Agricultural Systems 229 (2025) 104431

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Research Paper

Assessing extensive pasture-based beef production in South Africa under future climate change conditions

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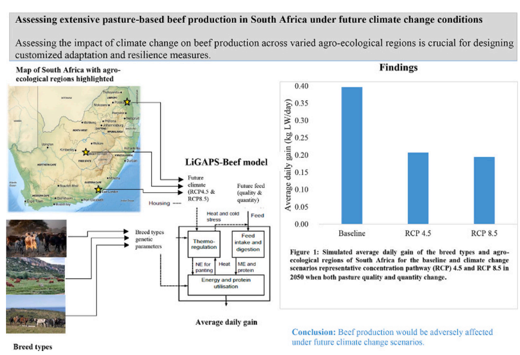
HIGHLIGHTS

- Quantifying climate change impact on beef production is vital for coping measures.
- Beef cattle growth was simulated under RCP 4.5 and RCP 8.5 in South Africa.
- 2050 simulated growth declined by 48 % in RCP 4.5 and 51 % in RCP 8.5 from baseline.
- Growth of *Bos taurus* was most adversely affected, but Sanga was the most resilient.
- Location-specific intervention is vital to sustain beef production in South Africa.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Paul Crosson

Keywords:
Average daily gain
Cattle
Representative concentration pathway
Simulation

ABSTRACT

CONTEXT: Assessing the impact of climate change on extensive pasture-based beef production across varied agro-ecological regions is crucial for designing customized adaptation measures.
OBJECTIVE: This study assesses the effects of climate change on extensive pasture-based beef production systems in three South African agro-ecological regions (Bloemfontein, Phalaborwa and Buffalo Berlin) under two climate change scenarios, namely the representative concentration pathways (RCPs) 4.5 and 8.5.
METHODS: The LiGAPS-Beef model, previously calibrated for the region, was used to evaluate the impact of climate change on beef cattle production under pasture-based extensive systems. Four breed types, namely *Bos taurus*, Composite, *Zebu indicine* and Sanga cattle were included in this study. Genetic parameters for each breed were obtained from SA Stud Book, Livestock Registering Federation (LRF) and literature. Measured historical weather data was obtained from the South African Weather Service for the three agro-ecological regions. An ensemble of eight regional climate model (RCA4) simulations from the CORDEX Africa initiative was used to generate future climate change projection data for the period 2036–2065 under RCP 4.5 and RCP 8.5 scenarios.

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https://doi.org/10.1016/j.agsy.2025.104431
Received 4 March 2024; Received in revised form 5 May 2025; Accepted 15 June 2025
Available online 20 June 2025

The future nutritional composition data for forage was collected from studies that simulated and predicted future forage quality under climate change conditions.
RESULTS AND CONCLUSION: The study found that the baseline average daily gain (ADG) was significantly higher (0.40 kg/head/day) than the simulated RCP 4.5 (0.21 kg/head/day, −48 %) and RCP 8.5 (0.20 kg/head/day, −51 %) ADGs regardless of breed type when both feed quality and feed quantity limited growth. Although the effect of the climate change scenarios on beef production was agro-ecological region dependent, the performance of *Bos taurus* declined more than other breeds under future climate scenarios while the Sanga and the Composite types were the most resilient, especially in hot climate areas. Model simulations predict that future climate change will have a greater negative impact on cattle in Buffalo Berlin and Phalaborwa, while those in Bloemfontein will be least affected. The study also highlights that under future climate change scenarios, pasture quality will be the key factor influencing cattle growth in Bloemfontein and Buffalo Berlin, while pasture quantity will be the dominant factor in Phalaborwa if stocking rates remain unchanged. The study highlights the need for nutritional and pasture management interventions for pasture-based extensive system (e.g., feed supplementation, adjusting the stocking rate to match pasture availability, identifying and integrating drought and/or heat tolerant ecotypes, fodder trees that provide shade for the animals) to mitigate the expected decline in beef cattle performance in South African agro-ecological regions.
SIGNIFICANCE: Quantifying the impact of anticipated climate change on pasture-based extensive beef production and identifying specific factors that limit beef production per breed type in the different agro-ecological regions is crucial for assessing the potential ramifications on beef production. This information empowers farmers and policy makers to develop targeted mitigation and adaptation strategies that promote resilience of the beef production system in the respective regions.

1. Introduction

The adverse effects of climate change on livestock production are projected to increase largely due to the progressive increase in global warming and changes in precipitation patterns which will in turn shift disease and parasite dynamics, and alter feed quality and availability among other factors (Angel et al., 2018). The projected global changes in both precipitation patterns and temperature (Rebecca et al., 2018) are likely to be the major drivers of these negative effects. Over the past five decades, average annual temperatures in South Africa have increased by at least 1.5 times the global mean of 0.65 °C (Ziervogel et al., 2014). It is projected that by 2050, South Africa's temperature will have risen by about 1.5 to 2 times the global rate (Engelbrecht, 2019). Specifically, temperature is projected to increase by 1 °C to 2.5 °C from the past six decades to 2050 along coastal areas and may exceed an increase of 3 °C in the interior regions (Ziervogel et al., 2014; Engelbrecht, 2019).

Direct negative effects of climate change on livestock production are mainly related to heat stress while indirect effects are related to reduced forage quantity and quality as well as increased disease prevalence among others (Angel et al., 2018). Heat stress is a direct result of increased temperature and relative humidity as well as an increased frequency and intensity of heat waves (Bernabucci, 2019). This affects animal production through a reduced feed intake and reduced animal health and welfare. Heat stress affects livestock health through metabolic disruptions, immune suppression and oxidative stress, resulting in increased vulnerability to infections and higher mortality rates (Lacetera, 2019).

South Africa is diverse in terms of climatic conditions, geology and topography, giving rise to a range of agro-ecological regions or vegetation zones (Department of Environmental Affairs, 2015). With climate change, the species composition and nutritive values of forage species in these different climatic regions will change, mainly due to the influence of a combination of climatic factors which include temperature and rainfall (Hatier et al., 2014). In relatively good rainfall areas, sustained high temperatures are expected to speed up plant growth and maturity, which in turn results in lower forage quality if not used at the right stage due to a higher rate of cell wall lignification, lower crude protein content, and lower digestibility and metabolisable energy content of a mature forage (Marais, 2005; Küchenmeister et al., 2013). Long summer days also reduce the grass leaf to stem ratio by increasing the number of stems per plant, the diameter of the stem, and internode length (Liebig et al., 2014).

Temporal and spatial variations in the composition of grassland species and/or forage quality thus occur due to changes in climatic factors such as temperature, precipitation or interactions of these two factors (Evans et al., 2011). In temperate regions of Southern Africa for instance, climate change may result in the deterioration of pasture towards inferior quality due to a shift in species composition from C3 grass species to subtropical C4 grasses as a result of less frost and higher temperatures (Rust and Rust, 2013). On the other hand, forage quality and production may increase due to the increase in carbon dioxide levels (Campbell et al., 1996; Reilly et al., 1996; Dumont et al., 2014). The complex interaction between plant species, carbon dioxide levels, temperature and rainfall among other factors renders different biomes to respond differently to the projected climate change scenarios, which in turn affects forage availability and quality. Thus, future extensive beef cattle production systems are likely to be affected through altered forage quantity and quality.

Therefore, projections for pasture-based livestock production under future climate change scenarios should account for the effects of climate change on grass and animals simultaneously. The magnitude and direction of the response to future climate change scenarios can be captured for different ecological regions by using suitable climate and biophysical models validated for specific regions in South Africa. In this regard, mechanistic models such as Livestock Simulator (LIVSIM) and Livestock Simulator for Generic analysis of Animal Production Systems - Beef cattle (LiGAPS-Beef) have been successfully validated and used to simulate related effects of climate change on livestock production in Africa and Europe respectively (Rufino et al., 2009; Descheemaeker et al., 2018; Van der Linden et al., 2019a). Projections for pasture-based beef production under climate change however can be explicitly done by a mechanistic model such as LiGAPS-Beef which simultaneously includes the effect of diet, climate, and genetics on cattle growth (Van der Linden et al., 2016).

Since the magnitude of the effect of future climate change is determined by the levels of implementation of strategies to mitigate greenhouse gas emissions, evaluation of future livestock production can be more meaningful if it is carried out under different representative concentration pathways (RCPs). Modelling the future effects of climate change on extensive beef cattle production systems in South African ecological regions will provide insights on the magnitude of these effects on beef production per specific region and the biophysical factors that limit beef cattle growth, which are currently largely unknown. The objective of this study was to assess the effects of climate change on the average daily gain (ADG) of four beef cattle breed types in extensive pasture-based beef production systems (under when only forage quality limits growth and under when both forage quality and quantity limit cattle growth) in South Africa under two future climate scenarios, namely the RCP 4.5 and RCP 8.5 using the LiGAPS-Beef model.

2. Materials and methods

2.1. Study areas

The impact of climate change on beef production in the provinces Free State (Bloemfontein), Limpopo (Phalaborwa) and Eastern Cape (Buffalo) Berlin for grass-fed beef cattle under continuous grazing was investigated. These locations were chosen as representatives of three agro-ecological regions in South Africa (semi-arid, semi-desert, and temperate oceanic) across three provinces (Free State, Limpopo and Eastern Cape). The climatic characteristics of each region are described by Magona et al. (2023).

2.2. LiGAPS-Beef

LiGAPS-Beef, an R-based mechanistic model (R version 2.15.3; R Core Team, 2013) was used to simulate beef production of four beef breed types in the three agro-ecological regions. The model has been used to evaluate beef production in Europe, Australia and Uruguay (Van der Linden et al., 2019b) and has been calibrated and validated under South African conditions by Magona et al. (2023). The model considers 89 generic parameters for cattle, 22 breed-specific parameters, 24 diet or feed composition parameters, and daily weather data as input to generate outputs such as ADG, beef production (boneless meat), feed intake, feed efficiency (FE), total body weight (TBW), and the bio-physical factors that define and limit growth (Van der Linden et al., 2019a). The model considers genotype and climate (heat and cold stress) as defining factors and feed quality and available feed quantity as limiting factors for beef cattle growth. The inputs to the model and outputs are detailed in Van der Linden et al. (2019a) and Magona et al. (2023). When energy and protein supply are sufficient to support all metabolic processes of an animal, the genotype defines growth in the model. The climate defines growth via heat stress when the maximum capacity to release heat is reached and feed intake has to be reduced. The climate defines growth via cold stress when heat release is at a minimum and feed intake has to increase. Feed quality limitations occur when the animal's digestive tract's maximum capacity for feed digestion is reached, resulting in insufficient energy or protein supply to support growth. Feed quantity limitations occur when feed availability limits intake, resulting in energy or protein deficiency (Van der Linden et al., 2019a).

2.3. Data collection

2.3.1. Genetic parameters

Beef cattle breeds included in this study were classified into four breed types, namely exotic (*Bos taurus*), indigenous/Sanga (African taurine), *Bos indicus* (Zebu), and Composite, as proposed by Makina et al. (2016). European breeds such as Hereford, Simmentaler, and Charolais belong to the *Bos taurus* group while the African indigenous breeds such as Nguni and Tuli belong to the Sanga group, and the Boran and Brahman are part of the Zebu group. Composite breeds, such as the Bonsmara, are a combination of at least two breeds (e.g., *Bos taurus* × Sanga), designed to maintain heterosis in future generations. The study included male animals of the four beef cattle breed types to provide a comprehensive representation of all breed groups and frame sizes prevalent in South African beef production. Genetic parameters for the *Bos taurus*, Composite, and Sanga breed types were obtained from literature and SA Stud Book. The genetic parameters for the *Zebu indicine* type were obtained from literature and the Livestock Registering Federation (LRF). The genetic parameters included Gompertz curve parameters such as maximum bodyweight, and birth weight as well as carcass percentage and coat characteristics such as hair length (Supplementary material S1).

2.3.2. Weather data

Historical measured daily weather data (temperature, rainfall, wind speed, vapour pressure and solar radiation) for the three locations, Bloemfontein, Phalaborwa, and Buffalo Berlin, from 2008 to 2020 was sourced from the South African Weather Service. This data was used to simulate beef production in the baseline. Table 1 summarises the climatic characteristics of the three agro-ecological regions included in the study whilst Fig. 1 shows key baseline mean daily weather data inputs for study areas across months for the regions.

2.3.3. Future climatic scenarios

Representative concentration pathways are trajectories of greenhouse gas concentrations used for climate modelling in the IPCC Fifth Assessment Report (Stocker et al., 2013). The RCP 2.6 pathway is a very stringent and optimistic pathway which assumes maximum adoption of greenhouse gas emission reduction strategies envisaging a decline of carbon dioxide emissions to zero by 2100 (Meinshausen et al., 2011; Stocker et al., 2013) to keep global mean temperature increase below 2 °C, but it was considered unrealistic and not included in analyses. RCP 4.5 is a stabilization pathway with radiative forcing at 4.5 W/m^2 by 2100 through policies limiting emissions, while RCP 8.5 represents an unconstrained pathway with significantly increasing emissions and a radiative forcing of 8.5 W/m^2 by 2100 (Meinshausen et al., 2011; Stocker et al., 2013; Davis-Reddy and Vincent, 2017).

Climate change projections were analysed using data from eight Global Climate Models (GCMs): CanESM2m, CNRM-CM5, CSIRO-Mk3, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, NorESMI-M, GFDL-ESM2M (Giorgi and Gutowski, 2015). The spatial resolution of the GCMs grid squares is coarse, especially for generating climate change projections at a sub-provincial scale. To overcome the spatial scale limitations of the GCM fields, dynamically downscaled simulations over the African domain to a grid spatial resolution of (0.44° × 0.44°) were conducted using the Coordinated Regional Downscaling Experiment (CORDEX). The Rossby Centre regional model (RCA4), forced by the GCMs models of the 5th phase of the Coupled Model Inter-comparison Project (CMIP5) (Taylor et al., 2012), was utilised. The RCA4 is a coupled ocean-atmosphere regional climate model based on the numerical weather prediction model HARLAM (Undén et al., 2002). Eight ensemble member projections were calculated to reduce uncertainty and bias from individual ensemble member projections, and are referred to as "ensemble means".

Projected changes were expressed relative to the historical or baseline reference 30-year period of 1976 to 2005. The CORDEX-Africa model simulations under RCP 4.5 and RCP 8.5 scenarios were used for the climate change projections. Daily simulated values of rainfall totals and temperature averages were used to generate projections of annual

Table 1
Climatic and forage characteristics of Bloemfontein, Phalaborwa and Buffalo Berlin.

Location	Average weather values	Dominant forage grass species
Bloemfontein	Tropical and subtropical steppe (semi-arid) climate at an altitude of 1227 m; and average annual rainfall of 549 mm	*Digitaria eriantha, Themeda triandra, Cymbopogon citratus* and *Eragrostis curvula*
Phalaborwa	Hot semi-arid subtropical (hot semi-desert) climate at an altitude of 410 m; and average annual rainfall of 520 mm	*Eragrostis rigidior, Digitaria eriantha, Panicum maximum* and *Urochloa mozambicensis*
Buffalo Berlin	Temperate oceanic climate at an altitude of 391 m; and average annual rainfall of 650 mm	*Panicum maximum, Digitaria eriantha, Themeda triandra, Eragrostis curvula, Penisetum clandestinum* and *Cynodon dactylon*

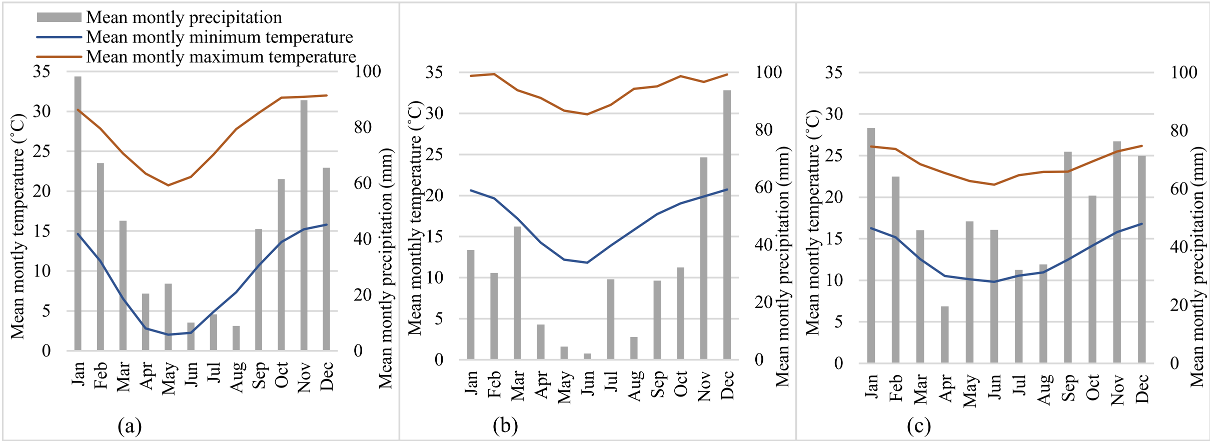

Fig. 1. Observed mean monthly maximum and minimum temperatures and precipitation (2008–2020) for Bloemfontein (a), Phalaborwa (b) and Buffalo Berlin (c).

changes. Future projections of rainfall and near-surface temperature are presented for the period extending from 2036 to 2065. Table 2 shows the expected changes in temperature and rainfall between the baseline reference climate and 2050 (midpoint 2036 to 2065) in each agro-ecological region under the RCP 4.5 and RCP 8.5 scenarios.

Climate change projections are based on likely future scenarios and are thus linked to uncertainties. It is understood that combining results from multiple climate models through ensemble averaging may provide a more accurate representation of reality compared to using a single model (Giorgi and Mearns, 2002). Rainfall patterns are reported to show more uncertainty than projected changes in temperature in South Africa (Van Niekerk et al., 2019). In order to gain more insights on the wide uncertainty range of projections for each RCP scenario, values are presented for the 10th, 50th (median), and 90th percentiles of the ensemble of model projections.

2.3.4. Feed quality and quantity

Nutrition data was gathered for different agro-ecological regions under scenarios where feed quality and quantity were limiting cattle growth. The details of the baseline diet including the dominant grass species for each agro-ecological region (Table 1) are fully described by Magona et al. (2023). To simulate the baseline, the ME and CP content of the total cattle diet for each agro-ecological region were calculated as the weighted average (DM basis) of the ME and CP contents of the individual plant species. Other nutritional parameters such as fill units, heat increment of feeding and soluble non-structural carbohydrates were calculated using empirical equations based on ME or digestibility and CP (Van der Linden et al., 2019a).

For the climate change scenario simulations, projected average forage quality (nutritional composition) and feed quantity were derived from literature, primarily from field experiments and meta-analyses that simulated and predicted future forage quality and quantity changes under climate change conditions in the studied agro-ecological regions or similar ones (Table S2). Projected changes in herbaceous net primary productivity (HNPP) for each agro-ecological region were used as proxies to estimate future feed quantity changes. Literature reviews provided the average future percentage change in HNPP for each agro-ecological region, serving as a basis for diet quantity adjustments in the simulations. Where specific projected data for the studied agro-ecological region were unavailable, such as for Buffalo Berlin under RCP 8.5, data from similar agro-ecological regions elsewhere were used (Table S2).

A comprehensive database of parameters was compiled by gathering information from peer-reviewed journal articles that examined feed quality and quantity under various warming or future climate change scenarios across different biomes. The studies included in the meta-analysis were carefully selected based on their grouping of data and results according to ecological region and vegetation type. Articles were included in the database if their nutritive measurements pertained to specific tropical or temperate pastures cultivated under experimental or field conditions within a defined agro-ecological region (Supplementary material S2). Studies that did not specify climatic scenarios or involved climatic variable manipulation were excluded. Data from each article were extracted from text or tables, and when unavailable in these formats, information was obtained from figures. The average values from at least three studies per agro-ecological region were used to adjust the baseline nutrition parameters (feed quality and quantity) for the corresponding region in this study. The baseline and future diet ME and CP across the three ecological regions are shown in Table 3.

2.4. Model settings, simulations and data analysis

Simulations of ADG in male beef cattle (7 months at the start of simulations and 8 months at the end of simulations and for a period

Table 2
Projected changes in annual mean temperature (°C) and changes in total annual rainfall (mm per year and %) under RCP 4.5 and RCP 8.5 for Bloemfontein, Phalaborwa and Buffalo Berlin for 2050, relative to the baseline reference period (1976–2005).

Location	Bloemfontein			Phalaborwa			Buffalo Berlin		
Percentile	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**
RCP4.5									
Temperature increase (°C)	1.12	1.77	2.15	1.47	1.88	2.35	0.99	1.29	1.74
Rainfall change (mm year^{-1})	−99	13	131	−207	−71	52	−135	−67	65
Rainfall change (%)	−14.3	1.9	18.8	−36.1	−12.3	9.0	−26.9	−13.3	12.9
RCP8.5									
Temperature increase (°C)	1.21	1.80	2.56	1.57	2.03	2.49	1.00	1.52	1.89
Rainfall change (mm year^{-1})	−109	−6	179	−210	−34	65	−126	−59	51
Rainfall change (%)	−15.7	−1.0	25.8	−36.6	−5.8	11.4	−25.0	−11.6	10.2

Table 3
Baseline average metabolizable energy (ME) and crude protein (CP) content of diets and the average future changes in ME, CP and available feed quantity in agro-ecological regions under climate change scenarios.

Location	Baseline		RCP 4.5 (% change)			RCP 8.5 (% change)		
	ME (MJ/kg DM)	CP (g/kg DM)	ME	CP	Feed quantity	ME	CP	Feed quantity
Bloemfontein	8.3	98.0	−2.15	−2.74	−6.65	−2.36	−3.26	−4.61
Phalaborwa	8.5	115.0	−2.15	−2.61	−17.30	−2.17	−3.00	−16.36
Buffalo Berlin	8.2	95.0	−3.48	−1.34	−6.69	−4.41	−1.47	−9.21

CP = Crude protein, ME = Metabolizable energy, RCP = Representative concentration pathway.

spanning from January to December) were conducted under two different feed limitation scenarios: feed quality limited conditions and feed quantity limited conditions. This approach allowed for the independent evaluation of the effects of feed quality and quantity on animal growth. In feed quality limited conditions, animal growth can be constrained even when feed is available ad libitum. Under feed quantity limited conditions, animal growth can be restricted by both feed quality and available feed quantity. Limitations only related to the available feed quantity can be managed through interventions such as the reduction of stocking densities. As a result, simulations of climatic scenarios involving only changes in feed quantity were not included in this study, as these were considered unrealistic under climate change.

Under feed quality limited conditions, feed availability was assumed to be ad libitum. In the model, both available feed and DM feed intake by animals were expressed as a percentage of total body weight. After multiple iterations to determine the ad libitum feed intake as a percentage of total body weight, no effect on ADG was observed when daily DM feed intake exceeded 2.30 % of total body weight in most simulations, except for 42 % of cases. Consequently, the ad libitum DM feed intake was set at 2.30 % of total body weight (dry matter per day) for the majority of simulations, while for the remaining 42 %, it was set at 2.37 % under the respective baseline simulations. In each future scenario, feed quantity available to animals was expressed as a change or deviation from the ad libitum feed intake set for the baseline simulations (Table 3).

Simulations were carried out across three agro-ecological regions for four breed types, considering both the baseline and two climate change scenarios (RCP 4.5 and RCP 8.5, three percentiles per climate change scenario). Each climate change scenario was simulated under both feed quality limited and feed quantity limited conditions, resulting in a total of 156 simulations. The study focused on weaned bulls, starting at 212 days of age (7 months), during a grazing period extending from January to December.

Simulated ADGs under the baseline and climate change scenarios were compared, and the differences were calculated. These differences were expressed as percentages of the baseline ADGs. The model was designed to determine the percentage of time a biophysical factor defined or limited animal growth across all scenarios.

3. Results and discussion

3.1. Future cattle growth without feed quantity limitation

The study found that simulated baseline ADG (0.40 kg/head/day) was higher than ADG under RCP 4.5 (0.27 kg/head/day, −31 %) and RCP 8.5 (0.26 kg/head/day, −35 %) when averaged across all ecological regions and breed types, considering only changes in feed quality. The ADGs across the three percentiles (10th, 50th and 90th) for each scenario were similar (Fig. 2). The largest differences between ADGs in the 10th and 90th percentiles were found for Phalaborwa, which is located in the hot and dry province Limpopo. This suggests greater uncertainty regarding the direct future effects of temperature and rainfall on beef cattle in hot semi-desert climates compared to semi-arid and temperate oceanic climates, as ME and CP content were not adjusted for the 10th and 90th percentiles. The simulated ADGs for RCP 4.5 were significantly higher than those for RCP 8.5 (Fig. 2), indicating that all breed types will likely experience greater negative impacts under RCP 8.5. These findings align with expectations, as RCP 8.5 is generally associated with harsher climatic conditions compared to RCP 4.5 (Tables 2 and 3; Riahi et al., 2017).

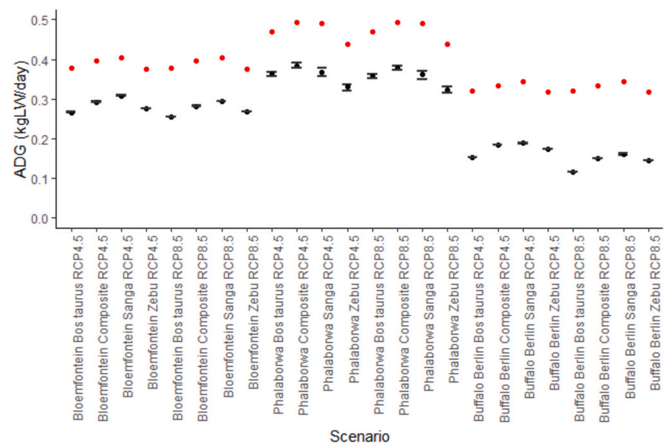

Fig. 2. Average simulated ADGs (50th percentile) across the four breed types and three agro-ecological regions for the climate change scenarios RCP 4.5 and RCP 8.5 (black dots) when only feed quality changes. Baseline ADGs (red dots) are provided for comparison. The ADGs at the 10th and 90th percentiles are indicated by the black horizontal lines. ADG (kgLW) = Average daily gain (kg) live weight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The findings of this study are consistent with previous reports on future climatic limitations affecting cattle productivity in South Africa, particularly in grassland biomes used for grazing (Meissner et al., 2013; Department of Environmental Affairs, 2018). These areas are often classified as high-risk areas requiring priority intervention to mitigate the negative effects of climate change (Meissner et al., 2013; Department of Environmental Affairs, 2018). Key drivers of future pasture quality include rising temperatures, increased rainfall intensity, and drought conditions. Combined with projected increases in heat stress, these factors are expected to significantly reduce cattle productivity (Department of Environmental affairs, 2018).

Among the regions studied, beef cattle in Buffalo Berlin experienced the greatest absolute and relative decrease in ADG when averaged across all breed types and RCP scenarios (−0.17 kg/head/day, −51.5 %), compared to Phalaborwa (−0.12 kg/head/day, −25.5 %) and Bloemfontein (−0.11 kg/head/day, −28.2 %) (Fig. 2; Supplementary material S3). The pronounced decline in growth performance for beef cattle in Buffalo Berlin was expected due to its already low baseline feed quality, which deteriorated further under both RCP 4.5 and RCP 8.5 scenarios (Table 3). Among breed types, *Bos taurus* exhibited the highest relative decrease in ADG under RCP 4.5 (−33.0 %), followed by the Composite, and Sanga breeds (−32.0 % each), while *Zebu indicine* had the lowest decline (−29.0 %) (Fig. 2; Supplementary material S3). A similar pattern was observed under RCP 8.5, with *Bos taurus* again experiencing the greatest reduction (−38.5 %), while the Composite, Sanga, and *Zebu indicine* breeds showed a decline of −34.1 %, −34.1 % and − 36.8 %, respectively. These results align with previous research indicating that *Bos taurus* breeds are less heat-tolerant and therefore more susceptible to rising temperatures (Mwai et al., 2015; Rocha et al., 2019; Cooke et al., 2020).

Bos indicus, Composite and Sanga cattle breeds have been shown to exhibit superior heat tolerance and enhanced ability to utilize low quality forages compared to *Bos taurus* breeds (Brown and Lalman, 2010; Mwai et al., 2015; Nyamushamba et al., 2017; Latham et al., 2018; Fontes et al., 2021; Kooverjee et al., 2022). Therefore these breed types demonstrated a slightly smaller percentage decline in ADG under both RCP 4.5 and RCP 8.5, reflecting their greater adaptability to climate change conditions. Previous research has also shown that African taurines (Sanga), Zebu and some Composite cattle breeds possess a higher number of genomic copy number variations (CNVs) (Matukumalli et al., 2009; Liu et al., 2010) in regions associated with genes responsible for environmental responses and adaptation compared to exotic European taurine breeds (Matukumalli et al., 2009; Kijas et al., 2011). This genetic advantage may contribute to the inferior performance of *Bos taurus* breeds under RCP 4.5 and RCP 8.5 when faced with lower forage quality compared to the baseline scenario (Table 3).

The study found that the pattern of ADG decline remained consistent across all ecological regions and breed types, regardless of whether the scenario was RCP 4.5 or RCP 8.5. The highest percentage decline in ADG (−56.5 %), averaged across breeds, was observed in Buffalo Berlin under RCP 8.5, corresponding to the largest decline (−4.41 %) in pasture ME concentration recorded in this region (Table 3). Among breed types, *Bos taurus* exhibited the greatest reduction in ADG (−63.4 %) in Buffalo Berlin under RCP 8.5, followed by the Composite (−55.4 %) and *Zebu indicine* (−54.6 %) breeds, while the Sanga breed exhibited the smallest decline (−52.8 %) in ADG (Supplementary material S3). These findings align with previous studies highlighting the lower suitability of exotic cattle breeds in harsh African environmental conditions, a challenge expected to intensify under climate change (Ameni et al., 2007; Menjo et al., 2009; Van Marle-Köster et al., 2021). Furthermore, the high sensitivity of non-indigenous cattle breeds in areas dominated by Albany thicket vegetation (characteristic of Buffalo Berlin) under future climate change conditions supports the pronounced decline in ADG among *Bos taurus* breeds in this area under RCP 8.5 (Department of Environmental Affairs, 2015). While pasture quantity in such ecological regions (Buffalo Berlin) is not expected to undergo significant changes due to climate change, the adverse effects of extreme temperatures on pasture quality will likely negate any potential benefit to livestock production (Department of Environmental Affairs, 2015).

3.2. Future cattle growth with feed quantity limitation

Similar to the scenario where only pasture quality changed, the baseline ADG for beef cattle (0.40 kg/head/day) was higher than the simulated ADGs under RCP 4.5 (0.21 kg/head/day, −48 %) and RCP 8.5 (0.20 kg/head/day, −51 %) in scenarios where both feed quality and feed quantity were affected. However, unlike the scenarios without feed quantity limitations, the ADGs for RCP 4.5 and RCP 8.5, as well as ADGs across different percentiles for each scenario, were generally similar. In Phalaborwa and Bloemfontein, however, ADGs for RCP 8.5 tended to be higher than those for RCP 4.5 (Fig. 3) due to the lower feed availability under RCP 4.5 compared to RCP 8.5 in these two locations. The similarity in ADGs between RCP 4.5 and RCP 8.5 may be attributed to the fact that changes in feed quality and quantity were comparable across both scenarios (Table 3). This could be explained by the potential benefits of higher atmospheric carbon dioxide levels in RCP 8.5 than in RCP 4.5 thereby offsetting some of the negative effects of increased warming on forage quality and quantity (Dumont et al., 2014).

Similarly to this study, large decreases in ADGs were reported for

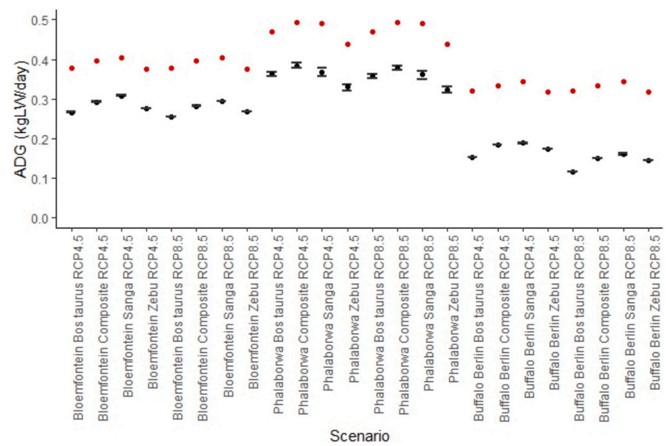

Fig. 3. Average simulated ADGs (50th percentile) across the four breed types and three agro-ecological regions for the climate change scenarios RCP 4.5 and RCP 8.5 (black dots) when both pasture quality and quantity change. Baseline ADGs (red dots) are provided for comparison. The ADGs at the 10th and 90th percentiles are indicated by the black horizontal lines. ADG (kgLW) = Average daily gain (kg) live weight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sheep in the Inner Mongolia steppe desert of China under RCP 4.5 and RCP 8.5. Using a mechanistic, dynamic model, the ADG with a medium stocking density decreased by 17 % from 2021 to 2100 under RCP 4.5 and by 84 % under RCP 8.5 compared to RCP 2.6, which was not significantly different from the baseline. The ADG with high stocking density decreased by 84 % under RCP 4.5 and 194 % under RCP 8.5 in this period, the latter meaning that ADG was highly negative (Wang et al., 2024). In another modelling study, net revenues from cattle in mixed farms in semi-arid Zimbabwe decreased by 8 to 32 % under RCP 4.5 and 11 to 43 % under RCP 8.5 from 1995 to 2055. Revenues from milk production and meat production decreased even further, whereas manure production and draught power were less affected (Descheemaeker et al., 2018). The decreases in ADGs even might have been underestimated in both studies, because the models used did not account for the direct effect of increased temperatures (i.e., heat stress) on livestock.

The decline in ADG from the baseline to the RCP 4.5 and RC8.5 climate change scenarios (−50 % for both feed quality and quantity limited scenarios, and − 33 % for scenarios with only feed quality limitations) was primarily attributed to the combined effects of reduced feed quality and less favourable climatic conditions for pasture growth. When averaged across all agro-ecological regions and breed types, the simulated ADGs under feed quantity-limited scenarios were lower than those in scenarios where only feed quality was affected by climate change. The differences in ADGs between these scenarios highlight the net additional impact of feed quantity limitations on cattle growth.

Despite slightly higher ADGs in Phalaborwa (0.18 kg/head/day) compared to Buffalo Berlin (0.17 kg/head/day), the additional effect of feed quantity across all breed types was found to be the highest in Phalaborwa among the three agro-ecological regions studied Fig. 2 and 3) which can be explained by the reduction in feed availability being largest in this region (Table 3). This finding aligns with the ongoing challenges faced in cattle production within Limpopo, where forage quantity has historically been a major concern (Maluleke and Mokwena, 2017). Future projections indicate that climate change will exacerbate cattle production issues in Limpopo, primarily due to forage quantity limitations (Maluleke and Mokwena, 2017; Mudzengi et al., 2020). A study by Descheemaeker et al. (2018) also projected a 9 % reduction in feed intake due to inadequate feed availability in hot-dry environments, such as Limpopo province.

The growth of beef cattle in Bloemfontein and Buffalo Berlin was predominantly constrained by feed quality rather than feed quantity. This outcome was anticipated, given that the reduction in feed availability was lower for these regions than for Phalaborwa (Table 3). The finding aligns with those of Descheemaeker et al. (2018), who assessed forage and livestock production across various environments under RCP 4.5 and RCP 8.5 projections for the mid-century (2040–2070). Their study indicated that grass production in rangelands decreased mainly under hot-dry scenarios, particularly in RCP 8.5, while remaining largely consistent with baseline levels in moderate or cooler, wetter conditions - similar to those in Bloemfontein and Buffalo Berlin. This suggests that, under future climate change scenarios, feed quality constraints will likely have a greater impact than feed quantity limitation on beef cattle growth in these regions, provided current stocking densities remain unchanged.

Another possible explanation for the high feed quality limitation in Bloemfontein and Buffalo Berlin, compared to the less feed quality limitation in Phalaborwa, could be the fixed standard feed intake set at 2.30 % and 2.37 % of total body weight in the model. The ME and CP content of diets were highest per kg DM for Phalaborwa (Table 3) and therefore the effect of feed quantity limitation is greatest. Therefore, the absence of feed quantity limitation in Bloemfontein and Buffalo Berlin could be an artefact of the approach which used the fixed level of 2.30 % for most simulations. If we adopt percentages lower than 2.30 %, the ADG with feed quantity limitation may decrease too for these locations. If the standard value is 2.30 %, but the cattle for instance do not go beyond 2.10 % of the total body weight (threshold value for energy limitation), a slight decrease (i.e., by 5 or 6 %) from the 2.30 % will not result in any differences in ADGs.

The *Bos taurus* and Composite breed types experienced the most significant decline in productivity in the Phalaborwa region, primarily due to feed quantity limitations. Under the RCP 4.5 scenario, their productivity decreased by 0.31 kg/head/day (66.1 %) and 0.30 kg/head/day (60.7 %), respectively (Fig. 3), relative to the baseline. In contrast, the Sanga and the *Zebu indicine* breeds demonstrated a somewhat greater resilience, with a decline of 0.29 kg/head/day (59.1 %) and 0.27 kg/head/day (60.4 %) under combined feed quantity and quality limitations in Phalaborwa across both RCP4.5 and RCP8.5 climatic scenarios. These findings suggest that feed quantity limitations will have a more pronounced impact on *Bos taurus* and Composite breeds in Phalaborwa under RCP 4.5. This aligns with existing literature, which indicates that temperate *Bos taurus* breeds are more vulnerable to the adverse effects of climate change in hot climates compared to tropically adapted Sanga and *Zebu indicine* breeds, as well as their crosses (Polsky and von Keyserlingk, 2017).

The Sanga breed type has been widely recognized for its resilience in arid and semi-arid climates, where both feed quality and quantity constrain cattle growth (Matukumalli et al., 2009; Kijas et al., 2011; Mwai et al., 2015; Nyamushamba et al., 2017; Kooverjee et al., 2022). The findings of this study indicate a consistent trend: Sanga and *Zebu indicine* breed types exhibit the highest resilience across all agro-ecological regions, whereas *Bos taurus* breeds are more likely to experience significant declines in performance under future conditions of limited feed quality and quantity. These findings align with previous studies by Hanotte et al. (2003) and Hansen Hansen (2004), which highlight the substantial functional genetic diversity in African taurine and Zebu indicine breeds, enabling them to better adapt to tropical climates with feed resource constraints.

The Sanga breed type demonstrated the highest resilience in Bloemfontein (0.29 kg/head/day) and Phalaborwa (0.21 kg/head/day), followed by the Composite breed (0.28 and 0.20 kg/head/day, respectively) and *Zebu indicine breed* (0.27 and 0.18 kg/head/day, respectively). In contrast, the *Bos taurus* was the most negatively affected breed under RCP 8.5 scenario, with productivity declines of 0.25 kg/head/day in Bloemfontein and 0.16 kg/head/day in Phalaborwa. In Buffalo Berlin, the more resilient breed types, namely Composite (0.14 kg/head/day, −45.8 %), Sanga (0.14 kg/head/day, −47.2 %), and *Zebu indicine* (0.13 kg/head/day, −45.7 %) performed relatively better than *Bos taurus* (0.10 kg/head/day, −52.8 %). These findings suggest that the relatively smaller framed breeds (Composite, Sanga and *Zebu indicine*) may be more suitable for future production in currently cooler regions such as Buffalo Berlin under RCP 8.5 scenario. This is likely due to their well-documented adaptability to hotter climates, a key characteristic projected under RCP 8.5, compared to the less heat-tolerant *Bos taurus* breeds (Kooverjee et al., 2022).

The impact of feed quantity and quality on ADG varied depending on the agro-ecological region and cattle breed. However, the most significant decline in ADG compared to the baseline was observed in Phalaborwa under both RCP 4.5 (−0.29 kg/head/day) and RCP 8.5 (−0.29 kg/head/day) when both feed quality and quantity were restricted. In contrast, Bloemfontein exhibited the smallest decline in ADG across all breed types under both RCP 4.5 (−0.12 kg/head/day) and RCP 8.5 (−0.12 kg/head/day) (Fig. 3 and supplementary material S4). This may be attributed to Bloemfontein experiencing the smallest reduction in feed quantity under RCP 4.5 (−6.65 %) and RCP 8.5 (−4.61 %) (Table 3), which likely minimized the impact on ADG. These findings suggest that enhancing forage availability would be the most effective strategy for improving beef production in Phalaborwa, whereas efforts to improve forage quality would be relatively more beneficial in Bloemfontein and Buffalo Berlin.

The study indicates that ADGs will generally remain similar between RCP 4.5 and RCP 8.5, except in Buffalo Berlin, where lower ADGs are projected under RCP 8.5. These findings somehow align with a global study by Thornton et al. (2021), which predicts that over 60 % of the global cattle population will experience extreme heat stress for approximately 70 days per year due to elevated greenhouse gas emissions under RCP 8.5. This scenario is associated with atmospheric carbon dioxide concentrations surpassing 630 ppm by 2060 and reaching 1020 ppm by 2100 (Riahi et al., 2017). While some cattle breeds may develop adaptations to these conditions (Ahmed et al., 2017; Collier et al., 2019), failing to mitigate extreme climatic stress could significantly impact cattle production, reproductive cycles, and feed intake, ultimately leading to increased mortality (Silanikove, 2000; Silanikove and Koluman, 2015).

Overall, the findings of the current study highlight the need for climate change mitigation strategies in beef production to account for both cattle breed and specific production conditions (e.g., extensive versus intensive). As noted by Thornton et al. (2021), each production scenario has distinct dynamics that influence animal performance. Furthermore, the threshold at which production losses occur varies significantly under different heat stress conditions (Hammami et al., 2013), depending on factors such as breed, genetic potential, body size, age, nutritional status, physiological condition, and prior exposure to heat stress (Godde et al., 2021).

3.3. Heat stress, cold stress and forage quality and availability

Under conditions where feed quality was the primary limiting factor, this study found that animal growth in Bloemfontein and Buffalo Berlin was predominantly constrained by digestion capacity. In these regions, digestion capacity restricted growth 100 % of the time under both RCP 4.5 and RCP 8.5 (Fig. 4). Digestion capacity was thus more limiting for feed intake and cattle growth than any reductions in feed intake as a result of heat stress. The effect of cold stress on growth remained minimal in Phalaborwa, the warmest location, and declined for all breed types from the baseline scenario to the RCP 4.5 and RCP 8.5 scenarios in the other two agro-ecological regions. This decline was expected, as all climate change scenarios projected higher temperatures than the current baseline. In Phalaborwa, digestion capacity limited growth 66.5 % of the time under the baseline scenario and slightly increased to 66.9 % under both RCP 4.5 and RCP 8.5. Meanwhile, the percentage of time heat stress restricted growth remained largely unchanged at 29.0 % across both climate scenarios. These findings on cold stress, heat stress, and

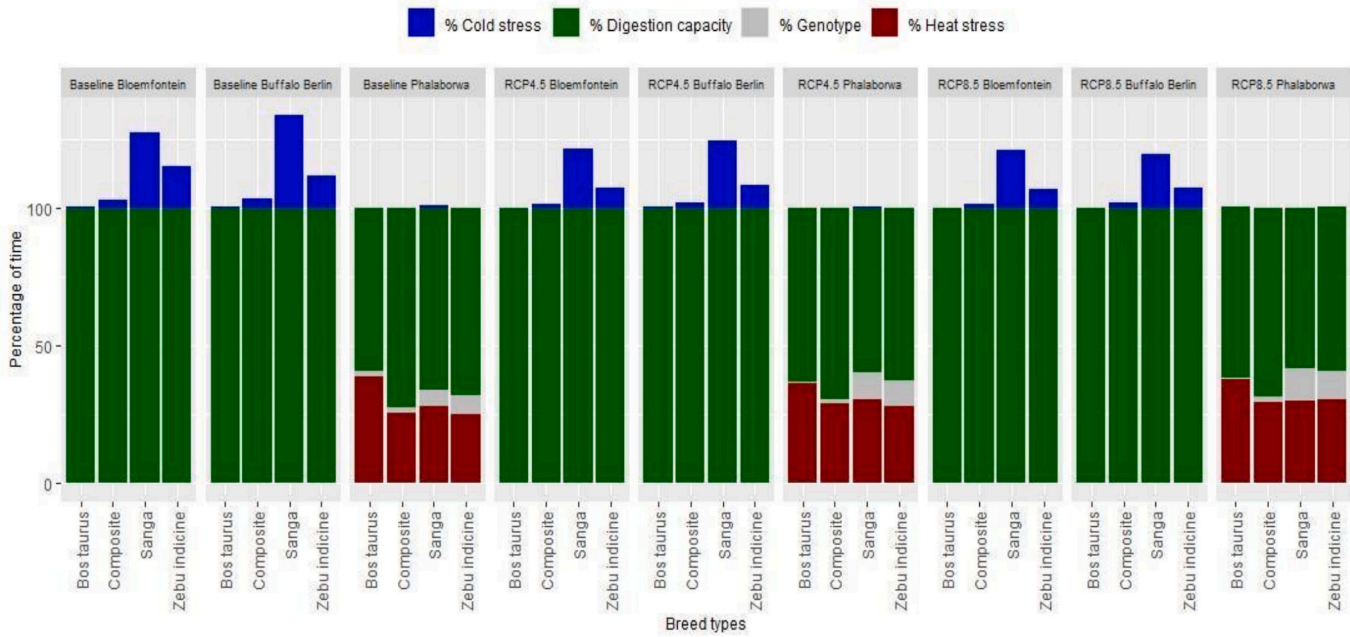

Fig. 4. Percentage of time that defining and limiting factors influenced growth of breed types in the three ecological regions under future feed quality limited production (50th percentile). Digestion capacity limitation and cold stress can occur at the same time. Genotype, heat stress and cold stress are defining factors for cattle growth, while digestion capacity is related to feed quality, a limiting factor for cattle growth.

digestion capacity align with previous research by Magona et al. (2023) where the average heat stress of breed types in Phalaborwa and Buffalo Berlin was 36 % and 0 %; average digestion capacity 49 % and 100 % (Buffalo Berlin), and cold stress 0 % and 43 % for these two locations respectively.

The percentage time digestion capacity limited growth of *Bos taurus* breed types remained high and was slightly lower for other breeds (Fig. 4). When digestion capacity constraints decreased for Sanga, Composite and *Zebu indicine* breeds, a corresponding slight increase in genotype limitations was observed under RCP 8.5 (Fig. 4). The digestion capacity limitation reflects the impact of energy or protein deficiencies on breed growth due to poor pasture quality and high fill units per kg DM (Magona et al., 2023). Consequently, in simulations where digestion restricted growth 100 % of the time under the baseline scenario, feed quality limitations were expected to remain high, as pasture quality was lower under both RCP 4.5 and RCP 8.5 compared to the baseline (Table 3). In such cases, improving pasture quality through interventions like fertilisation could enhance growth across all breed types.

While this study specifically examined heat stress in Phalaborwa under future scenarios, similar trends are likely across other agro-ecological regions. Previous research has documented heat stress in beef cattle in Bloemfontein (Foster et al., 2009) and Buffalo Berlin (Katiyatiya et al., 2014) during certain hot months. However, the LiGAPS-Beef model may not have detected heat stress in these regions due to lower frequency of extreme heat events compared to Phalaborwa. Additionally, digestion capacity limitation, related to low feed quality, could have masked the effect of heat stress. It remains uncertain whether heat stress or digestion capacity limitations will have a greater influence on future cattle performance. In Phalaborwa, where occurrence of digestion capacity limitations were more pronounced in the baseline scenario than under RCP 4.5, heat stress increased by 1.4 % and 0.9 % (relative to full 100 %) under RCP 4.5 and RCP 8.5, respectively, compared to the baseline (Fig. 4). The percentage of time in which heat stress and genotype affected growth remained largely stable across the baseline, RCP 4.5, and RCP 8.5 scenarios in Phalaborwa, with minor declines in some cases. However, these factors (heat stress and genotype) did not significantly impact animal growth in other agro-ecological regions. Notably, genotype had a more substantial effect on the growth of Sanga and *Zebu indicine* breeds in Phalaborwa. These findings are illustrated in Fig. 4 and Supplementary material S5.

The influence of biophysical factors on growth remained unchanged under the RCP 8.5 scenario. Results indicated that under future conditions, and when only feed quality limitations were considered, the Sanga breed type was less affected by digestion capacity constraints (64.1 % for both RCP 4.5 and RCP 8.5). However, heat stress increased slightly, from 27.9 % in the baseline scenario to 29.3 % under RCP 4.5 and 28.8 % under RCP 8.5. In contrast, for other breeds, digestion capacity limitation overtook and masked the effect of both genotype and heat stress. These findings align with research indicating that the Sanga breed demonstrates greater resilience to climate change, with an enhanced ability to tolerate heat and efficiently utilize low-quality forage compared to other breeds (Mwai et al., 2015; Nyamushamba et al., 2017; Kooverjee et al., 2022). As expected, heat stress had a more pronounced impact on growth in Phalaborwa (the warmest region) compared to Buffalo Berlin and Bloemfontein.

Under climate change scenarios where both pasture quality and quantity were altered, digestion capacity emerged as the primary limiting factor for growth in most cases. However, exceptions were observed in Phalaborwa (across all breed types) and in Buffalo for the Sanga and *Zebu indicine* breeds, particularly under RCP 8.5 (Fig. 5). In Phalaborwa, animal growth under RCP 4.5 and RCP 8.5 was predominantly constrained by feed quantity, affecting growth between 88 % and 99 % of the time, respectively. Overall, the Sanga and the *Zebu indicine* breeds exhibited similar responses in Phalaborwa, while the *Bos taurus* and Composite breeds were more similarly affected in colder locations Bloemfontein and Buffalo Berlin. This aligns with expectations, as the Sanga and the *Zebu indicine* breeds are well adapted to African environments (Jang et al., 2021). Genotype had minimal influence on growth across most scenarios, with only a slight impact on the Composite (0.5 %) and *Zebu indicine* (1.4 %) breeds in Phalaborwa under RCP 8.5 (Fig. 5).

The lowest limitations on digestion capacity were observed in Phalaborwa under both RCP 4.5 (0.075 %) and RCP 8.5 (0.075 %). This

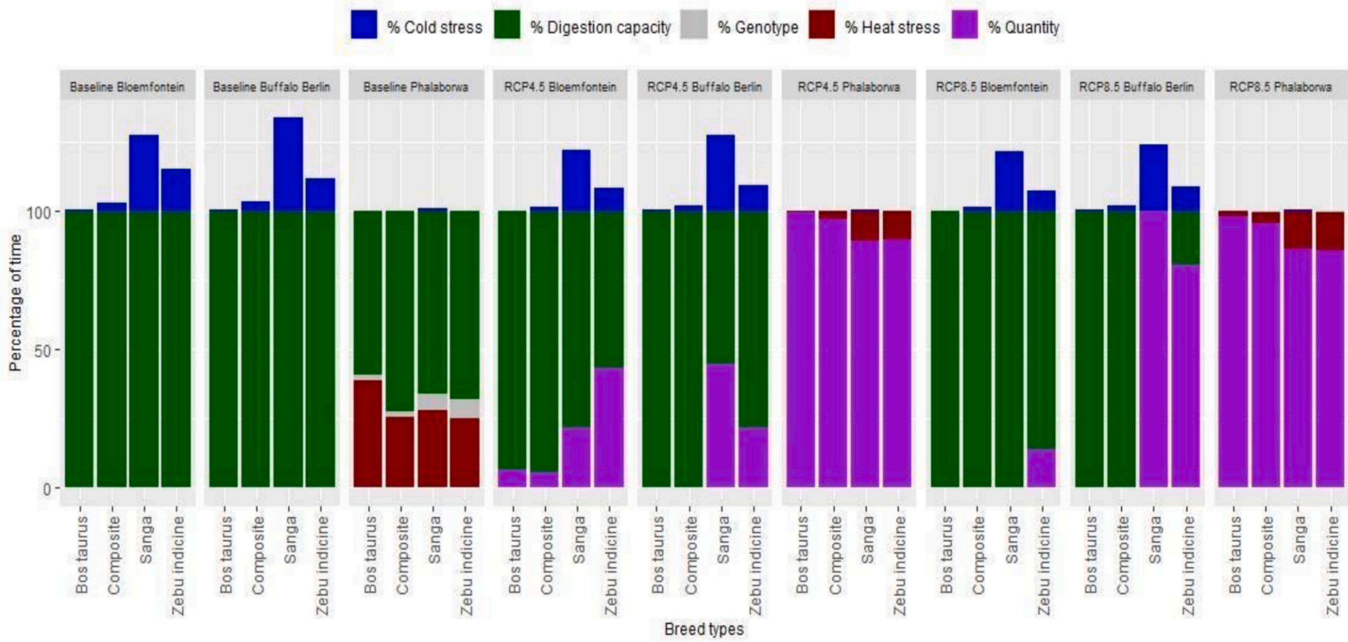

Fig. 5. Percentage of time that defining and limiting factors influenced growth of breed types in the three ecological regions under future feed limited production (50th percentile). Digestion capacity limitation and cold stress can occur at the same time. Genotype, heat stress and cold stress are defining factors for cattle growth, while digestion capacity is related to feed quality, a limiting factor for cattle growth. Available feed quantity is a limiting factor for cattle growth too.

outcome was anticipated because the projected pasture quality, which was used as input to the model, remained higher compared to the other two agro-ecological regions (Table 3). Although heat stress was expected to occur across all locations at varying levels, heat stress impacted animal growth only in Phalaborwa. This was still expected given that Phalaborwa is the warmest region. These findings align with existing literature, which suggests that beef cattle productivity will primarily be influenced by limitations in feed quantity and quality under climate change conditions (Rust and Rust, 2013; Rojas-Downing et al., 2017; Zwane, 2019; Jordaan et al., 2021). A summary of the key defining and limiting factors under the feed-limiting scenario for each region and breed type can be found in supplementary material S6.

3.4. Study limitations

A limitation of this study's findings is the uncertainty associated with climate change projections. While many climate models incorporate all critical mechanisms, they do so in varying ways (e.g., levels of detail and scales), leading to differences in model results and accuracy. However, this is not considered a significant issue in this study, as a robust approach was employed, utilizing results from multiple climate models. Climate projections can sometimes create unrealistic expectations by implying a level of precision and confidence that current models cannot fully support, which could lead to misunderstandings among users of climate information (Nissan et al., 2019). Nevertheless, this study acknowledges the expected uncertainties by presenting results for the 10th, 50th (median) and 90th percentiles of the projected values.

The analysis of beef cattle production under future climatic scenarios revealed a decline in performance across South African agro-ecological regions, primarily due to limitations in feed quality and quantity. Grouping breeds into broader categories may have also introduced a potential source of error in the results. Additionally, estimates of ME and CP content as well as feed quantity, were averaged from the literature, and again biomass (quantity), ME and CP dynamics over time were not taken into account which could all influence the accuracy of the study's findings.

3.5. Adaptation under climate change conditions

The reduction in ADG under future climate change conditions across South African agro-ecological regions indicates that beef production will decline in the absence of mitigation and adaptation strategies in South Africa. The results of this study were for male animals after weaning, but results may be similar for female animals kept for beef production. Effects of climate change on the larger reproductive animals may be even more severe. In addition, occurrence of cattle diseases, which were not included in LiGAPS-Beef, may increase under climate change. All in all, the results of this study suggest significant reductions in beef production in South Africa without mitigation and adaptation measures. Although this study focuses on South African agro-ecological regions, similar outcomes may be expected in other Southern African regions where the climates and vegetation resemble those of the simulated regions.

Despite the uncertainty inherent in modelling future beef production, this study's findings support previous research (Angel et al., 2018; Thornton et al., 2018; Bernabucci, 2019) that emphasizes the need to adapt livestock production systems for improved performance in the face of climate change. While there are no prior studies quantifying future beef production under climate change in South Africa, a global surface temperature increase of between 1.8 °C and 4.0 °C by 2100 is expected to lead to a 10 % to 20 % reduction in beef yield per animal by 2050 (Scholtz et al., 2013). The projected decline reported in this study exceeded the global projection, underscoring the urgent need for mitigation and adaptation in South Africa. Strategies may include transitioning to more resilient breeds, such as indigenous Sanga types or crossbreeding *Bos taurus* with indigenous breeds. Enhancing breed adaptability to climate change can also be achieved through animal breeding interventions, such as selecting and breeding for greater efficiency and heat tolerance, in addition to improving feed quality and quantity.

Given the variability in how different breed types are affected across agro-ecological regions, it is crucial to match breed types and other adaptation strategies with specific agro-ecological regions to enhance productivity in South Africa. Similar recommendations have been made globally for aligning production systems and management practices with regional conditions to improve climate resilience (McIntosh et al., 2023). Integrating drought- and heat tolerant grass species, along with fodder trees that provide shade, can improve pasture quality. Additionally, interventions such as fertilisation, irrigation, and reducing stocking density can improve feed availability per animal under future climate scenarios. These strategies, combined with animal supplementation (e.g., nitrogen and phosphorus licks), can help mitigate the anticipated decline in beef cattle performance across South African agro-ecological regions.

4. Conclusions

The average simulated ADGs of beef cattle in South Africa in 2050 were 48 % lower under RCP 4.5 and 51 % lower under RCP 8.5 compared to the baseline scenario, indicating that beef production will be negatively impacted by climate change. Among the breed types, Sanga and Composite cattle were the least affected by climate change across all agro-ecological regions, while *Bos taurus* proved to be the most susceptible. The ADGs of breed types were most impacted in Buffalo Berlin, followed by Phalaborwa, and least affected in Bloemfontein under both RCP 4.5 and RCP 8.5. Under feed-limited conditions, simulated cattle growth was primarily driven by feed quantity in Phalaborwa and by feed quality in Bloemfontein and Buffalo Berlin. To mitigate the adverse effects of future climate change, it is crucial to focus on breeding heat-tolerant and feed-efficient animals. Additionally, pasture management interventions aimed at improving feed quality and quantity, such as integrating forage-legume, seeding for water-efficient pastures, and applying pasture fertilisation and irrigation, should be implemented to ensure the sustainable performance of beef cattle in South Africa under future climate conditions.

CRediT authorship contribution statement

Christopher Magona: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abubeker Hassen:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Eyob Tesfamariam:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Michael Mengistu:** Formal analysis, Resources. **Carina Visser:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Simon Oosting:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Aart van der Linden:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Carina visser reports financial support was provided by Red Meat Research and Development South Africa (RMRD SA). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Red Meat Research and Development SA (RMRD) for providing funding for the study (VAT No: 401 0257 386). They also thank the South African Weather Services (SAWS) for providing weather data, which was obtained through the Agricultural Research Council of South Africa. Further, the authors acknowledge SA Stud Book and LRF for providing cattle breed type data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104431.

Data availability

Data will be made available on request.

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