Supplementary material

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

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Table S1: Genetic parameters for the *Bos taurus*, Composite, Sanga, and *Zebu indicine* breed types used as input for the LiGAPS-Beef model. Parameter values are from Van der Linden et al. (2019) unless indicated otherwise with footnotes.

	Bos taurus		**Composite**		**Sanga**		***Zebu indicine***	
Parameter	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
1. Reflectance coat	0.60	0.60	0.56	0.56	0.60	0.6	0.56	0.56
2. Coat length[2,3]	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
3. Body area (body area: weight factor) [2,3]	1	1	1.09	1.09	1.16	1.12	1.1	1.1
4. Maximum cond. body core skin (W m^{-2} K^{-1})	64.1	64.1	64.1	64.1	64.1	64.1	64.1	64.1
5. Birth weight (kg)[2,3]	39.5	37.6	35.8	32.9	30.3	28.8	30.7	28.3
6. Maximum adult TBW (Gompertz curve) (kg)[1]	1207.16	748.15	1019	691.68	917.44	448.4	942.69	669.2
7.Birth weight (Gompertz curve) (kg)[1]	39.5	37.6	35.8	33.9	30.3	28.8	30.7	28.3
8. Constant of integration (Gompertz curve)[1]	1.4	1.6	1.6	1.6	1.8	4.2	1.7	2.9
9. Rate constant (Gompertz curve)[1]	1.1	1.1	1.4	1.2	1.1	1.5	1.4	1.5
10.Gompertz reduction (kg TBW)[1]	289.16	144.15	199.91	133.68	147.44	6.4	167.69	144.2
11.Lactation curve parameters A or milk production (kg per day; A = 0, no milk production male)[4]	0	8	0	5.68	0	4	0	5.68
12. Lactation parameter B (milk available for calf)[4]	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068
13. Adult maximum weight[2,3] (kg TBW)	918	604	820	558	770	442	775	525
14. Sex (male = 0, female = 1)	0	1	0	1	0	1	0	1
15.Lactation curve parameters A (kg per day; milk available for calf)[4]	8	8	6.5	5.68	3.5	4	5.8	3.12
16. Lactation curve parameter B (milk available for calf)[4]	0.068	0.068	0.068	0.068	0.068	0.068	0.068	0.068
17. Minimum fraction mature TBW for gestation %[2,3]	0.60	0.6	0.575	0.575	0.55	0.55	0.55	0.55
18. Maintenance correction factor[2,3]	0.97	1	0.93	0.93	0.91	0.91	0.92	0.92
19. Minimum fat tissue % in carcass for gestation	0.32	0.32	0.32	0.2	0.32	0.2	0.32	0.26
20. Lipid bone parameter[2,3]	11.1	11.5	12.2	13.5	13.3	14.3	12.5	13.0
21. Maximum carcass fraction %	0.61	0.57	0.5935	0.55	0.578	0.55	0.5858	0.55
22. Maximum muscle: bone ratio[2,3]	4.4	4.3	4.1	3.6	4.1	3.6	4.1	3.6
23. Minimum conduction body core skin factor	1	1	1.10	1.225	1.3	1.3	1.26	1.26
24.Maximum latent heat release	4.00	3.08	4.5	3.985	7.5	4.89	5.4	4.44
25.Minimum latent heat release	1.73	1.73	1.265	1.265	0.8	0.8	1	1
26. Latent heat release (latent heat of water vapour)	35.3	35.3	34.9	34.9	34.5	34.5	34.7	34.7
27. Lactation curve parameter C[4]	0.00338	0.00338	0.00338	0.00338	0.00338	0.00338	0.00338	0.00338

TBW = total bodyweight

[1] Gompertz curves: TBW = (A + (B – A + E) × e(-C × e(-D × t)) – E, where A = birth weight; B = maximum adult weight; C = integration constant; D = rate constant; t is time in days, and E is a reduction factor

[2] Studbook.co.za. (2019).

[3] The Cattle Site. (n.d.).

[4] Wood's lactation curve: Y(t) = At^B * e^(-Ct), Where Y(t) = milk yield at time t; A = initial milk yield; B = rate of increase in milk yield; C = rate of decline in milk yield; t = time (e.g. days or weeks) in lactation; e = base of natural logarithm

Table S2: Feed quality and quantity changes for Bloemfontein, Phalaborwa and Buffalo Berlin from the baseline to the year 2050.

Climate change scenario	Locations in agro-ecological regions	CP content change (%)	ME content change (%)	Feed quantity change (%)	References
RCP 4.5	Bloemfontein	-2.74	-2.15	-6.65	Deinum and Dirven (1976); Minson and Wilson (1980); Thorvaldsson et al. (2007); Dumont et al. (2015); Boone et al. (2018); Lawal et al. (2019); Ngoma et al. (2019); Hart et al. (2022)
	Phalaborwa	-2.61	-2.05	-17.30	Deinum and Dirven (1976); Minson and Wilson (1980); Thorvaldsson et al. (2007); Webb et al. (2012); Dumont et al. (2014); Boone et al. (2018); Lawal et al. (2019); Magandana et al. (2020); Hart et al. (2022)
	Buffalo Berlin	-1.34	-3.48	-6.69	Deinum (1966); Minson and McLeod (1970); Perring et al. (2010); Dugmore and Nsahlai (2012); Ghahramani and Moore (2013); Boone et al. (2018); Lawal et al. (2019); Gili, (2020)
RCP8.5	Bloemfontein	-3.26	-2.36	-4.61	Deinum and Dirven (1976); Minson and Wilson (1980); Thorvaldsson et al. (2007); Dumont et al. (2015); Boone et al. (2018); Lawal et al. (2019); Hart et al. (2022)
	Phalaborwa	-3.00	-2.17	-16.36	Deinum and Dirven (1976); Minson and Wilson (1980); Thorvaldsson et al. (2007); Webb et al. (2012); Dumont et al. (2014); Boone et al. (2018); Ngoma et al. (2019); Zarei et al. (2021); Hart et al. (2022)
	Buffalo Berlin	-1.47	-4.41	-9.21	Deinum (1966); Minson and McLeod (1970); Dugmore and Nsahlai (2012); Perring et al. (2010); Ghahramani and Moore (2013); Dumont et al. (2014); Boone et al. (2018); Lawal et al. (2019); Gili, (2020); Zarei et al. (2021); Churchill et al. (2022)

CP = crude protein; ME = metabolizable energy; RCP= Representative concentration pathway

Projected forage quality (CP and ME content) and quantity changes by 2050 were derived from field experiments and meta-analysis results reported in studies referenced in Table S2. The studies included in Table S2 were carefully selected based on their grouping of data and results according to agro-ecological region and vegetation type. In terms of forage quantity, the studies in Table S2 projected changes in herbaceous net primary productivity (HNPP) for each agro-ecological region hence HNPP was used as a proxy to estimate future feed quantity changes. Data from each article were extracted from text or tables, and when unavailable in these formats, information was obtained from figures. Whilst an equal number of articles for the agro-ecological regions could not be obtained, there was at least three articles from which information could be obtained for each agro-ecological region and future climate change scenario. The average value from at least three studies per agro-ecological region was then calculated and used to adjust the baseline nutrition parameters for the corresponding region in this study. The baseline nutrition parameters which were adjusted using average values obtained are detailed by Magona et al. (2023). It is to be noted that specific projected data for the studied agro-ecological regions were not always available. In such instances, articles which reported project forage changes in similar agro-ecological regions were used. Thus some articles in Table S2 report about projected forage changes in similar agro-ecological regions to the South African regions included in this study.

Table S3: Simulated average daily gain for the baseline and climate change scenarios representative concentration pathway (RCP) 4.5 and RCP 8.5 in 2050 across four breed types and three agro-ecological regions of South Africa when only feed quality changes.

		Average daily gain (kg live weight/day)						
			RCP 4.5			RCP 8.5		
Locations in agro-ecological regions	**Breed type**	**Baseline**	**10th percentile**	**50th percentile**	**90th percentile**	**10th percentile**	**50th percentile**	**90th percentile**
Bloemfontein	*Bos taurus*	0.378	0.266	0.266	0.267	0.256	0.255	0.256
	Composite	0.397	0.293	0.292	0.292	0.283	0.282	0.282
	Sanga	0.405	0.306	0.308	0.309	0.293	0.293	0.295
	Zebu indicine	0.376	0.276	0.275	0.275	0.268	0.269	0.269
	Average	0.389	0.285	0.285	0.286	0.275	0.275	0.276
Phalaborwa	*Bos taurus*	0.469	0.367	0.363	0.358	0.361	0.356	0.352
	Composite	0.494	0.390	0.384	0.378	0.383	0.378	0.372
	Sanga	0.491	0.378	0.368	0.358	0.371	0.361	0.349
	Zebu indicine	0.439	0.336	0.330	0.321	0.331	0.324	0.315
	Average	0.473	0.368	0.361	0.354	0.362	0.355	0.347
Buffalo Berlin	*Bos taurus*	0.320	0.153	0.153	0.153	0.116	0.117	0.117
	Composite	0.334	0.184	0.183	0.184	0.149	0.149	0.149
	Sanga	0.343	0.187	0.189	0.190	0.159	0.162	0.164
	Zebu indicine	0.317	0.174	0.174	0.175	0.144	0.144	0.145
	Average	0.329	0.175	0.175	0.176	0.142	0.143	0.144

Table S4: Simulated average daily gain for the baseline and climate change scenarios representative concentration pathway (RCP) 4.5 and RCP 8.5 in 2050 across four breed types and three agro-ecological regions of South Africa when both pasture quality and quantity change.

		Average daily gain (kg live weight/day)						
			RCP 4.5			RCP 8.5		
Locations in agro-ecological regions	**Breed type**	**Baseline scenario**	**10th percentile**	**50th percentile**	**90th percentile**	**10th percentile**	**50th percentile**	**90th percentile**
Bloemfontein	*Bos taurus*	0.378	0.250	0.251	0.253	0.255	0.254	0.255
	Composite	0.397	0.281	0.280	0.280	0.281	0.281	0.281
	Sanga	0.405	0.280	0.285	0.285	0.286	0.286	0.288
	Zebu indicine	0.376	0.264	0.263	0.262	0.267	0.267	0.267
	Average	0.389	0.269	0.270	0.270	0.272	0.272	0.273
Phalaborwa	*Bos taurus*	0.469	0.159	0.157	0.156	0.163	0.162	0.162
	Composite	0.494	0.193	0.192	0.189	0.199	0.198	0.198
	Sanga	0.491	0.203	0.200	0.200	0.210	0.209	0.205
	Zebu indicine	0.439	0.176	0.174	0.169	0.184	0.181	0.178
	Average	0.473	0.183	0.181	0.179	0.189	0.188	0.186
Buffalo Berlin	*Bos taurus*	0.320	0.150	0.151	0.151	0.097	0.099	0.098
	Composite	0.334	0.182	0.181	0.182	0.135	0.136	0.136
	Sanga	0.343	0.178	0.181	0.182	0.130	0.135	0.139
	Zebu indicine	0.317	0.172	0.172	0.173	0.132	0.132	0.133
	Average	0.329	0.171	0.171	0.172	0.124	0.126	0.127

Table S5: Defining and limiting factors for growth and beef production of breed types in three agro-ecological regions of South Africa under climate change scenarios when only feed quality changes. Occurrence of defining and limiting factors is expressed as a percentage of the simulated time period.

Scenario	Locations in agro-ecological regions	Breed type	Genotype (% time)[1]	Heat stress (% time)[1]	Cold stress (% time)[1,2]	Digestion capacity (% time)[2]
Baseline	Bloemfontein	*Bos taurus*	0.0	0.0	0.5	100.0
	Bloemfontein	Composite	0.0	0.0	3.0	100.0
	Bloemfontein	Sanga	0.0	0.0	27.1	100.0
	Bloemfontein	Zebu	0.0	0.0	14.5	100.0
	Phalaborwa	*Bos taurus*	2.2	38.6	0.0	59.2
	Phalaborwa	Composite	1.9	25.5	0.0	72.6
	Phalaborwa	Sanga	6.0	27.9	0.8	66.0
	Phalaborwa	Zebu	6.8	24.9	0.0	68.2
	Buffalo Berlin	*Bos taurus*	0.0	0.0	0.3	100.0
	Buffalo Berlin	Composite	0.0	0.0	3.3	100.0
	Buffalo Berlin	*Sanga*	0.0	0.0	32.9	100.0
	Buffalo Berlin	Zebu	0.0	0.0	11.5	100.0

Table S5 continued

Scenario	Location in agro-ecological region	Breed type	Genotype (% time)[1]			Heat stress (% time)[1]			Cold stress (% time)[1,2]			Digestion capacity (% time)[2]		
		Percentile	10th	50th	90th	10th	50th	90th	10th	50th	90th	10th	50th	90th
RCP4.5	Bloemfontein	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	100.0	100.0	100.0
	Bloemfontein	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.4	100.0	100.0	100.0
	Bloemfontein	Sanga	0.0	0.0	0.0	0.0	0.0	0.0	23.6	21.9	21.6	100.0	100.0	100.0
	Bloemfontein	*Zebu*	0.0	0.0	0.0	0.0	0.0	0.0	10.1	7.7	7.1	100.0	100.0	100.0
	Phalaborwa	*Bos taurus*	0.3	0.5	0.5	32.3	33.7	36.2	0.0	0.0	0.0	67.4	65.8	63.3
	Phalaborwa	Composite	1.4	1.6	1.9	24.1	25.5	27.4	0.0	0.0	0.0	74.5	72.9	70.7
	Phalaborwa	Sanga	6.6	6.6	8.8	28.2	29.3	30.7	0.3	0.3	0.3	65.2	64.1	60.5
	Phalaborwa	*Zebu*	7.4	7.9	9.0	24.9	27.4	28.5	0.0	0.0	0.0	67.7	64.7	62.5
	Buffalo Berlin	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	100.0	100.0	100.0
	Buffalo Berlin	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.9	100.0	100.0	100.0
	Buffalo Berlin	*Sanga*	0.0	0.0	0.0	0.0	0.0	0.0	27.1	25.8	22.2	100.0	100.0	100.0
	Buffalo Berlin	*Zebu*	0.0	0.0	0.0	0.0	0.0	0.0	9.9	9.0	7.7	100.0	100.0	100.0
RCP8.5	Bloemfontein	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	100.0	100.0	100.0
	Bloemfontein	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.4	100.0	100.0	100.0
	Bloemfontein	Sanga	0.0	0.0	0.0	0.0	0.0	0.0	23.6	22.2	21.1	100.0	100.0	100.0
	Bloemfontein	*Zebu*	0.0	0.0	0.0	0.0	0.0	0.0	9.9	7.7	6.3	100.0	100.0	100.0
	Phalaborwa	*Bos taurus*	0.3	0.3	0.5	32.1	33.7	35.9	0.0	0.0	0.0	67.7	66.0	63.6
	Phalaborwa	Composite	1.4	1.6	1.9	24.1	25.8	27.4	0.0	0.0	0.0	74.5	72.6	70.7
	Phalaborwa	Sanga	6.6	7.1	9.0	28.2	28.8	30.7	0.3	0.3	0.3	65.2	64.1	60.3
	Phalaborwa	*Zebu*	7.7	8.5	9.3	24.7	26.8	28.2	0.0	0.0	0.0	67.7	64.7	62.5
	Buffalo Berlin	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	100.0	100.0	100.0
	Buffalo Berlin	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.9	100.0	100.0	100.0
	Buffalo Berlin	*Sanga*	0.0	0.0	0.0	0.0	0.0	0.0	27.1	22.5	19.5	100.0	100.0	100.0
	Buffalo Berlin	*Zebu*	0.0	0.0	0.0	0.0	0.0	0.0	9.9	7.9	7.7	100.0	100.0	100.0

[1] Genotype, heat stress and cold stress are defining factors for growth of cattle.

[2] Digestion capacity limitation and cold stress can occur at the same time.

Table S6: Defining and limiting factors for growth and beef production of breed types in three agro-ecological regions of South Africa under climate change scenarios when feed quality and quantity change. Occurrence of defining and limiting factors is expressed as a percentage of the simulated time period.

Scenario	Location	Breed	Genotype (% time)[1]			Heat stress (% time)[1]			Cold stress (% time)[1,2]			Digestion capacity (% time)[2]			Quantity (% time)[2]		
Baseline	Bloemfontein	*Bos taurus*	0.0			0.0			0.5			100.0					
	Bloemfontein	Composite	0.0			0.0			3.0			100.0					
	Bloemfontein	Sanga	0.0			0.0			27.1			100.0					
	Bloemfontein	Zebu	0.0			0.0			14.5			100.0					
	Phalaborwa	*Bos taurus*	2.2			38.6			0.0			59.2					
	Phalaborwa	Composite	1.9			25.5			0.0			72.6					
	Phalaborwa	Sanga	6.0			27.9			0.8			66.0					
	Phalaborwa	Zebu	6.8			24.9			0.0			68.2					
	Buffalo Berlin	*Bos taurus*	0.0			0.0			0.3			100.0					
	Buffalo Berlin	Composite	0.0			0.0			3.3			100.0					
	Buffalo Berlin	*Sanga*	0.0			0.0			32.9			100.0					
	Buffalo Berlin	Zebu	0.0			0.0			0.5			100.0					
		Percentile	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**
RCP4.5	Bloemfontein	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0	92.6	92.3	93.7	7.4	7.7	6.3
	Bloemfontein	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	2.2	1.6	94.8	94.5	94.5	5.2	5.5	5.5
	Bloemfontein	Sanga	0.0	0.0	0.0	0.0	0.0	0.0	24.1	22.2	21.9	81.4	82.5	82.2	18.6	17.5	17.8
	Bloemfontein	Zebu	0.0	0.0	0.0	0.0	0.0	0.0	11.2	9.3	7.7	92.3	91.8	91.5	7.7	8.2	8.5
	Phalaborwa	*Bos taurus*	0.0	0.0	0.0	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0	99.2	99.2	99.2
	Phalaborwa	Composite	0.3	0.0	0.0	1.9	2.2	3.3	0.0	0.0	0.0	0.0	0.0	0.0	97.8	97.8	96.7
	Phalaborwa	Sanga	0.0	0.0	0.0	6.0	6.8	9.0	0.3	0.3	0.3	0.3	0.3	0.3	93.7	92.9	90.7
	Phalaborwa	Zebu	0.3	0.0	0.0	8.5	9.9	10.7	0.0	0.0	0.0	0.0	0.0	0.0	91.2	90.1	89.3
	Buffalo Berlin	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	100.0	100	100.0	0.0	0.0	0.0
	Buffalo Berlin	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.9	100.0	100	100.0	0.0	0.0	0.0
	Buffalo Berlin	*Sanga*	0.0	0.0	0.0	0.0	0.0	0.0	27.7	26.6	22.2	100.0	100.0	100.0	0.0	0.0	0.0
	Buffalo Berlin	Zebu	0.0	0.0	0.0	0.0	0.0	0.0	9.9	9.0	7.7	100.0	100.0	100.0	0.0	0.0	0.0

Table S6 continued

Scenario	Location	Breed	Genotype (% time)[1]			Heat stress (% time)[1]			Cold stress (% time)[1,2]			Digestion capacity (% time)[2]			Quantity (% time)[2]		
		Percentile	10th	50th	90th	10th	50th	90th	10th	50th	90th	10th	50th	90th	10th	50th	90th
RCP8.5	Bloemfontein	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	100.0	100.0	100.0	0.0	0.0	0.0
	Bloemfontein	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.4	100.0	100.0	100.0	0.0	0.0	0.0
	Bloemfontein	Sanga	0.0	0.0	0.0	0.0	0.0	0.0	23.6	22.2	21.4	100.0	100.0	100.0	0.0	0.0	0.0
	Bloemfontein	Zebu	0.0	0.0	0.0	0.0	0.0	0.0	9.9	7.7	6.6	100.0	100.0	100.0	0.0	0.0	0.0
	Phalaborwa	*Bos taurus*	0.0	0.0	0.0	1.1	1.6	1.9	0.0	0.0	0.0	0.0	0.0	0.0	98.9	98.4	98.1
	Phalaborwa	Composite	0.3	0.5	1.1	2.7	2.7	3.0	0.0	0.0	0.0	0.0	0.0	0.0	97.0	96.7	95.9
	Phalaborwa	Sanga	0.0	0.0	0.0	6.8	9.0	10.7	0.3	0.3	0.3	0.3	0.3	0.3	92.9	90.7	89.0
	Phalaborwa	Zebu	1.9	1.4	1.9	8.2	10.7	11.8	0.0	0.0	0.0	0.0	0.0	0.0	89.9	87.9	86.3
	Buffalo Berlin	*Bos taurus*	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	100.0	100	100.0	0.0	0.0	0.0
	Buffalo Berlin	Composite	0.0	0.0	0.0	0.0	0.0	0.0	2.7	1.9	1.9	100.0	100	100.0	0.0	0.0	0.0
	Buffalo Berlin	*Sanga*	0.0	0.0	0.0	0.0	0.0	0.0	28.8	23.8	21.1	74.2	76.7	78.6	25.8	23.3	21.4
	Buffalo Berlin	Zebu	0.0	0.0	0.0	0.0	0.0	0.0	10.4	8.5	7.7	99.7	98.9	99.7	0.3	1.1	0.3

[1] Genotype, heat stress and cold stress are defining factors for growth of cattle.

[2] Digestion capacity limitation and cold stress can occur at the same time.

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