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4 **Direct and indirect effects of heat stress on cattle in East Africa**

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11
12
13 **Abstract**

14 **CONTEXT**

15 East Africa has a heterogenous climate, ranging from arid and semi-arid zones to humid highlands.
16 This leads to diverse agroecological conditions and livestock production systems, from extensive
17 pastoral and agro-pastoral systems in drier regions to intensive zero-grazing dairy systems. Climate-
18 driven factors are anticipated to impact animal welfare, as well as reproduction and production
19 parameters. Understanding the latter is paramount in a region where dairy production represents a
20 lifeline for pastoral systems.

21
22 **OBJECTIVE**

23 Here we use state-of-the-art climate projections (CORDEX-CORE) across two representative
24 concentration pathways (RCP) 2.6 and 8.5 to assess the direct (animal welfare) and indirect (fodder
25 supply) effects of climate change on indigenous and climate resilient-breeds (Boran) in Tanzania,
26 Kenya, Uganda, and Rwanda.

27
28 **METHODS**

29 Our approach involves applying the Temperature-Humidity Index (THI) and Milk Production
30 Decline (MDEC) equations to assess heat stress on animal welfare and milk production, alongside
31 evaluating the indirect effects on fodder supply, particularly maize and Napier grass through the
32 Python Agroecological Zoning (AEZ) eco-physiological model.

33
34 **RESULTS**

35 Moderate stress ($81 < \text{THI} \leq 91$) is likely to spread across the region under future climate, threatening
36 milk production and reproductive performance. Boran daily milk yields losses can attain 0.45 kg/day
37 (~14%) by 2070-2099 under RCP 8.5. Similarly, fodder shortages are anticipated in northern parts
38 of Kenya and Uganda, threatening consistent animal fodder supply and affecting smallholder farmers
39 dependent on rain-fed agricultural systems.

40
41 **CONCLUSION**

42 The compounded effect of simultaneous weather hazards intensifies risks in vulnerable regions
43 facing limited coping capacity. As demand for meat and dairy continues to rise in East Africa,
44 immediate climate actions are essential to safeguard livestock productivity and to enhance food
45 security in a region confronting the dire consequences of climate change.

46
47 **SIGNIFICANCE**

48 This comprehensive analysis is, therefore, instrumental in guiding public and private investments
49 aimed at fostering climate resilience and improving disaster risk management across livestock
50 production systems in the region.

51

52 **Keywords:** THI; indigenous breeds; heat-tolerance; food security; climate resilience

53

54 **1. Introduction**

55 1.1. Cattle: a lifeline for smallholder farmers in East Africa

56 About 19.6% of the 390 million cattle heads in Africa are found in the United Republic of Tanzania
57 (9.7%), as well as in the Republic of Kenya (5.6%), Uganda (3.9%), and Rwanda (0.4%) (FAO,
58 2023a). While cattle production is crucial in the region, dairy farming is the lifeline for East African
59 farmers, serving as a multifaceted cornerstone sustaining households and community livelihoods
60 amid the challenges of climate change. In the diverse agricultural landscape of East Africa, where
61 smallholder farming predominates, dairy farming not only provides income but also holds cultural
62 significance, promotes social cohesion, and enhances resilience against economic shocks and
63 environmental stresses. Dairy farming is, therefore, a primary source of income and wealth
64 accumulation (Orodho, 2019; Rufino et al. 2013; Ngigi et al. 2010). Cattle, as the main source of
65 dairy, provides a steady stream of milk that is processed and sold, contributing to household income
66 generation and diversification. This additional income enables access to credit and financial services,
67 empowering farmers to invest in agricultural inputs, education, and healthcare for their families.
68 Beyond its economic importance, dairy farming is fundamental to food security and human nutrition
69 due to its high-quality protein content, essential amino acids, vitamins, and minerals critical for
70 health and growth, especially for vulnerable groups such as children and pregnant women (Beal,
71 2023; FAO, 2023b; Lokuruka, 2020).

72

73 Dairy production in East Africa is primarily smallholder and low-input systems. Three dairy
74 production systems are typically identified: pastoralism, agro-pastoralism, and mixed crop-livestock
75 (Hunt et al., 2019; Dawson et al. 2014). Production types vary based on the climatic conditions, the
76 availability of fodder, access to land production resources, consumer demands, and market
77 availability. Seasonal climatic variations, particularly rainfall and temperature, impact fodder and
78 water availability, leading to detrimental effects on milk yields and reproductive performance of dairy
79 animals (Ongadi et al. 2020). In a changing climate, rising temperatures, erratic rainfall patterns, and
80 prolonged droughts, along with their complex interactions, are expected to further constrain water
81 and fodder availability and quality (Trisos et al. 2022). Climate change may also influence the
82 distribution and prevalence of livestock diseases and pests, which threaten fodder and dairy
83 productivity, ultimately impacting food security and nutrition (Nalinya et al. 2020; Tadesse and
84 Dereje, 2018).

85

86 1.2. Behavioral and physiological effects of heat stress on cattle

87 Climatic parameters such as air temperature, relative humidity, solar radiation, and rainfall patterns
88 significantly impact livestock welfare, survival, disease, parasitism, and fodder availability and
89 quality (Brychkova et al. 2022; Nardone et al. 2008). Among these climatic parameters, heat stress
90 is the most critical factor affecting dairy production systems in the Horn of Africa (Rahimi et al.
91 2021). The normal temperature range, referred to as the thermoneutral zone (TNZ) (Ahmad et al.
92 2018), is the comfort zone at which dairy cows do not require additional energy to regulate their body
93 temperature. TNZ is influenced by factors such as age, breed, feed intake, diet composition, prior
94 temperature acclimatization, production levels, housing and stall conditions, tissue insulation (fat and
95 skin), external insulation (coat), and animal behavior. Different dairy breeds exhibit varying abilities

96 to maintain a relatively constant internal body temperature, regardless of the external environmental
97 conditions, due to various temperature-regulating physiological mechanisms (Gianone et al. 2023;
98 Tao et al. 2020).

99

100 Heat stress is generally calculated using the Temperature Humidity Index (THI), with a value greater
101 than 79 considered the onset of heat stress (see Table 1). However, the latter THI threshold can vary
102 considerably depending on the breed. Heat stress arises when the animal's body temperature exceeds
103 their normal range due to prolonged exposure to excessive heat and humidity (Becker et al. 2020).
104 This condition occurs when an animal's ability to dissipate heat is compromised, leading to
105 physiological and behavioral changes. Some physiological responses to heat stress in dairy cattle
106 include sweating, elevated respiration rates, vasodilation with increased blood flow to the skin
107 surface, higher rectal temperatures, reduced metabolic rates, decreased dry matter intake, diminished
108 feed utilization efficiency, and altered water metabolism (Ganaie, 2013). These responses can
109 adversely affect the productivity and health of dairy animals. Specifically, heat stress leads to
110 decreased feed intake, lower milk yields, and changes in milk quality (Tao et al. 2020; Kumar et al.
111 2020; Smith et al. 2013). Heat stress exerts strong and well-documented constraints on livestock
112 reproductive performance, with critical implications for the long-term sustainability of pastoral
113 systems. It affects dairy cattle reproduction parameters, resulting in reduced fertility and conception
114 rates (Dovolou et al. 2023; Ahmad et al. 2018). These reproductive challenges arise from various
115 physiological effects, including reduced blood flow to the uterus, altered hormone levels, and
116 decreased quality of oocytes and embryos (Dovolou et al. 2023; Thatcher et al. 2010). Elevated
117 thermal load also disrupts endocrine regulation and directly impairs ovarian and testicular function,
118 leading to reduced conception and pregnancy rates, extended service and calving intervals, and
119 increased early embryonic loss (Marai et al. 2007; Thornton et al. 2021). Female fertility is
120 particularly vulnerable because the follicle-enclosed oocyte is highly sensitive to hyperthermia,
121 while heat stress in males reduces spermatogenesis and semen quality, further constraining herd
122 fertility. These reproductive impacts translate into cumulative demographic and economic
123 consequences for pastoral herds, including lower replacement rates and reduced productivity over
124 successive seasons.

125

126 Breed-specific differences strongly mediate reproductive resilience under heat stress. Tropically
127 adapted *Bos indicus* cattle consistently exhibit greater reproductive tolerance than *Bos taurus* breeds,
128 with experimental evidence showing higher embryo survival and developmental competence under
129 elevated temperatures (Silva et al. 2013). Heat stress also impairs immune function, increasing
130 disease susceptibility and compounding reproductive losses, particularly in pastoral systems with
131 limited veterinary and nutritional buffering (Renaudeau et al. 2012). Together, these interactions
132 highlight reproductive capacity and immune robustness as key traits underpinning heat tolerance
133 and long-term adaptation in climate-stressed livestock systems. Heat stress is also linked to
134 decreased rumen pH, which can alter rumen microbial populations, promoting the growth of lactic
135 acid-producing microbes. Several hormonal responses, triggering immune reactions, are activated
136 during heat stress (Cartwright et al. 2023; Bagath et al. 2019), leading to increased incidences of
137 intramammary infections among heat stressed animals (Rakib et al. 2020).

138

139 1.3. Study rationale

140 In the Horn of Africa, recent failures in rainy seasons from 2020 to 2023, intensified by inter-annual
141 rainfall variability associated with El Niño Southern Oscillation, have led to significant declines in
142 crop yields and milk production. Insufficient water and fodder availability has resulted in the loss of
143 over 9 million livestock heads (NASA, 2023). Such alarming statistics underscore the urgent need
144 for the Food and Agriculture Organization (FAO) to broaden its understanding of heat stress on
145 animal's welfare in a region where livelihoods are increasingly compromised, and food security is

146 under severe threat. While literature on this topic is emerging (Rahimi et al. 2021; Ekine-Dzivenu et
147 al. 2020), our work aims to build on the existing foundational work by exploring the dual effects
148 (direct impacts on animal welfare and productivity and indirect effects on animal food supply) of
149 heat stress on livestock. Given the complex interactions between climate variables and the
150 physiological responses of livestock, this research is both timely and necessary.

151

152 To achieve this objective, we apply advanced climate projections from the Coordinated Regional
153 Downscaling Experiment (CORDEX) and the Coordinated Output for Regional Evaluations
154 (CORE). Additionally, we adopt well established scientific analytical frameworks such as the THI
155 and Agroecological Zoning (AEZ) eco-physiological model to assess the evolving situation in a
156 holistic manner. By linking climate science with impacts and actions, our goal is to provide evidence-
157 based insights for decision-makers, agricultural extension workers, and researchers. This research
158 also aims to equip pastoral communities with the knowledge and strategies necessary to tackle the
159 increasing challenges posed by climate change, thereby enhancing resilience and promoting
160 sustainable livelihoods.

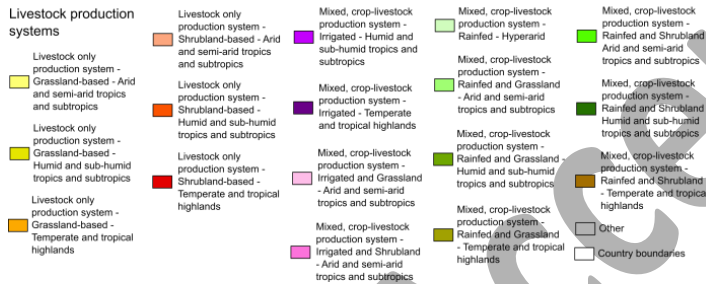
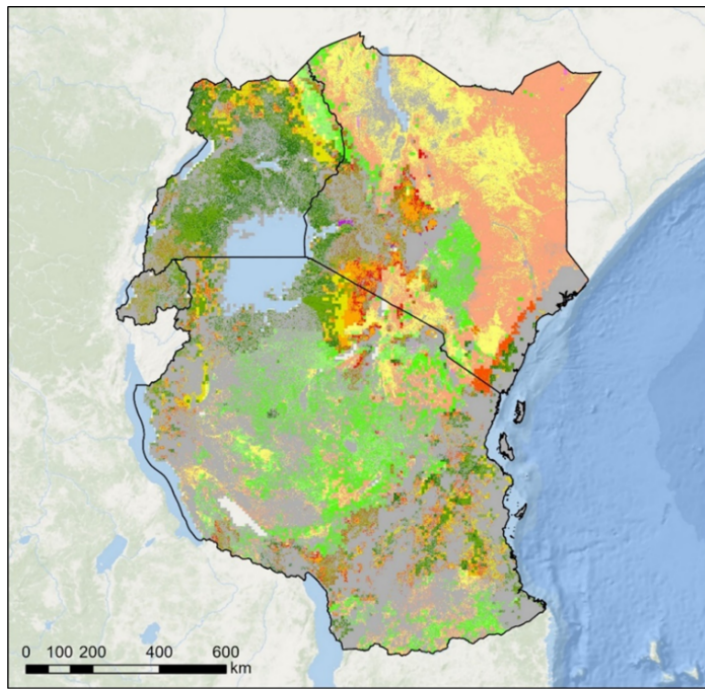
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162 **2. Materials and methods**

163 2.1. Climatic and ecosystem characterization

164 A tropical savannah climate covers the four countries, interrupted by a corridor of arid steppe and
165 desert climates along the Indian Ocean coastline and across northwest Kenya and central Tanzania.
166 Tropical rainforest conditions are found in the Lake Victoria Basin, while temperate climates occur
167 in the high-altitude regions of the Great Rift Valley. Kenya is the driest among the four countries,
168 with a total annual precipitation ranging from 400 to 600 mm near Lake Turkana and in areas
169 bordering Somalia. In contrast, southern parts of Uganda and Rwanda receive an annual rainfall
170 between 1,000 and 1,600 mm. These climatic conditions create a mosaic of environments, resulting
171 in a diverse range of agroecological zones and livestock production systems across East Africa (Fig.
172 1).

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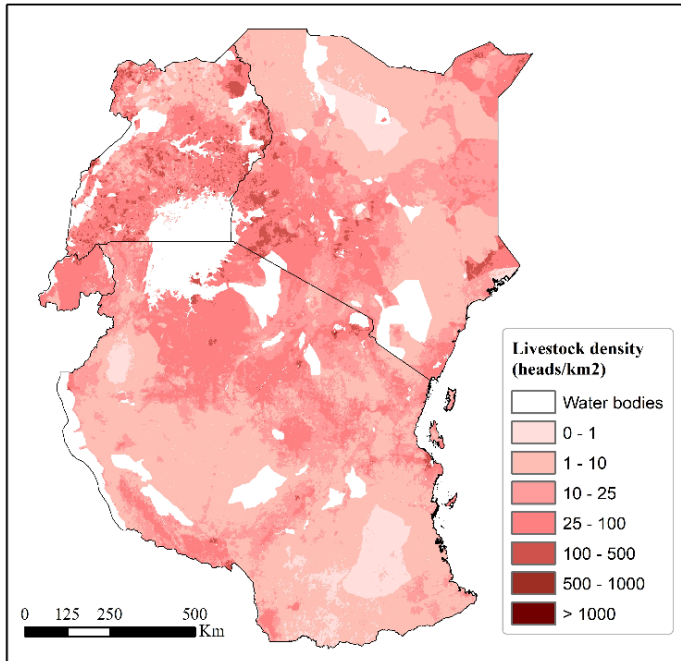
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Figure 2. Livestock production systems in East Africa. Source: [Robinson et al. \(2011\)](#)

2.2. Livestock production systems

2.2.1. Livestock density

Before characterizing the livestock production systems in East Africa, it is essential to have an overview of livestock density in Kenya, Rwanda, Tanzania, and Uganda. Although disaggregated values specifically for cattle are not available, [Fig. 2](#) illustrates the number of livestock units per km². Regions within approximately 150 km of Lake Victoria exhibit the highest livestock density, exceeding 50 heads per km², along with areas in northeastern Kenya. In contrast, southeastern Tanzania and the Lake Turkana region have densities of less than one animal per km².



185
 186 **Figure 2.** Livestock density (heads/km²) in East Africa. Figure adapted from Global Livestock of the World
 187 (GLW3) distribution dataset per km² for buffaloes, cattle, chicken, ducks, goats, horses, pigs and sheep (Gilbert
 188 et al. 2018)

189
 190 *2.2.2. Kenya*

191 The livestock production landscape in Kenya is categorized into three main systems (intensive, semi-
 192 intensive, and extensive) based on herd size, management practices, and inputs (FAO, 2018a). About
 193 39% of the country's milk is produced by intensive systems, known as zero-grazing, while 43% by
 194 semi-intensive, and 18% by extensive systems (FAO, 2022). In the Kenyan highlands, for example,
 195 over three-quarters of the smallholder dairy farms already fall under semi-intensive or intensive
 196 systems (Paul et al. 2022). Extensive farming systems relying on pasture are typically adopted by
 197 farms with larger herds, whereas agro-pastoral systems are key to livelihoods in arid regions.

198
 199 *2.2.3. Rwanda*

200 Rwanda's livestock production systems include intensive or zero-grazing, pastoral or open grazing,
 201 and semi-grazing (Habiyaremye et al. 2021). Notably, 94% of dairy animals are raised on zero-
 202 grazing farms and produce 93% of national milk (FAO, 2022). The zero-grazing systems consist of
 203 feeding cut-and-carry fodder, mostly Napier grass and crop residues to animals kept in sheds
 204 (Eugene, 2018). Semi-grazing systems involve feeding cattle a mix of grass and fodder, combining
 205 elements of both zero and open grazing, with only 4% of Rwandan dairy cows categorized as semi-
 206 grazing. Only 2% of national dairy herd is kept under open grazing, contributing to 3% of the national
 207 milk production.

208 *2.2.4. Tanzania*

209 Tanzania's traditional pastoralist system focuses on the production of meat and milk while managing
 210 large cattle herds grazing on natural pastures. These herds may be family-owned or part of
 211 commercial operations, with large-scale production concentrated in the northern and western regions,
 212 while smallholders dominate the southern highlands (FAO and NZAGGRC, 2019a). Traditional
 213 pastoral systems produce 91% of national milk, whereas intensive dairy systems produce 9% of
 214 national milk and keep 2% of the dairy herd (FAO, 2022).

215
 216 *2.2.5. Uganda*

217 Uganda's dairy industry is primarily led by traditional systems (extensive, agro-pastoral, and
218 pastoral), accounting for 86% of the country's milk production (FAO and NZAGGRC, 2019b).
219 Extensive systems keep around 18% of the herd and produce 24% of national milk (FAO, 2022).
220 Agro-pastoral systems are mainly managed using family labor and few purchased inputs, keeping
221 around 54% of the herd and producing 53% of the national dairy milk. Lastly, pastoral and semi-
222 nomadic pastoralists keep about 27% of the herd and produce 9% of national milk.

223

224 2.3. Livestock breeds

225 In East Africa, livestock breeds can be categorized into three genetic groups: indigenous breeds (e.g.,
226 Boran, Kenyan Sahiwal, Maasai Zebu, Bahima, Chagga, Iringa Red, Kigezi, Mpwapwa, Ruzizi,
227 Watusi, and Winam), exotic breeds (e.g., Holstein-Friesian, Jersey, Guernsey, Ayrshire, Brown Swiss,
228 and Milking Shorthorn), and crossbreeds between indigenous and exotic breeds (Kambal et al. 2023;
229 Rege, 1999). Indigenous breeds generally yield lower milk quantities and are kept for dual purposes,
230 such as meat and milk production (Akinsola et al. 2023). Indigenous breeds are highly adapted to
231 harsh environmental conditions and tolerant to endemic diseases. Indigenous cattle groups in Kenya,
232 Tanzania, and Uganda include large and small East African Zebu, Zenga, and Sanga, whereas
233 Rwanda mostly has the Sanga breed (Mwai et al. 2015).

234

235 In this work, we assessed the effects of heat stress on Boran's welfare and production. Boran cattle
236 (*Bos indicus*) possesses a combination of morphological, structural, and physiological traits that
237 confer high tolerance to heat stress in East African pastoral systems (Haile, 2011) and is more
238 productive than other indigenous breeds (Cossins et al. 1998). It can survive and reproduce under
239 high ambient temperatures while utilizing low-quality fodder resources and enduring water shortages
240 and long watering intervals (Bayssa et al. 2021). Boran cows in, for example, Ethiopia can produce
241 843 kg of milk over a 36-week lactation period (about 3.3 kg/day) under the pastoralist system in the
242 Borana rangelands. Morphologically, they typically have a light grey to fawn coat that reflects solar
243 radiation, along with a short hair coat and thin, highly pigmented, and motile skin that enhances
244 convective and evaporative heat loss while protecting underlying tissues from ultraviolet radiation.
245 Structurally, long legs elevate the body above hot ground surfaces, reducing conductive heat gain
246 and enabling long-distance trekking, while large dewlaps and wide ears increase surface area for
247 metabolic heat dissipation. Physiologically, Boran cattle exhibits low maintenance energy
248 requirements, efficient fat mobilization, and adaptive water-conservation mechanisms, allowing
249 sustained productivity and reproductive performance under high temperatures, feed scarcity, and
250 limited water availability (Bayssa et al. 2021).

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256 2.4. Historical and future climate data

257 The W5E5 dataset for the 1980-2009 period, which is an observational gridded dataset with global
258 coverage at a 0.5° spatial resolution, was adopted in this study due to its strong performance ratings
259 for temperature and precipitation variables (Cucchi et al. 2020). The W5E5 dataset is derived from
260 the ERA5 dataset and adjusted using global observational datasets such as CRU TS4.03 and
261 GPCPv2018 (Harris et al. 2020; Schneider et al. 2018). It provides daily information for twelve
262 climatic variables covering the period from 1980 to 2019 and is recognized as the reference dataset
263 by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for impact assessment studies
264 such as this one.

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For future climate projections, this study embraces CORDEX-CORE, which aims to establish a common climate modeling framework globally (Giorgi et al. 2021a). The CORDEX-CORE initiative provides consistent regional climate projections across most inhabited land regions using nine CORDEX domains at a 0.22° spatial resolution (~25 km). The reason for selecting three specific GCMs in this work is that, on the one hand, these GCMs have a high (HadGEM2-ES), medium (MPI-ESM-MR), and low (NorESM1-M) equilibrium climate sensitivity within the Coupled Model Intercomparison Project-5 (CMIP5) ensemble; and, on the other hand, they perform reasonably well over most of the CORDEX-CORE domains (Elguindi et al. 2014; McSweeney et al. 2025). Future simulations were run for two climate change scenarios: Representative Concentration Pathway (RCP) 2.6 and 8.5, which correspond to approximately 490 and 1370 ppm CO₂ equivalent by 2100, respectively (Van Vuuren et al. 2011; Clarke et al. 2007; Riahi et al. 2011). The selection of RCPs 2.6 and 8.5 covers the Intergovernmental Panel on Climate Change (IPCC) range of greenhouse gas concentration pathways for the 21st century. Therefore, projected changes under the intermediate scenario (RCP 4.5), aiming to stabilize global temperature increases at 2 to 3 °C, are considered to fall within the simulation range of RCPs 2.6 and 8.5. Outputs from the GCMs are dynamically downscaled using the Regional Climate Model (RCM) REMO2015 at a 0.22° spatial resolution (Giorgi et al. 2021b). REMO2015 is selected because it has completed the full set of CORDEX-CORE experiment simulations (Giorgi et al. 2022; Jacob et al. 2012). Although RCMs can effectively represent regional climates, they often suffer from systematic biases that may limit their usefulness in impact assessment studies. To address these biases and correct climate projections, we selected the period running from 1976 to 2005 as the overlapping timeframe between the W5E5 reanalysis dataset and the CORDEX-CORE historical simulation runs, concluding in 2005.

2.5. Direct effects of climate change

The analytical framework used to assess the effects of heat stress on dairy animals was based on the THI formula (Eq. 1) adopted in Sub-Saharan Africa by Ekine-Dzivenu et al. (2020), slightly differing from that of Hahn et al. (2009). However, a cross-validation of both formulas yielded nearly identical THI results (results not shown for brevity). After computing the THI units for each day using temperature and relative humidity data from CORDEX-CORE simulation runs, the THI units were categorized into four THI classes using the thresholds (Table 1) proposed by Rahimi (2020) for beef cattle in East Africa. Lastly, the THI daily data was aggregated into 30-year periods: 1980-2009 for the historical period and 2010-2039, 2040-2069, and 2070-2090 for future periods.

Table 1. Degree of heat stress on beef cattle in East Africa.

THI category	THI units	Animal's responses
None	THI ≤ 75	- Both productive and reproductive performance are optimum
Mild	75 < THI ≤ 81	- Livestock body can control heat stress by chemical and physical means. - Livestock seeks shade. - Rectal temperature and respiration rates increase. - Dilatation of blood vessels.
Moderate	81 < THI ≤ 91	- Body temperature increases and productive and reproductive are severely affected. - Respiration rates significantly increase.

		- Dry matter intake and ratio of forage to concentrate intake decreases.
		- Water intake significantly increases.
Severe/Danger	THI >91	- Respiration and excessive saliva production increases.
		- Productive and reproductive performance significantly decrease.
		- Rumination and urination decrease.
		- Livestock may die under extreme stress conditions.

305

$$306 \quad \text{THI} = (1.8 \times T_{\text{max}} + 32) - [(0.55 - 0.0055 \times \text{RH}) \times (1.8 \times T_{\text{max}} - 26.8)] \quad (\text{Eq.1})$$

307 *Where T_{max} is the maximum daily temperature in °C and RH the daily relative humidity in %*

308

309 The increase in air temperature and relative humidity can result in a significant milk production
 310 decline (MDEC). From a quantitative perspective, [Bernabucci et al. \(2010\)](#) reported a daily milk loss
 311 of 0.27 kg for each THI unit increase. In this study, changes in milk production were calculated using
 312 the formula (Eq. 2) proposed by [Berry et al. \(1964\)](#) and extensively applied in literature (see, for
 313 example, [Hammami et al. 2013](#)):

314

$$315 \quad \text{MDEC (kg/day)} = -1.075 - 1.736\text{NL} + (0.02474\text{NL} \times \text{THI}) \quad (\text{Eq.2})$$

316 *Where NL is the normal level of daily milk production (kg/day) for Boran (3.3 kg/day) under TNZ*

317 In Eq. 2, the baseline net lactation yield ($\text{NL} = 3.3 \text{ kg day}^{-1}$) for Boran cattle represents an average daily milk
 318 yield under extensive pastoral conditions, derived from published estimates for indigenous cattle in East
 319 African arid and semi-arid systems. This value reflects a long-term mean across the lactation period, rather
 320 than peak yield, and implicitly integrates seasonal variability in feed and water availability characteristic of
 321 pastoral production systems. The baseline is, therefore, intended as a reference production level under non-
 322 intensive management, suitable for use in comparative and climate-sensitivity analyses rather than as a stage-
 323 specific or high-input performance estimate.

324

325 2.6. Indirect effects of climate change

326 Climate change may affect the availability and quality of fodder indirectly. It can result in feed
 327 shortages and decline in livestock productivity. To gain a better understanding of fodder changes, we
 328 estimated the impacts of climate change on potential yields using the AEZ method developed by the
 329 FAO and the International Institute for Applied Systems Analysis (IIASA) for land evaluation ([FAO
 330 and IIASA, 2000](#)). AEZ integrates crop simulation models with land management decision analysis
 331 to capture changes in agroclimatic resources over time ([Fischer et al. 2021](#)). To simplify the
 332 application of AEZ, a Python package (referred to as PyAEZ) is used to encapsulate the complex
 333 calculations involved in AEZ.

334

335 PyAEZ includes six main modules: (i) climate regime, (ii) crop simulations, (iii) climate constraints,
 336 (iv) soil constraints, (v) terrain constraints, and (vi) economic suitability analysis. All the climate
 337 data generated during the historical (W5E5) and future (CORDEX-CORE) simulation runs were used
 338 as data input in module 1. PyAEZ calculates biomass based on an eco-physiological model
 339 ([Deshapriya et al. 2020](#)). Constraint-free crop biomass accumulates throughout the growing season,
 340 driven mainly by incoming solar radiation, temperature, and crop-specific characteristics (e.g., crop
 341 length, maximum photosynthesis rate, leaf area index at full development, harvest index, and crop
 342 sensitivity to heat). To maximize yields, PyAEZ automatically determines the optimal start of the
 343 growing season. Here, simulations are conducted under rain-fed conditions and yield projections are
 344 bias-corrected based on historical simulations and by using the differences between simulated yields
 345 in the first projected year and those of the last historical year (2010). The results are then averaged
 346 by administrative boundaries, as PyAEZ produces outputs at the same spatial resolution as the
 347 climate models. Yield results from different climate models are ensembled for various periods (2031-
 348 2060 and 2061-2090) and analyzed for two RCPs (2.6 and 8.5).

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To assess the indirect impacts of climate change on livestock production, we selected maize (*Zea mays*) and Napier grass (formerly *Pennisetum purpureum*, now *Cenchrus purpureus*). Maize is commonly used as a basal feed and a source of fiber, carbohydrates, and protein in the form of silage, stover (residues), and grain (Nyokabi et al. 2022; Maleko, 2018). Maize starch provides a combination of rumen-fermentable energy, fueling the microbial population, and rumen bypass starch, which is then converted into glucose that the animal absorbs and utilizes. On the other hand, Napier grass is a fast-growing perennial grass native to Sub-Saharan Africa and serves as a multipurpose fodder crop, primarily used for feeding cattle in cut-and-carry production systems (Islam et al. 2024). Napier grass is used by East African smallholder farmers for cattle fattening and obtaining higher milk yields (Islam et al. 2023). Given that most smallholder farmers own small and fragmented land parcels, Napier grass represents an ideal alternative to other feed options due to their high yield, low input requirements, and minimal acreage needed for cultivation.

3. Results

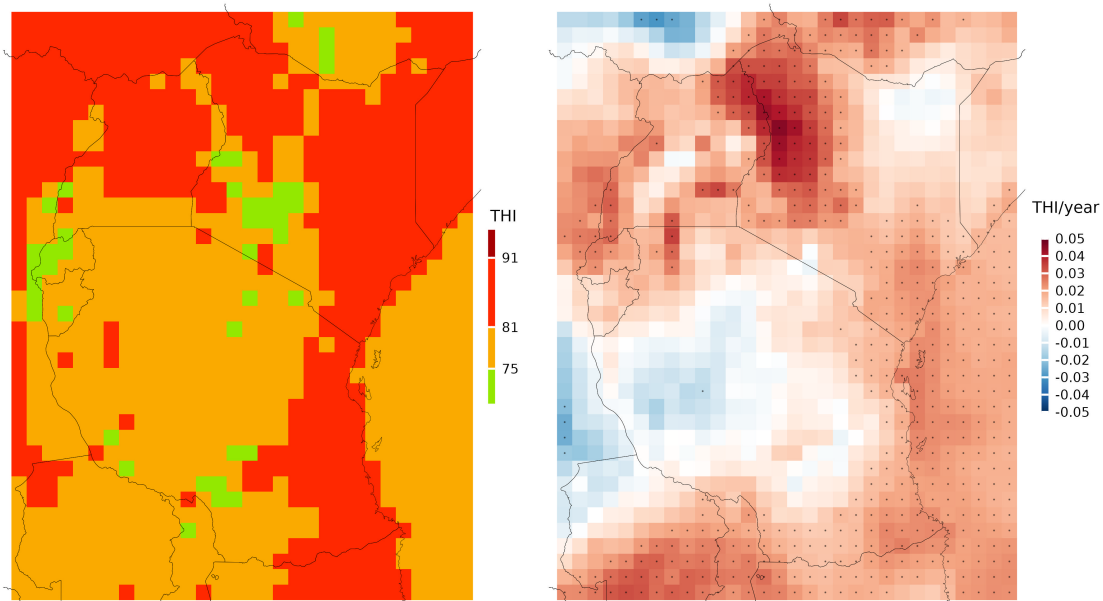
3.1. Effects of climate change on animal welfare

3.1.1. Historical THI analysis

Annual-averaged THI historical (1980-2009) results shows moderate stress ($81 < \text{THI} \leq 91$) conditions across Uganda, Kenya, and the eastern region of Tanzania (Fig. 3a). In these areas, moderate THI has already affected milk production (see Table 1) and reproductive parameters. Conversely, in high-altitude areas of south-west Kenya, Tanzania, and Rwanda the level of THI stress was either mild ($75 < \text{THI} \leq 81$) or none ($\text{THI} \leq 75$). In areas experiencing mild stress, animal respiration rates have been noted, though the impact of heat on milk yields was minimal. Historical THI trends also reveal statistically significant differences ($p < 0.05$) across the arid and semi-arid zones of Kenya, including Uganda's Karamoja drylands and the coastal and southern regions of Tanzania (Fig. 3b). In these areas, THI units have risen at a rate of 0.02 to 0.04 units per year, totaling an increase of 0.70 to 1.40 since 1980. In contrast, THI units in central Tanzania and northeast Kenya have remained unchanged or slightly decreased since 1980.

a)

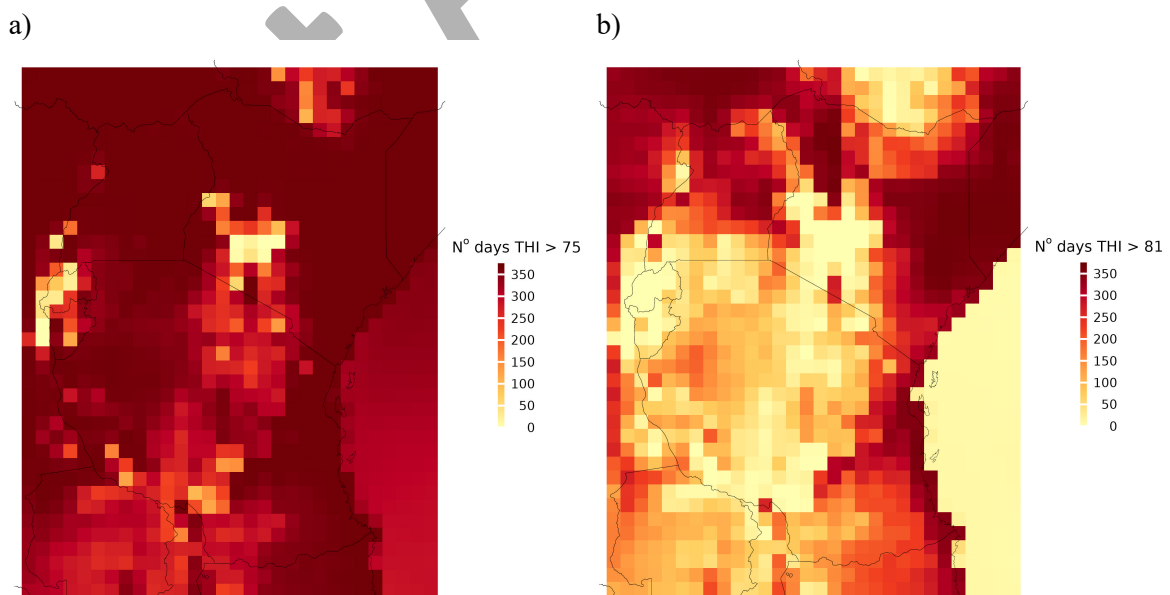
b)



389
 390 **Figure 3.** (a) Annual-averaged THI classes and (b) yearly change (THI units/year) over 1980-2009. Pixels with
 391 a black dot in Fig. 1b show statistically significant differences ($p < 0.05$) over the historical period
 392

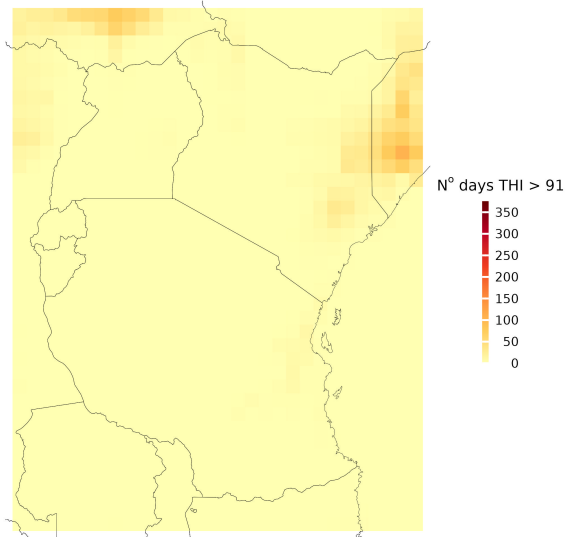
393 Fig. 4 displays the annual count of days with above mild (THI > 75), moderate (THI > 81), and
 394 severe/danger (THI > 91) heat stress conditions during the historical period from 1980 to 2009. Year-
 395 round (>300 days/year) mild stress conditions were observed in most regions, with exceptions in the
 396 mountainous south-western parts of Kenya, Rwanda, and south-western Tanzania (Fig. 4a).
 397 Additionally, the highest (300 days/year) annual count of days with above moderate stress conditions
 398 were reported in central parts of Uganda, areas around Lake Turkana and eastern parts of Kenya, as
 399 well as the coastal areas of Tanzania (Fig. 4b). Lastly, severe/danger (~50days/year) conditions
 400 were only observed in small pockets of eastern Kenya (Fig. 4c). However, short-duration extreme (THI >
 401 91) conditions fatal to animals may have occurred but are not detectable in annual averages.

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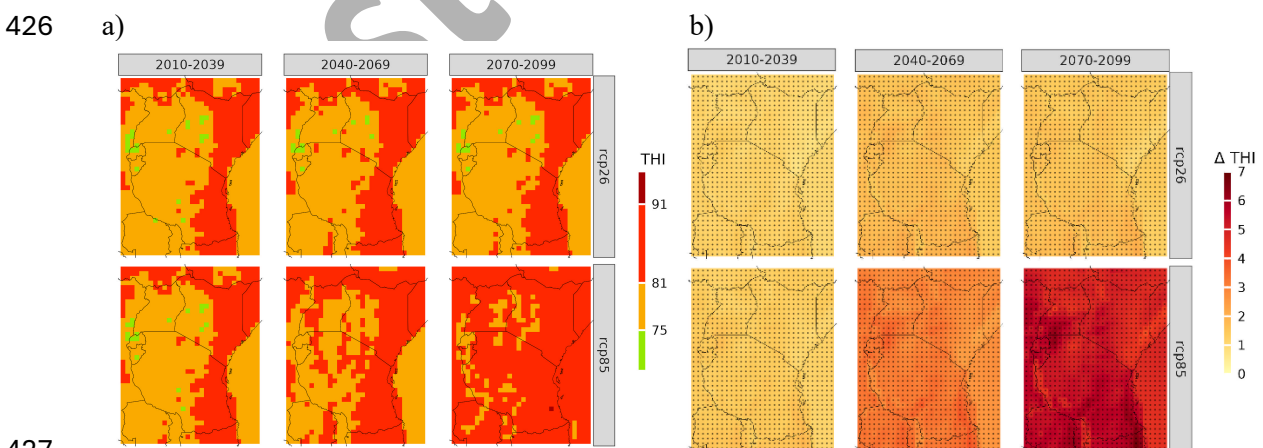
c)



409
410 **Figure 4.** Annual-averaged count of days under (a) mild (THI >75), (b) moderate (THI >81), and (c)
411 severe/danger (THI >91) heat stress over 1980-2009
412

413 *3.1.2. Future THI analysis*

414 Climate change is expected to increase Boran's exposure to heat stress (Fig. 5a). Under RCP 2.6,
415 areas under moderate (81 < THI ≤ 91) stress rise slightly until mid-century and then remain constant.
416 In contrast, under RCP 8.5, moderate stress expands across all territories, particularly by mid- to late-
417 century. Only a few areas will experience mild (75 < THI ≤ 81) stress whereas areas under no stress
418 (THI < 75) vanish completely under both RCPs. This significant rise in body temperature and
419 respiration rates driven by heat stress will likely lead to substantial losses in milk production and a
420 decrease in reproductive success for cows in these areas. Additionally, Fig. 5b illustrates the
421 incremental change in THI units for both RCPs throughout the century relative to 1976-2005. THI
422 units are projected to increase by 1 to 2 units under RCP 2.6, and by 3 to 4 and 5 to 6 units by the
423 mid and end of the century, respectively, under RCP 8.5. In the southern regions of Uganda and along
424 the Tanzanian coastline, the THI increase could reach 6 to 7 units by 2070-2099 under RCP 8.5.
425

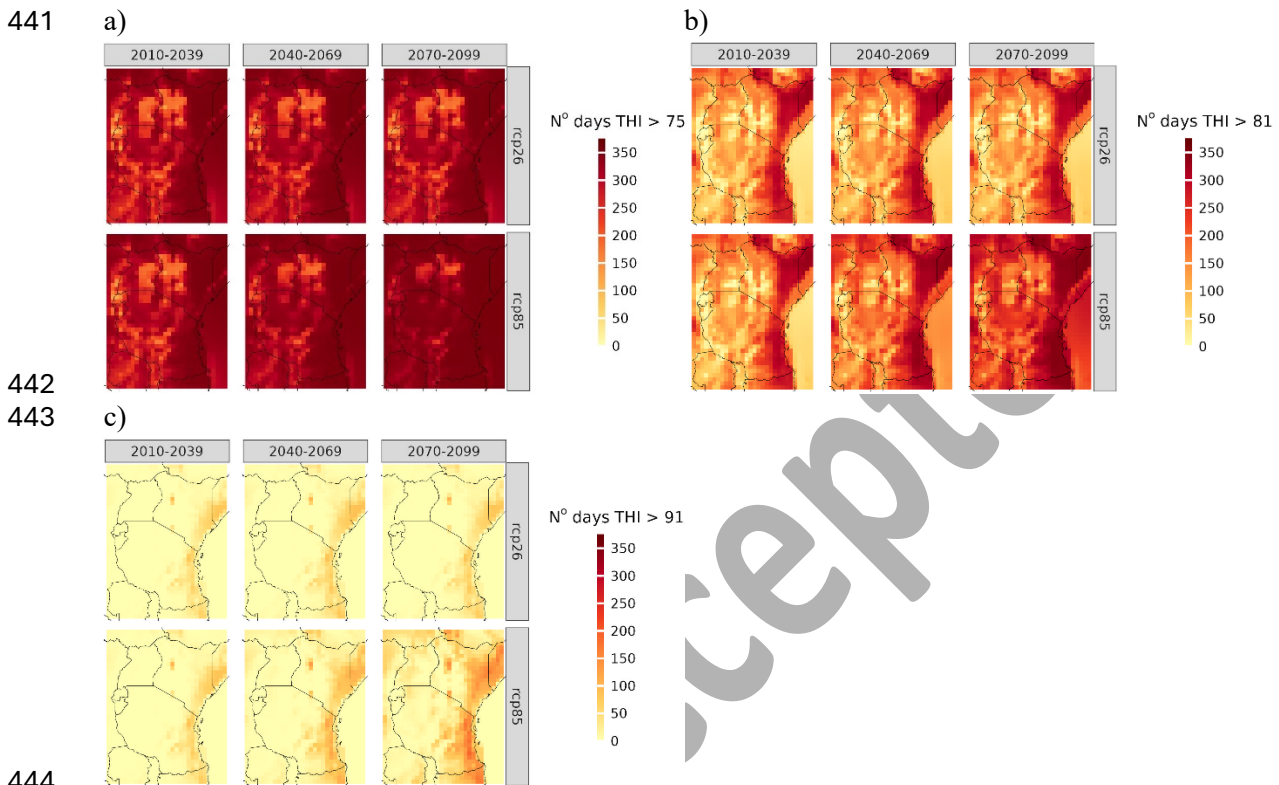


427
428 **Figure 5.** Projected (a) THI classes and (b) THI unit increase over the century for RCPs 2.6 and 8.5 relative to
429 1976-2005. A black-dot in Fig. 3b represents a high GCM agreement in the climate change signal
430

431
432 Fig. 6 depicts the change in the annual average number of days when specific THI conditions are met
433 across the century for different RCPs relative to 1976-2005. Fig. 6a shows a year-round and

434 widespread increase of mild ($75 < \text{THI} \leq 81$) stress conditions across all countries, throughout the
 435 century and under both RCPs. Moderate ($81 < \text{THI} \leq 91$) stress, characterized by substantial milk
 436 yield losses and reduced reproductive rates, further increase (250-350 days/yours) in coastline areas
 437 by 2070-2099 under RCP 8.5 (Fig. 6b). Under the worst-case scenario, recurrent fatal conditions
 438 ($\text{THI} > 91$) for animals may increasingly occur (0-50 days/year under RCP 2.6 and 100-150 days/year
 439 under RCP 8.5), particularly along the Tanzanian and Kenyan coastlines (Fig. 6c).

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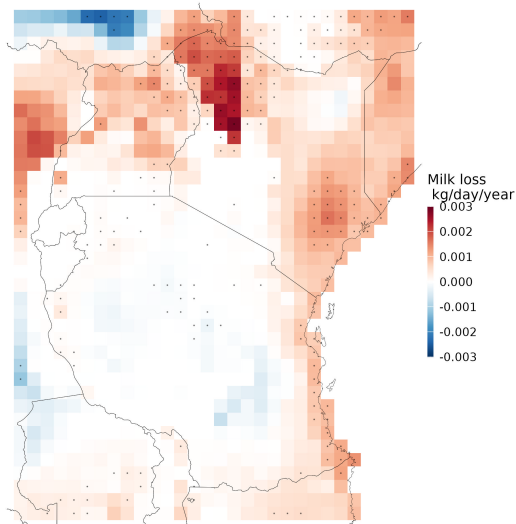
444

445 **Figure 6.** Change in the average count of days under (a) mild ($\text{THI} > 75$), (b) moderate ($\text{THI} > 81$), and (c)
 446 severe/danger ($\text{THI} > 91$) heat stress over the century for RCPs 2.6 and 8.5 relative to 1976-2005. A black-dot
 447 represents a high GCM agreement in the climate change signal
 448

449 3.2. Effects of climate change on milk production

450 3.2.1. Historical milk yield analysis

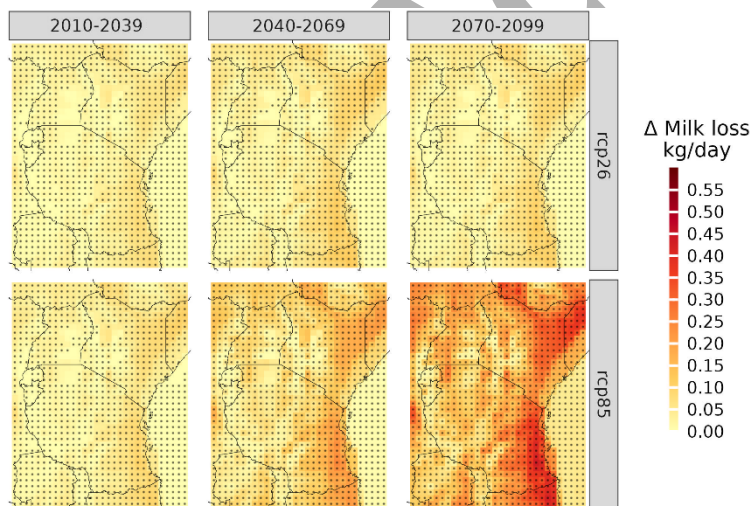
451 Fig. 7 illustrates the annual average milk losses (kg/day) for the Boran breed from 1980 to 2009.
 452 Since 1980, areas along Lake Turkana have experienced a statistically significant ($p < 0.05$) decrease
 453 in milk yield losses of 0.002 kg/day per year. This decline corresponds to a daily milk reduction of
 454 0.6 kg/day from a baseline of 3.3 kg/day under TNZ. Coastal regions of Tanzania and Kenya have
 455 also reported a statistically significant decline in milk yields, although these reductions are less
 456 pronounced (0.001 kg/day per year) than those observed along Lake Turkana. In contrast, in central
 457 and southeastern areas of Tanzania milk yields have remained stable since 1980.
 458



459
 460 **Figure 7.** Annual-averaged daily milk losses (kg/day per year) for Boran over 1980-2009. Pixels with a black-
 461 dot show statistically significant differences ($p < 0.05$) over the historical period
 462

463 3.2.2. Future milk yield analysis

464 Future milk yield projections indicate strong GCM consensus regarding the impact of climate
 465 change. Under RCP 2.6, estimates suggest a slight loss of about 0.15 kg/day by 2070-2099 relative
 466 to 1976-2005 (Fig. 8). However, milk yield losses are intensified under RCP 8.5. For instance, along
 467 the Tanzanian coastline and northeastern parts of Kenya, milk yields are expected to decline by 0.30-
 468 0.45 kg/day by 2070-2099. Other areas in Uganda will see additional milk declines of about 0.15-
 469 0.25 kg/day by 2070-2099. Overall, Rwanda is the country that will experience the least declines in
 470 milk yields.
 471



472
 473 **Figure 8.** Projected daily average milk production losses (kg/day) for Boran breed over the century for RCPs
 474 2.6 and 8.5. A black-dot represents a high GCM agreement in the climate change signal
 475

476 3.3. Effects of climate change on fodder resources

477 Fig. 9a illustrates the areas in East Africa with the highest potential to sustain maize yields under
 478 rain-fed conditions during the baseline period and across future timeframes (2031-2060 and 2061-
 479 2090). The highest yield potential during the baseline period is observed across the entirety of
 480 Rwanda, western Tanzania, the western and central regions of Uganda, and northwestern Kenya.
 481 Conversely, the eastern and southern parts of Tanzania and Kenya exhibit the lowest yield potential
 482 for maize in the baseline period. In the mid-term (2031-2060) and long-term (2061-2090), northern

483 Kenya and Uganda are expected to experience the most significant changes in maize yields, with
 484 yield losses estimated at 5 to 10% under RCP 2.6 and 15 to 25% under RCP 8.5 by 2061-2090. On
 485 the other hand, in central, western, and eastern regions of Uganda, the entirety of Rwanda, and most
 486 of Tanzania (except for northern areas) maize yields are unaffected under both RCPs. Maize yield
 487 variations are primarily driven by changes in precipitation and temperature patterns, particularly
 488 pronounced under RCP 8.5 (results not shown for brevity).

489

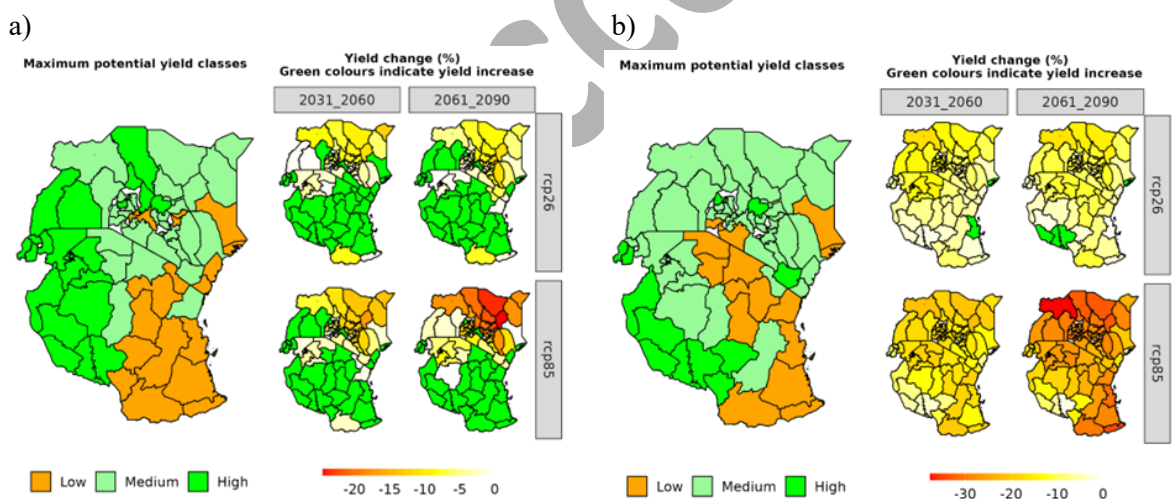
490 **Fig. 9b** shows medium potential yield class for Napier grass in most parts of Uganda and Kenya in
 491 the baseline period, while high potential in Rwanda and southwestern Tanzania. Conversely, the
 492 eastern and northern parts of Tanzania are classified as low potential. Most areas are anticipated to
 493 experience yield declines ranging 0 to 10% in the mid-term (2031-2060) and further into the future
 494 (2061-2090) under RCP 2.6; except for southwestern Tanzania, which is expected to face minor yield
 495 losses. Under RCP 8.5, the most significant declines in Napier grass yields are anticipated in northern
 496 Uganda (30-35%), northern Kenya (30%), and southeastern Tanzania (20-30%).

497

498 Overall, livestock production systems in northern Kenya, which are predominantly extensive and
 499 heavily reliant on cultivated maize, may be at a higher risk compared to Rwanda, where maize yields
 500 are anticipated to remain unchanged. In northwestern Kenya and northern Uganda, animal feed
 501 shortages are likely to worsen due to a decline in Napier grass, primarily impacting the cut-and-carry
 502 fodder systems. Although southwestern Tanzania is not a livestock predominant area, the analysis
 503 shows rising yields for both maize and Napier grass, presenting a potential opportunity for enhancing
 504 livestock production systems across these areas.

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Figure 9. Maximum potential yield classes and yield change (%) for (a) maize and (b) Napier grass under rain-fed conditions over the century for RCPs 2.6 and 8.5. Yield results from different climate models are averaged (ensemble) for different time periods

512

4. Discussion

513

4.1. Direct impacts on cattle

514

Heat stress is generally considered the most detrimental climate factor affecting cattle welfare and productivity (Carvajal et al. 2021; Rahimi et al. 2021; Thornton et al. 2021; Kadzere et al. 2002). Cattle exhibit various physiological responses to heat stress, including sweating, increased respiration rates, vasodilation that enhances blood flow to the skin's surface, elevated rectal temperature, reduced metabolic rate, decreased dry matter intake, lower feed utilization efficiency, and changes in water metabolism. Heat stress also negatively impacts reproduction, leading to diminished fertility and lower conception rates (Dovolou et al. 2023; Ahmad et al. 2018; Ganaie,

520

521 2013). Boran is recognized as one of the hardiest indigenous breeds for milk and meat production
522 (Bayssa et al. 2021), whereas high-producing dairy cattle breeds are more susceptible to heat stress.
523 Boran's ability to survive, produce, and reproduce under high ambient temperatures and water
524 scarcity is attributed to a combination of morphological, physiological, biochemical, metabolic,
525 cellular, and molecular adaptations (Bayssa et al. 2021). Some behavioral responses to climate stress
526 observed in arid and semi-arid of East African rangelands is the reduction in feed intake and
527 decreasing water excretion (Valente et al. 2015)

528

529 Our analysis indicates that Boran cattle is already experiencing some level (mild or moderate) of heat
530 stress during the baseline period, except for high-altitude areas in the Great Rift Valley and the
531 Buberuka Highlands in Rwanda, where heat stress is minimal (Fig. 3). These findings align with
532 those of Rahimi et al. (2021), who reported a higher frequency of moderate THI stress across the four
533 studied countries, excluding high-altitude regions in Kenya and Tanzania. Future climate scenarios
534 suggest a widespread increase in moderate stress conditions, particularly by the end of the century
535 and under RCP 8.5. The Tanzanian coastline is expected to experience severe/danger levels that could
536 be fatal to animals (Figs. 5a, 6c), though these areas are not livestock predominant (Fig. 1). In
537 contrast, northeastern and eastern Kenya, which are characterized by extensive livestock systems that
538 rely on shrubland, are projected to see an increase in the annual average number of days with
539 severe/danger (Fig. 6c) heat stress, particularly under RCP 8.5.

540

541 THI values are projected to rise by 1 to 2 units under RCP 2.6 and by 5 to 6 units under RCP 8.5.
542 Bernabucci et al. (2010) noted a milk loss of 0.27 kg per day for each THI unit increase, highlighting
543 the potential magnitude of milk losses in the region. According to Bernabucci et al. (2010) this is
544 expected to result in an estimated milk production decline ranging from 0.54 to 1.62 kg/day. The
545 latter per-unit THI loss rate was derived from high-producing Holstein cows and, as anticipated,
546 exceeds our estimates (0.15-0.45 kg/day by 2070-2099) for the low-producing Boran breed, which
547 shows proportionally lower absolute losses but potentially similar relative impacts on production
548 capacity. The former represents a reduction of 4.5% to 14% for RCPs 2.6 and 8.5, respectively. Other
549 regional studies (Rahimi et al. 2020) using three GCMs (GFDL-ESM2M, HadGEM2-ES, and MPI-
550 ESM-MR) show milk production losses of 9%, 17%, and 35% under RCP 4.5 for the period 2071-
551 2100 in West Africa.

552

553 4.2. Impacts on fodder supply

554 Feed shortage is a major constraint in dairy production systems in East Africa, leading to high milk
555 production fluctuations due to pastoralists' dependence on precipitation for fodder production. Even
556 during the wet season, there is not adequate fodder to be preserved and stored for use during the dry
557 season (Ongadi et al. 2020). Climate-driven fluctuations in maize and Napier grass yields threaten
558 consistent fodder supply, particularly for smallholders reliant on rain-fed systems. Additionally,
559 reduced fodder quality (e.g. lower protein content in Napier grass) may decrease milk yields,
560 especially for high-producing exotic breeds (Brychkova et al. 2022). Our findings on maize and
561 Napier grass reveal even direr consequences to the dairy sector in East Africa, especially for extensive
562 livestock production systems in the north of Uganda and Kenya. In these areas, smallholder dairy
563 farms mostly rely on rain-fed production systems, though rainfall is erratic and sometimes
564 inadequate.

565

566 The decline in maize yields is primarily driven by heat stress conditions reducing pollen viability,
567 which subsequently affects kernel development (Lizaso et al. 2018). Additionally, water deficit
568 stresses during the flowering and grain-filling stages can lead to significant yield penalties,

569 particularly among non-drought-tolerant varieties (Sah et al. 2020). Stuch et al. (2021) estimate a
570 decrease in maize yields of approximately 32% in East Africa between 1971-2000 and 2041-2070,
571 with some exceptions in high-altitude areas where yields might increase as current cold related stress
572 will diminish under future warmer conditions. Other regional studies, such as those conducted in
573 Ethiopia, report declines in maize yields ranging from 24% to 43% in regions experiencing high
574 rainfall variability and the greatest temperature increases (Abera et al. 2018). Additionally, there are
575 few studies addressing the impacts of climate change on forage grass species in East Africa; however,
576 existing literature indicates that perennial C4 grasses are expected to benefit from rising ambient CO₂
577 levels (Brychkova et al. 2022). A study conducted on Ethiopia suggests that fodder demands of the
578 dairy system could be met by the production of forage grasses under both current and future climate
579 conditions. However, if land availability decreases and herd composition shifts towards higher-
580 productivity exotic breeds, such as Holstein-Friesian, the forage resources may not be sufficient to
581 meet cattle demand, even with improved agronomic management. Our findings contrast with those
582 of Brychkova et al. (2022), likely because the PyAEZ model does not account for changes in
583 atmospheric CO₂. PyAEZ predicts Napier grass yield losses of up to 10% under RCP 2.6 and between
584 20% and 30% under RCP 8.5 in northern Uganda and Kenya.

585

586 Overall, our study findings indicate a significant decrease in both maize and Napier grass yields
587 along the Lake Turkana region in Kenya and in the Karamoja Drylands in Uganda. As cultivated
588 fodder availability declines, livestock dependence on natural rangelands is likely to increase,
589 intensifying grazing pressure in already fragile dryland ecosystems. In extensive livestock systems,
590 this increased pressure often exceeds the regenerative capacity of native pastures, leading to
591 reductions in perennial grass cover, increased bare soil exposure, and declining soil organic matter;
592 key indicators of land degradation (Brychkova et al. 2022). These processes create a reinforcing
593 feedback loop in which degraded rangelands further reduce forage availability, prompting wider herd
594 movements and greater spatial concentration of grazing. Resulting feed shortages have already
595 contributed to internal and cross-border competition over grazing and water resources among
596 pastoral communities (Anno and Ameripus, 2022), a dynamic that is likely to intensify under
597 projected climate change through increased rainfall variability and more frequent drought conditions.

598

599 4.3. Adaptation strategies

600 Effective adaptation to increasing heat stress in East African pastoral systems requires integrated
601 strategies that operate at animal, herd, and rangeland levels and are aligned with local socio-
602 ecological realities. Recent evidence from extensive livestock systems in East Africa indicates that
603 relatively low-cost management interventions such as improved access to water, provision of shade
604 (natural or artificial), and heat-aware grazing schedules can substantially reduce thermal load and
605 productivity losses, making them economically feasible for pastoralists and smallholders with
606 limited capital (Bashiru and Oseni, 2025). At the landscape scale, sustainable rangeland management
607 practices, including controlled grazing, seasonal mobility, and restoration of degraded pastures, have
608 been shown to enhance forage availability, reduce land degradation, and strengthen ecosystem
609 resilience under increasing climate variability (Njuguna, 2024).

610 Breed-based and system-level strategies are particularly important for long-term sustainability. The
611 conservation and strategic use of heat-tolerant indigenous breeds, especially *Bos indicus* cattle,
612 represent a cost-effective and climate-robust adaptation pathway compared with reliance on high-
613 producing but heat-susceptible exotic breeds (Bashiru and Oseni, 2025). Complementary measures
614 such as forage diversification, emergency feed reserves, and early warning systems that integrate
615 climate and heat-stress indicators can further support anticipatory decision-making by policymakers

616 and field operators (Njuguna, 2024). Indigenous adaptation practices, including seasonal herd
617 mobility and local water-management strategies, remain central to sustaining livestock productivity
618 in arid and semi-arid lands and should be strengthened rather than replaced by external interventions
619 (Mungâ et al. 2019).

620

621 4.4. Uncertainties of this study and future research perspectives

622 Imprecise yield estimations are further exacerbated when simulating the impact of future climate on
623 crop yields, particularly due to the use of inappropriate climate downscaling methods and a limited
624 number of GCMs and RCMs. This study addresses these challenges by employing dynamic
625 downscaling methods with RCMs, utilizing state-of-the-art reanalysis datasets (W5E5) for impact
626 assessments, and selecting three GCMs with varying (high, medium, and moderate) equilibrium
627 climate sensitivities. Furthermore, the causes of inaccurate yield gap estimations using top-down
628 approaches, such as PyAEZ, have been thoroughly examined in literature (Alvar-Beltrán et al. 2023;
629 Mourtzinis et al. 2017). Critical issues associated with these methods include reliance on secondary
630 (unmeasured) gridded data, the coarse resolution of global soil maps, and insufficient ground data,
631 which can result in inaccurate parameterization of cropping systems. These factors contribute to a
632 misleading perception of data quality and availability in spatial grids. Additionally, since PyAEZ
633 does not account for CO₂ fertilization, it may have led to an overestimation of yield losses.

634

635 THI is valuable because it provides a simple, actionable proxy for heat risk, but it is inherently an
636 approximation — accurate assessment requires accounting for species, microclimate, physiology,
637 and management. While the thermal categories for cattle are broadly recognized in literature,
638 uncertainties emerge when evaluating the effects of heat stress on specific breeds, particularly heat-
639 tolerant breeds like the Boran. Additionally, existing MDEC formulas lack correction factors tailored
640 to individual cattle breeds, resulting in flexibility constraints that restrict their applicability.

641

642 Future research perspectives should focus on addressing the limitations of top-down approaches like
643 PyAEZ through the incorporation of CO₂ fertilization effects on fodder resources. This will help
644 improve future crop yield estimations. There is also a need for focused studies on the implications of
645 heat stress on various cattle breeds, especially heat-tolerant breeds, to develop breed-specific
646 correction factors for existing MDEC frameworks. This will allow for a quantitative assessment of
647 the impact of THI stress on various cattle breeds, helping to identify those that are better suited for
648 future climate conditions. Other heat-related factors such as accumulation of heat-load (balance of
649 heat gained and lost by an animal during the day and night) could be further explored.

650

651 5. Conclusion

652 This research comprehensively evaluates the direct (animal welfare and production) and indirect
653 (fodder availability) impacts of heat stress on the Boran breed, revealing the intricate repercussions
654 faced by pastoral systems in East Africa. The escalating challenges to animal welfare and milk
655 production, particularly in vulnerable pastoral regions, underscore a pressing need for intervention,
656 except for certain areas in Rwanda and the high-altitude areas of Kenya and Tanzania. As critical
657 issues such as livelihood loss, food insecurity, and conflicts over dwindling natural resources
658 intensify in already food-insecure areas of northern Kenya and Uganda, our study illuminates current
659 vulnerabilities and suggests adaptive solutions. Some of the actionable adaptation solutions (see also
660 section 4.3) to modulate increasing heat stress conditions include: (i) livestock housing and climate-
661 proofed processing plants; (ii) tree shelters in fields; (iii) animal bed and mattress cooling in barns;
662 (iv) ventilation and evaporative cooling methods using fans and water misters/springs in barns; (v)
663 timely and actionable agrometeorological services including nearby suitable grazing areas and water

664 points; (vi) heat index maps and transhumance corridors; (vii) risk transfer financial mechanisms;
665 (viii) breeding heat-tolerant animal species; (ix) use of drought-tolerant crops and forages; and (x)
666 dietary modifications, among many others.

667

668 Given the pivotal role of livestock research in supporting the livelihoods of dairy producers, agro-
669 pastoralists, and farmers in mixed crop-livestock systems across East Africa, our work lays a
670 foundation for future studies aimed at enhancing risk awareness. This study's strengths and
671 limitations serve as both a benchmark and an invitation for further exploration into the impacts of
672 climate change on other indigenous and improved exotic breeds across the region. Overall, the
673 science-based provided here informs targeted investments in climate resilience and disaster risk
674 management and empowers development agencies, research institutions, and national stakeholders
675 to identify high-risk areas while evaluating the cost-effectiveness of implementing climate actions
676 versus their anticipated benefits.

677

678 **Declaration of Interest Statement**

679 The authors declare that they have no known competing financial interests or personal relationships
680 that could have appeared to influence the results reported in this research paper. The views expressed
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683

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