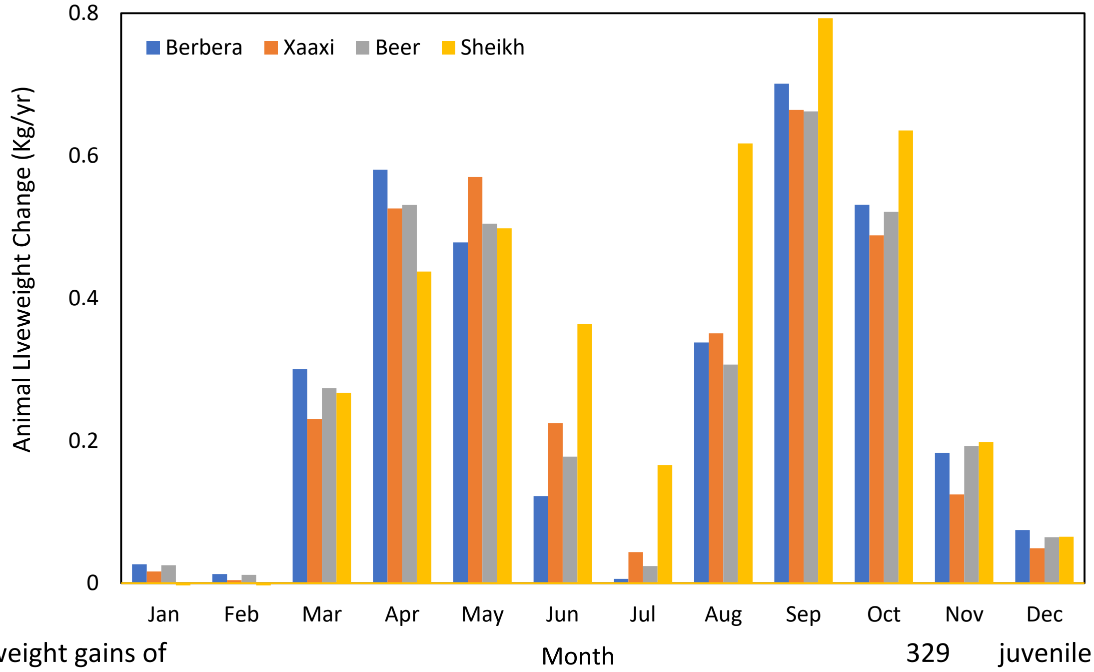


Fig. 5 Supplementary feed requirement (SR) across sites for the (a) Historical period (1981-2020), (b) mid-century (2021-2061 SSP245), (c) Late-century (2061-2100 SSP245), (d) Mid-century (2021-2061 SSP585), (e) Late-century (2061-2100 SSP585).

Animal liveweight gains

Fig 6:



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

Animal liveweight gain showed a similar trend across farms, with animals gaining the highest mean weight during autumn (1.41 kg/day) and spring (1.28 kg/day), followed by summer (0.68 kg/day), and the lowest in winter (0.076 kg/day). In January and February (winter), animals experienced significant weight loss due to the low growth and lack of pasture. Liveweight gain was highest during April, May, September, corresponding to periods of higher rainfall and increased grass growth (Figure 6). Sheikh recorded the highest liveweight gain among the locations, with a mean daily animal liveweight change of 0.33 kg/day. The other locations, Xaaxi and Beer, showed a similar mean daily animal liveweight change of 0.274 kg/day, while Berbera had a mean daily animal liveweight change of 0.279 kg/day.

Changes in productivity and profitability along rainfall gradient

Table 5 illustrates significant variation in farm profits over time. The productivity and profitability generally increased over time across emissions scenarios. Under the SSP245 scenario, farms exhibited varying levels of profit changes, from 8% in Beer to 20% in Sheikh. In contrast, Berbera showed a 4% reduction in profit. Under SSP585, all farms experienced increased profitability, ranging from 23% at Beer to 42% at Sheikh. Livestock productivity and profitability at all sites showed a direct proportional relationship with increasing annual rainfall (R^2 = 0.74).

Table 4: Mean monthly annual liveweight change for the four farms and mean monthly change across farms.

Date	Berbera	Xaaxi	Beer	Sheikh	Mean
Jan	0.02	0.01	0.02	-0.00	0.01
Feb	0.01	0.00	0.01	-0.03	-0.00
Mar	0.30	0.23	0.27	0.26	0.26
Apr	0.58	0.52	0.53	0.43	0.51
May	0.47	0.57	0.50	0.49	0.51
Jun	0.12	0.22	0.17	0.36	0.22
Jul	0.00	0.04	0.02	0.16	0.06
Aug	0.33	0.35	0.30	0.61	0.40
Sep	0.70	0.66	0.66	0.79	0.70
Oct	0.53	0.48	0.52	0.63	0.54
Nov	0.18	0.12	0.19	0.19	0.17
Dec	0.07	0.04	0.06	0.06	0.06
Mean	0.27	0.27	0.27	0.32	0.28

Seasonal rainfall variability increased under future climates, although annual precipitation was generally greater than historical climates. Monthly pasture growth variability generally increased; there were greater differences between future projections and each baseline than between emissions scenarios SSP245 and SSP585. Profits under future climates generally increased in line with reduced supplementary feed requirements and increased pasture growth availability. Under SSP585, inter-annual variability in profit diminished.

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Table 5: Historical, mid (2040) and late (2080) century impacts of climate change on profitability of Somalian livestock farms at Berbera, Xaaxi, beer and Sheikh under low and high greenhouse gas emissions scenarios.

	Low emissions scenario (SSP245)				High emissions scenario (SSP585)			
Berbera	**Mean Margin USD**	**STD**	**Difference USD**	**% change**	**Mean Margin USD**	**STD**	**Difference USD**	**% change**
Historical	2,187	1,228		0	2,187	1,228		0
Mid-century	2,124	970	1,323		2,386	1,293	USD 243	
Late century	2,186	1,350	61	-4%	2,825	1,274	USD 438	29%
Xaaxi				0	**Mean Margin USD**	**STD**	**Difference USD**	
Historical	2,412	1,087			2,412	1,087		0
Mid-century	2,894	1,067	USD 241		2,934	1,244	USD 291	
Late-century	2,769	1,168	-USD 124	15%	3,402	775	USD 468	41%
Beer					**Mean Margin USD**	**STD**	**Difference USD**	
Historical	2,414	1,049		0	2,414	1,049		0
Mid-century	2,540	1,113	-USD 19		2,765	1,272	USD 203	
Late-century	2,608	1,363	USD 67	8%	2,985	1,104	USD 219	23%
Sheikh					**Mean Margin USD**	**STD**	**Difference USD**	
Historical	2,945	763		0	2,945	763		0
Mid-century	3,246	1,491	USD 172		3,764	1,194	USD 301	
Late-century	3,558	1,037	USD 311	20%	4,188	698	USD 424	42%

Discussion

The SGS model accurately simulated the variation in pasture dry matter production during the 2021/2022 period (Fig 2). The annual mean grass aboveground biomass, as measured in all plots on farm, was 3,470 kg DM/ha, while the modelled mean was 3,365 kg DM/ha. The relationship between the measured and modelled grass indicated that the SGS model reasonably represented grassland biomass, accounting for up to 90% of the variation. Similar levels of agreement have been observed in simulation studies conducted in other tropical and temperate regions (Svinurai et al., 2021). Using SGS (Muleke et al., 2022) observed an R^2 of 0.58 in fertilised perennial grasses in subtropical region of south-eastern Queensland, whereas (Cobon et al., 2020a) obtained an R^2 of 0.6 in native perennial and annual grasses in tropical region of northern Australia. The expected effect of future climate scenarios on pasture production on four different farms systems across North-western Somalia was determined by modelling how existing well adapted pasture at each site responded to projected increases in temperature, and changes in rainfall pattern. This is the first comprehensive analysis undertaken for a range of sites and pasture types in this region.

The results demonstrate the projected impacts of climate change on pasture production in different locations across three time periods: baseline (1981-2020), mid-century (2021-2060), and late-century (2061-2099), considering two shared socio-economic pathways (SSP245 and SSP585). Depending on the amount and frequency of rainfall, the effects on pasture production can vary, either positively or negatively.The study findings indicate that all locations are expected to experience an increase in annual and seasonal rainfall during both study periods and climate scenarios compared to the baseline period. This increase in rainfall is projected to enhance pasture productivity and growth, ultimately improving the overall grazing capacity of the land. A study from (Brown et al., 2017) in Ethiopia found that increased rainfall had postive impact on pasture productivity, with a significant increase in aboveground biomass in areas with higher rainfall. However, previous studies have shown that excessive rainfall resulted in a decrease in pasture production and quality (Romera et al., 2010), leading to a derease in livestock productivity. Pasture productivity was not related with dry seasons (winter and summer); however, it was related with major rainy seasons (spring and autumn) (Fig. 6). Numerous research studies have established a significant connection between rainfall and productivity in regions with low rainfall (Society, 2021).

In terms of temperature, the projections consistently indicate an increase in mean maximum and minimum temperature across all study sites in both SSP scenarios and study periods. The results show that the magnitude of the Tmax projection is slightly higher than that of the Tmin projection, with a mean change of 2.0°C and 2.1°C, respectively. Specifically, the projected increase in maximum temperature in Sheekh and Berbera is slightly higher than that of the minimum temperature. These two sites, being more urban areas, align with previous studies such as (Oke, 1982), which suggest that urban areas tend to experience higher temperatures than rural areas due to the urban heat island effect caused by the absorption and re-radiation of heat by buildings (Arnfield, 2003)

The results indicate that a 10% increase in annual rainfall and a 1.7°C temperature increase lead to a 17% increase in pasture growth. However, in a study conducted by (Zhang et al., 2022). In temperate regions, a smaller 7% increase in pasture growth was observed for a 10% increase in annual rainfall and a 1°C temperature increase. On the other hand, a larger increase in annual rainfall by 40% and a higher temperature increase of 3.6°C led to a substantial 79% increase in pasture growth, suggesting that both rainfall and temperature play crucial roles in predicting pasture growth, and that greater increases in these factors can significantly impact pasture growth. The findings of the second study by (Zhang et al., 2022) are consistent with the notion that both rainfall and temperature are important factors in pasture growth, and larger increases in these factors can lead to larger increases in pasture growth. In the current study, it was found that for a 1% increase in rainfall and 1°C increase in temperature, there was a relative 1.41% increase in pasture growth. In contrast, the study conducted by (Zhang et al., 2022) showed that for a 1% increase in rainfall and 1°C increase in temperature, there was a smaller relative 0.58% increase in pasture growth. It is evident that the first study reported a significantly higher relative increase in pasture growth per unit of increase in rainfall and temperature. This suggests that the influence of rainfall and temperature on pasture growth may be more pronounced when there are greater temperature increases. However, it is important to note that the two studies were conducted in different contexts, with one focusing on temperate conditions and the other on tropical conditions. This difference in climate conditions is presumed to be a major contributing factor. The "warm-wet" climate in the tropical context is therefore advantageous for achieving higher pasture productivity.

The projections for various emissions scenarios, including both SSP245 and SSP585, indicate a consistent trend of increasing mean maximum and minimum temperatures across all study sites. However, the magnitude of this temperature increase is expected to be higher under the SSP585 scenario compared to the SSP245 scenario.Specifically, the Berbera location is projected to experience the highest increase in mean maximum temperature, with an increase of 5-6.8°C from mid to late century under both emissions scenarios. Similarly, the Xaaxi location is projected to have the highest increase in mean minimum temperature, with an increase of 1.3-2.5°C from mid to late century under both scenarios. These temperature projections have significant implications for fodder production, as changes in temperature and rainfall patterns can affect it. The anticipated increase in temperature, especially under the SSP585 scenario, may have a negative impact on the growth and quality of fodder crops, leading to potential challenges in feed availability for livestock. Consequently, this could affect the livelihoods of pastoralists and other farmers who depend on livestock for their income.

However, based on the climate prediction models, it can be concluded that the influence of temperature change is greater than that of rainfall on pasture productivity. These findings suggest that climate change will have significant impacts on pasture production in various locations, resulting in changes in temperature and rainfall patterns. While the projected increases in rainfall may potentially lead to increased pasture production, the rising temperatures could offset these gains. These results emphasize the importance of implementing adaptation strategies to mitigate the negative impacts of climate change on pasture productivity.

A model must be able to assist in achieving a specific goal to be considered useful. The objective of the SGS model was to provide a description of pasture production on beef farms, considering variations in production between different farms and seasonal fluctuations caused by climate change. The model closely simulated annual pasture production, with measurements at the site averaging 3400 kg DM/ha and the model simulating an average of 3396 kg DM/ha over a 40-year baseline period. However, the model does not perfectly capture seasonal production, as indicated by the root mean square error (RMSE) of 688.5. Some of the variability and errors in the model could be attributed to downscaled and bias-corrected climate data, while the remaining discrepancies may be due to model errors. Nevertheless, the SGS model aligns 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. Therefore, the availability of rainfall emerges as a significant factor driving net biomass production in Somalia.

The magnitude of the predicted biomass production response simulated was dependent on site and climate scenarios, with the largest annual increases generally occurring in Sheekh and Beer and largest seasonal increase during spring and autumn. These modelled production increases are consistent with comparable results from Tropical areas in Australia where average rainfall availability is similar. A similar study from (Pembleton, Cullen, Rawnsley, & Ramilan, 2021) modelled two subtropical areas with mean annual pasture production increase. This increase was associated with the heat tolerance of C4 grasses and the change of annual rainfall pattern that occurred in all climate scenarios and time. However, the same study modelled the seasonal pasture growth rate of two cool temperature regions in higher pasture growth rate in winter and early spring. At both sites of Sheekh and Beer, the elevated increase of net herbage accumulation and growth rate are associated with

Xaaxi and Berbera with increased rainfall availability and decreased temperature. The study also revealed that livestock farms in areas with higher rainfall tend to have higher animal productivity and liveweight change than farms with lower rainfall. This is due to better feed availability, while farms with Berbera region may need to invest more in supplementary feed and water sources to maintain productivity.

Concluding remarks

Over the past thirty years, livestock and dairy production that relies on forage has been the primary source of livelihood in Somalia. This agricultural sector has held great economic and cultural importance but has recently faced significant deterioration due to the impacts of climate change. The study aimed to test the performance of SGS on tropical pasture simulations, assessing the impact of climate change on pasture productivity and profitability, and to determine how productivity and profitability of livestock farms altered across a rainfall gradient. It was found that SGS model simulated tropical perennial grass biomass reasonably well. We found that both mean temperature and rainfall for this region will increase during the mid and late century, reducing need for livestock supplementary feed and increasing farm profit. Specifically, the projected increase in rainfall and cooler temperatures during rainy seasons is anticipated to result in higher pasture productivity and greater profitability for livestock farms in the future. Despite these optimistic futures, we also showed that climatic variability under future climates will increase, necessitating adaptive capacity to seasonal climate variation.

Data Availability Statement:

The data for this study comprises two main components: The model which plays a central role in this study created by (Johnson et al., 2003). The model can be accessed using the following link: https://www.dropbox.com/s/uy4gfne0qpmds5y/SGSinstall_5.3.8.msi?dl=0 using this installation key: F1YY-854Y-JHYY-L2HI.

In addition to the model, we have collected primary and secondary data for this study. Currently, we are actively engaged in discussions to determine the most suitable repository for archiving this data. The process of selecting the repository is currently underway, and we expect to finalize this step soon. Our primary goal is to ensure that the chosen repository adheres to the FAIR Data guidelines and offers a robust and sustainable platform for long-term data access. We are evaluating the suitability of the Centre for Environmental Data Analysis (CEDA) and the NASA Socioeconomic Data and Applications Center (SEDAC) among others. In the interim, to facilitate the peer-review process, we have temporarily uploaded a copy of our data as supporting information to the following drop box link: https://www.dropbox.com/home/Hussein%20et%20al.%2C%202023%20%20Paper%20to%20Earth's%20Future#:~:text=https%3A//www.dropbox.com/scl/fi/iikd9wlnqkpp1385cwqjy/Animal_liveweight_change_output_data.rar%3Frlkey%3D73bgcrn0etqoxao3t6me2tzfj%26dl%3D0

Acknowledgements

Jaabir Hussein would like to express gratitude to the International Livestock Research Institute and the University of Nairobi for their collaboration on this paper. Many thanks also go to the Institute of Agriculture at the University of Tasmania for their support in the conceptualization, data analysis of the paper and throughout the final write-up process.

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