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Regional impacts of heat stress on livestock in Brazil under climate change scenarios

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ABSTRACT

Rising temperatures and humidity threaten global livestock production and food security. This study assesses the future impacts of heat stress in regions with high livestock production in Brazil by analyzing high-resolution (5 km) climate projections from the Eta Regional Climate Model under the RCP4.5 and RCP8.5 scenarios. Using the Temperature-Humidity Index (THI), we evaluated future heat stress conditions for dairy and beef cattle, goats, sheep, pigs, broilers, and layers. The results indicate a substantial increase in both the frequency and intensity of heat stress events across Brazil during the 21st century, especially under the RCP8.5 scenario. The number of days reaching extreme heat-stress levels (*ndaysTHI*) is projected to increase significantly, particularly in the western and central regions of the study area, and for more vulnerable species such as pigs and poultry. For instance, the number of extreme THI days for dairy cattle and goats is projected to increase by up to 244 days by the end of the century (long-term period compared to historical) under RCP8.5. This research provides essential data for developing effective and sustainable adaptation strategies to mitigate the effects of climate change on Brazil's livestock sector, offering insights applicable to other countries facing similar challenges. It addresses a significant knowledge gap by providing high-resolution, localized projections of future heat stress across Brazil's major production regions.

1. Introduction

Global climate change poses a substantial threat to food security, with impacts widely varying regionally, especially considering the agriculture and livestock sector (Moustakas et al., 2026). In the context of animal-based food production, this issue is a global concern, particularly in developing countries, where population growth and the need to improve living standards intensify the demand for food. The different environmental elements interact and influence how animals experience hot climates, and the relevance of these climatic factors varies regionally according to local conditions.

In 2024, Brazil retained its position as the world's largest commercial beef cattle producer, with an estimated herd of 194 million head, accounting for 11.6% of the global total (ABIEC, 2025). In the same year, 39.27 million head of beef cattle were slaughtered, reflecting a significant increase of 15.2% compared with the previous year (IBGE, 2025). Data from IBGE (2023) indicate that the Brazilian Midwest region concentrates the largest share of the national beef cattle herd. The state of *Mato Grosso* accounts for 18.1% of national production, followed by *Goiás* with 10.2% (IBGE, 2025). Raw milk production increased by 3.1% in 2024 compared with the previous year (IBGE, 2025). *Minas Gerais* remains the leading milk-producing state, followed by *Paraná* and *Rio Grande do Sul* (IBGE, 2023). In the Midwest region, *Goiás* contributes a significant share of milk revenue. Nevertheless, overall production has remained relatively stable, with growth of only 0.7% reported in CNA (2025) assessments for the first half of 2025.

Brazil also ranks as the world's fourth-largest pork producer, contributing approximately 15% of global output. The majority of national pork production is concentrated in the southern region, with *Santa Catarina* standing as the leading producer, followed by *Paraná*.

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Although pork is also produced in southeastern and midwestern states, production in these regions occurs on a comparatively smaller scale (EMBRAPA, 2024).

According to data from IBGE (2025), in 2024, exports of fresh chicken meat reached all-time records in the historical series of the Secretariat of Foreign Trade (*Secretaria de Comércio Exterior* - Secex), in terms of both exported volume and dollar revenue. The slaughter of 172.73 million more chicken (head) in 2024 compared to the previous year was driven by an increase in slaughter in 19 of the 25 Federative Units (FUs) that participated in the survey. Among the states with participation above 1.0% that are part of this survey, an increase occurred in *Paraná* (+53.28 million head), *Santa Catarina* (+51.92 million head), *São Paulo* (+40.21 million head), *Minas Gerais* (+13.84 million head), and *Goiás* (+12.60 million head), among others. *Paraná* continued to lead the ranking of FUs in chicken slaughter in 2024 by a wide margin, with a 34.2% national share, followed by *Santa Catarina* (13.8%).

In 2024, Brazil's chicken egg production reached 4.67 billion dozen, marking a 10.0% increase compared to the previous year (IBGE, 2025). The most significant growth was seen in the states of *São Paulo* (+92.37 million dozen), *Minas Gerais* (+80.23 million dozen), *Pernambuco* (+69.74 million dozen), and *Espírito Santo* (+35.61 million dozen). The state of *São Paulo* continues to be the largest producer, accounting for 26.0% of the national output. It is followed by *Paraná* (9.8%), *Minas Gerais* (9.7%), and *Espírito Santo* (8.0%) in the national ranking.

A primary challenge is the increasing frequency and intensity of heat stress, a physiological state that occurs when an animal's ability to dissipate heat is overwhelmed by environmental conditions (Thornton et al., 2021). The repercussions are extensive, negatively affecting animal productivity, reproduction, health, and welfare, and in severe cases, leading to mortality (Herbut et al., 2021; Andrade et al., 2024). Climate change also introduces indirect pressures by disrupting feed and forage systems (Hopkins and Del Prado, 2007). The proposed approaches to effectively tackle climate change are highly relevant and must therefore be disseminated globally to ensure the future sustainability of livestock farming and other animal protein production (Sejian et al., 2022).

Assessing future climate-related risks to livestock requires detailed and localized projections that global climate models and their coarse resolution may not be able to provide. Regional Climate Models (RCMs) address this gap by dynamically downscaling climate information to a higher resolution. This fine-scale approach allows for a more accurate simulation of extreme weather events and a better representation of local features, such as complex topography, that modulate regional climate (Lyra et al., 2018), enabling the study of local impacts.

Different bioclimatic indices have been used to evaluate the impact of climate on livestock. Their main goal is to evaluate the heat stress level supported by animals and to support adaptation strategies to reduce this stress and to avoid declining productive responses (Hahn et al., 2009). In this context, the Thermal-Humidity Index is widely used to determine if climatic conditions may negatively affect productivity and health of animals, for different animals and under different conditions (Bohmanova et al., 2007; Dikmen and Hansen, 2009; Arias et al., 2008; de la Casa and Ravelo, 2003; Cruz and Urioste, 2009; Arias and Mader, 2010; Hernández et al., 2011; Lallo et al., 2018; Theusme et al., 2021).

To translate climate data into physiologically relevant impacts, bioclimatic indicators such as the Temperature-Humidity Index (THI) are commonly used (Ji et al., 2020). Calculating the THI from RCM outputs enables investigation of the future impacts of climate change on livestock comfort and productivity. This study leverages high-resolution climate simulations from the Eta Regional Climate Model (Chou et al., 2014a, 2014b, 2014c; Lyra et al., 2018) to project future climate change and its impacts on heat stress conditions for livestock in Brazil.

We present new information on the projected increases in extreme heat stress in major domesticated animal species raised in Brazil during the current century and projected in future scenarios. The species examined — including dairy and beef cattle, goats, sheep, and poultry — are critical to the country's food and nutritional security. The aim of this research is to assess future heat stress conditions for key livestock species in Brazil using high-resolution climate projections, identify the most vulnerable species and regions, and provide data to inform targeted adaptation strategies for sustainable livestock production. These strategies enhance the resilience of production systems and align Brazilian livestock farming with the United Nations Sustainable Development Goals (SDGs).

2. Material and methods

2.1. Study area

This research focuses on the study area that includes the Southwest region of Brazil and parts of the South and Midwest. As presented in Fig. 1, the evaluated domain includes the states of *Goiás* (GO), *Minas Gerais* (MG), *Rio de Janeiro* (RJ), *Espírito Santo* (ES), *São Paulo* (SP) and *Paraná* (PR).

The states considered in this study exhibit distinct climatic characteristics influenced by geographical orientation, atmospheric conditions, and relief, and are classified according to the Köppen climate classification (Fig. 1). *Goiás* (GO), located in the Midwest region, is classified as Aw (tropical climate with a dry winter). In *Minas Gerais*, climatic diversity is more pronounced: municipalities in the North are classified as As (hot and humid tropical climate with a dry winter season), those in the northwest as Aw, and those in the South as Cwa (subtropical climate with a dry winter) or Cwb (high-altitude subtropical climate with dry winters and mild summers). *Rio de Janeiro* and *Espírito Santo* are predominantly characterized by Am (humid or subhumid tropical climate), Cfa (subtropical climate with hot summers), and Cfb (temperate climate with mild summers). In *São Paulo*, the prevailing climates are Af (humid or super-humid tropical climate without a dry season) along the coast, in addition to Cfa and Cwb classifications inland. *Paraná* (PR), with most of its territory situated south of the Tropic of Capricorn, is primarily characterized by Cfa along the coast and in the northern, northwestern, and western regions, whereas Cfb predominates across the remaining areas (KÖPPEN BRASIL, 2025).

2.2. Climate dataset

The climate projections used in this study were generated through

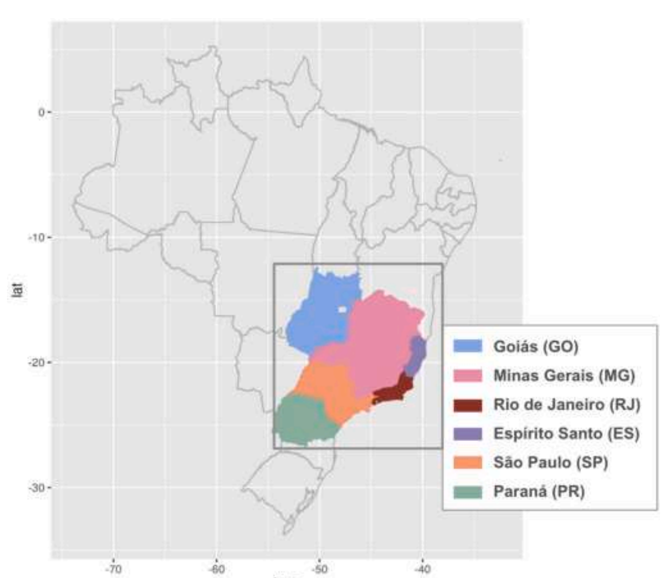

Fig. 1. Study region and Brazilian states evaluated.

dynamic downscaling of the Eta Regional Climate Model (RCM) from Coupled Model Intercomparison Project Phase 5 (CMIP5) models. The Eta climate model is a limited-area model that treats dynamics and physics at grid points. The model uses the vertical Eta coordinate, which represents topography in steps (Mesinger, 1984), and has been receiving updates (Mesinger et al., 2012; Chou et al., 2020) since the operational version used at NCEP (Mesinger et al., 1988). The 5-km resolution version of the Eta model used in this study is detailed in Lyra et al. (2018).

High-resolution (5 km) simulations for southeastern Brazil and parts of the South and Central-West regions were produced from a second downscaling of the outputs of the global climate model HadGEM2-ES for the RCP4.5 and RCP8.5 scenarios, as documented by Chou et al. (2014a, 2014b). Validation studies conducted by Lyra et al. (2018) confirmed that these 5-km simulations accurately reproduce historical spatial patterns of temperature and precipitation, particularly in regions with complex topography, and that they provide a gain over the 20-km projections from the first downscaling for extreme weather events. The robustness of this high-resolution model configuration is further corroborated by its successful application in numerous regional climate impact studies (Chou et al., 2014c; Tavares et al., 2018; Sondermann et al., 2022). At the farm scale, high-resolution data is essential for precisely modeling the microclimatic conditions to which animals are directly exposed. Other versions of the Eta model have also been widely used in the literature and applied in studies across different sectors (Ferreira et al., 2021; Ferreira et al., 2023; Tavares et al., 2023).

The Representative Concentration Pathways (RCPs) were adopted in the Fifth Assessment Report (AR5) of the IPCC. The RCPs are defined by their radiative forcing values (in watts per square meter, W/m^2) up to the year 2100. The RCP 8.5 corresponds to a high greenhouse gas emissions pathway compared to the scenario literature (Stocker, 2014) and also to the upper bound of the RCPs. The greenhouse gas emissions and concentrations in this scenario increase considerably over time, leading to a radiative forcing of 8.5 W/m^2 at the end of the century. RCP 8.5 is a so-called ‘baseline’ scenario that does not include any specific climate mitigation target. On the other hand, the RCP 4.5 (Thomson et al., 2011) represents an intermediate level of stabilization pathways, reaching 4.5 W/m^2 of radiative forcing by the end of the century. In the context of agricultural productivity, the RCP4.5 and RCP8.5 scenarios were selected to represent a range of plausible futures, from an intermediate trajectory to a high-emissions trajectory.

For analysis, the historical period of 1986–2005 serves as the baseline. Future projections were examined across three time slices, representing the short-term (2021–2040), medium-term (2041–2060), and long-term (2061–2080). The primary climate variables used were the simulated Near-Surface Air Temperature (*tas*) and Near-Surface Relative Humidity (*hurs*). The temperature and relative humidity variables used were obtained at a height of 2 m from the surface of the Eta numerical model.

A formal bias correction was not performed in this research due to the unavailability of corresponding high-resolution observational data. However, to assess the model's performance during the baseline period, the THI calculated from the Eta simulations was compared against a THI derived from a 10-km resolution observational dataset from Xavier et al. (2022). The dataset provided by Xavier et al. (2022) includes air temperature, relative humidity, and other variables.

2.3. Thermal-humidity index (THI)

The Thermal-Humidity-Index (THI) considers the combined effect of air temperature and humidity, and can be calculated using the following equation (NRC, 1971):

$$THI = (1.8^*T + 32) - [(0.55 - (0.0055^*RH))^*(1.8^*(T - 26.8))] \quad (1)$$

Where: T is the air temperature (°C) and RH is the relative humidity (%).

The climate has different impacts on each species. In cattle, the most significant damage caused by heat stress is the reproductive system, resulting in a significant reduction in fertility. Heat stress can affect reproductive performance in two ways: directly, through hyperthermia, and indirectly, via the redistribution of blood flow among organs. This redirection prioritizes peripheral tissues for heat dissipation, thereby compromising blood supply to the reproductive organs, which may result in reduced availability of reproductive hormones. In addition, this process is associated with decreased feed intake and the occurrence of respiratory alkalosis (Cordeiro et al., 2020). Different species were evaluated using the THI calculated in Eq. 1.

Additionally to the future changes in THI, we also evaluated the number of days with extreme heat stress for each animal, using THI onset for extreme heat stress found in literature and presented in Table 1. For convenience, the number of days with heat stress above the THI threshold for extreme heat stress will be denoted *ndaysTHI*. A similar methodology was previously applied in Ferreira et al. (2024), using coarse-resolution climate data from CMIP6 models. Applying this methodology to a high resolution dataset, such as the Eta climate model, will supply more accurate and detailed information, much needed to provide insights to adapt to climate change.

In this analysis, we only considered the thresholds used to characterize extreme heat stress for each species. As presented in Table 1, some species can be grouped, as they present the same onset for extreme heat stress (the general class was grouped with sheep, cattle-dairy with goat, pig with poultry-broilers). The onsets used in this analysis were used to indicate a problematic scenario for livestock welfare and production. Taking as an example the cattle-dairy, Armstrong (1994) indicated that the value of THI of 72 is already an indicator of heat stress, but in our analysis we use a higher value (89) defined in other researches - in order to be conservative - as shown in Table 1.

We highlight that the use of THI to estimate the impacts of climate changes in livestock may have limitations. These limitations are associated, for example, with the several possible equations that can be used to estimate THI, according to the study area, species and methodology applied (Mader et al., 2006; Bohmanova et al., 2007; Marai et al., 2007; Wegner et al., 2014). Also, the THI only considers climatic aspects and does not account for nutritional factors or genetic variation. Furthermore, this index does not consider other relevant climate variables, such as solar radiation and wind speed, that are used in indices such as the Thermal Globe-Humidity Index (Buffington et al., 1981).

3. Results and discussion

3.1. Eta model simulations

Projections of temperature (*tas*) and relative humidity (*hurs*) from the Eta model were used to assess the THI. The climatology of the *tas* simulated and the anomalies for short-, medium- and long-term periods were presented in Fig. 2, for the scenarios RCP4.5 and RCP8.5. Similarly, Fig. 3 presents the relative humidity (*hurs*).

The temperature (*tas*) climatology shows values of temperature ranging from about 11 °C to 30 °C, with higher values in the northwest region of the domain. The anomalies indicate an increase in temperature over the century, with higher values in the RCP8.5 (over 6 °C increase), and values over 4 °C in RCP4.5. The relative humidity (*hurs*) climatology indicated in Fig. 3 shows higher values in the coastal regions. Towards the continent, the *hurs* decrease, reaching values below 40% in some regions. The anomalies show decreasing in *hurs* in most part of the evaluated area, reaching a decreasing of 20% in the relative humidity in some central areas (mostly in GO and MG states), compared to the Historical period. It is worth noting that unfavorable levels of relative humidity increase the prevalence of infectious diseases, harming the animal's respiratory tract and making pathogens more contagious (Xiong et al., 2017).

Table 1
THI onset of the stress level for different species (cattle-dairy, cattle-beef, goats, sheep, pigs, poultry-layers, poultry-general), classified as High and Extreme heat stress.

Species	Stress		Source
	High	Extreme	
General[1]	78	90	Fuquay (1981)
Cattle-dairy	79	89	Dunn et al. (2014); Dash et al. (2016)
Cattle-beef	82	94	Valente et al. (2015)
Goat	79	89	Serradilla et al. (2018)
Hair Sheep	78	90	McManus et al. (2016); Slimen et al. (2019); Pérez et al. (2020)
Pig	79	84	Lallo et al. (2018); Mutua et al. (2020)
Poultry-broilers	79	84	Oliveira et al. (2019)
Poultry-layers	76	82	Du et al. (2020)
Poultry-general	81	85	Moraes et al. (2008)

[1] General - THI value considered by the literature for all animals. THI limit table adapted from Thornton et al. (2021).

3.2. THI evaluation

Fig. 4 shows the THI simulated for the Historical period (1986–2005) using the Eta model and THI calculated using observations. The results indicate that the THI calculated using the Eta model simulated a similar spatial pattern and intensity of THI calculated using observations. We highlight that small differences are expected, especially due to the differences in the spatial resolution of the datasets (Eta model has a 5-km grid, while the observational dataset has a 10-km grid). Therefore, further results presented in this research will use only Eta model projections, assuming that the base period (historical) simulations were able to represent the THI.

The Eta model was used to calculate the THI climatology and future anomalies (Fig. 5), indicating an increase of THI in future, with higher values towards the end of the century and in the RCP8.5 scenario (increasing of THI above 8 in some areas). The higher increase in THI projected under RCP8.5 compared to RCP4.5 is expected, since RCP8.5 represents a worst-case scenario characterized by higher temperatures and, consequently, a greater increase in THI. The results from Fig. 5 are aligned with the results presented in Ferreira et al. (2024), which showed increasing THI in the study area (using CMIP6 simulations with coarse resolution).

3.3. Extreme THI: climatology, trends and seasonality

The climatological values of the number of days with extreme heat stress (*ndaysTHI*) were calculated for each species using the thresholds presented in Table 1. Species with the same upper level threshold were grouped and presented in Fig. 6. It should be emphasized that even though some future scenarios reach the maximum thresholds shown in the Table 1, adverse effects on animal performance can be observed at even lower THI levels.

The impact of these phenomena on animal performance arises from physiological adjustments aimed at reducing body heat, which are also influenced by anatomical traits related to the animal's adaptation to the environment. Sensitivity to increases in temperature and environmental humidity may vary according to species, breed, and physiological stage (Wang et al., 2020; Prates, 2025).

It was observed that for the categories general, sheep, cattle-dairy and goats, the number of days with extreme heat stress (*ndaysTHI*) in the historical period are quite low, with few exceptions in the west part of SP and PR, and east of MS. Considering the cattle-beef, no days with extreme heat stress were identified, which is since beef-cattle are more resistant to heat stress. However, these animals are predominantly raised in Brazil using a pasture-based system.

This is because the Brazilian beef cattle herd is predominantly composed of Zebu breeds or Zebu crossbreeds. Zebu cattle *(Bos indicus)*, such as Nelore, Brahman, and Gir, are inherently adapted to tropical climates, which confers greater tolerance to heat stress. Furthermore, a large proportion of beef cattle production systems in Brazil are extensive, allowing animals access to natural shade. Long-term genetic selection also favors individuals with enhanced adaptation to high ambient temperatures.

For categories with lower thresholds of extreme stress (pigs & poultry-broilers, poultry-layers and poultry-general), the areas with the highest number of days with extreme heat stress (*ndaysTHI*) were concentrated especially in the continental areas on the west side of the domain. The anomalies of *ndaysTHI* for each species, scenario, and time-slice are presented in Fig. 7 and Fig. 8.

The animals tend to have higher stress (number of days with extreme THI - *ndaysTHI*) by the end of the century, and this stress is higher in RCP8.5. The northwest region of the evaluated area has the worst projected scenario, and this increase in the number of days with extreme

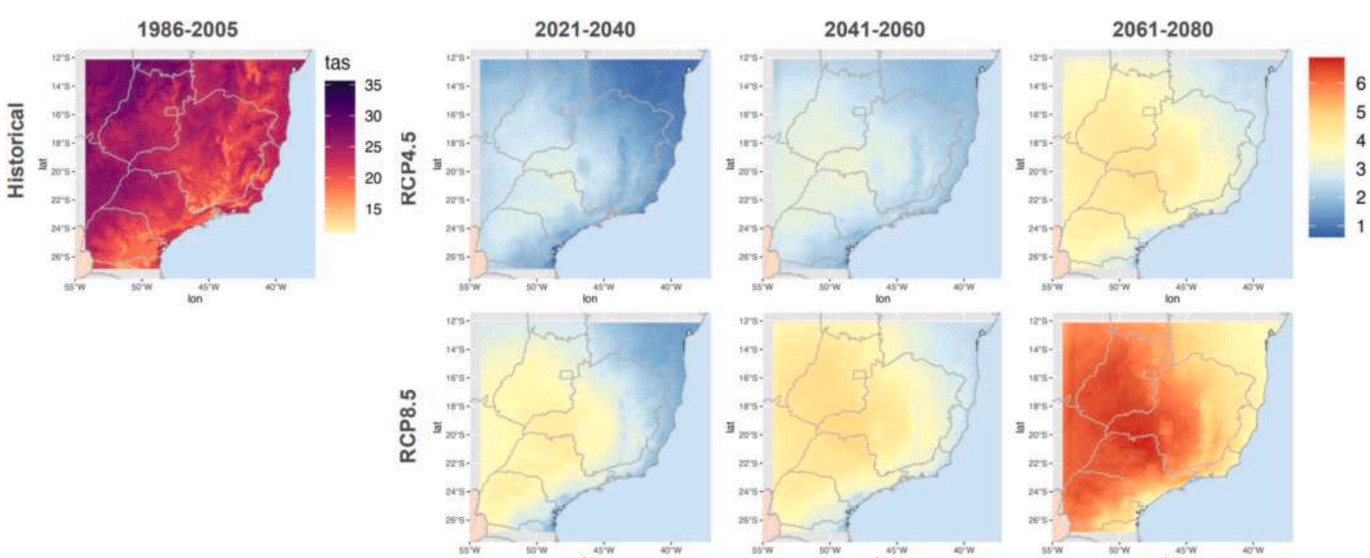

Fig. 2. Temperature climatology (historical, 1986–2005) and anomalies (lines: RCP4.5 and RCP8.5; columns: 2021–2040, 2041–2060, 2061–2080) simulated by the Eta model.

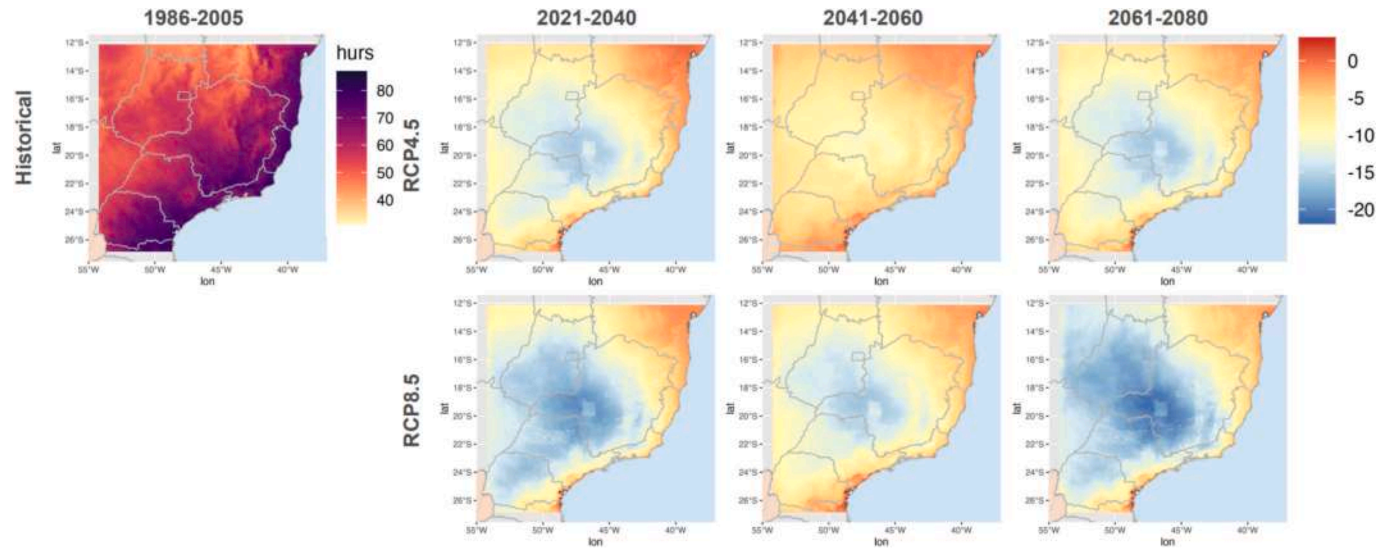

Fig. 3. Relative humidity climatology (historical, 1986–2005) and anomalies (lines: RCP4.5 and RCP8.5; columns: 2021–2040, 2041–2060, 2061–2080) simulated by the Eta model.

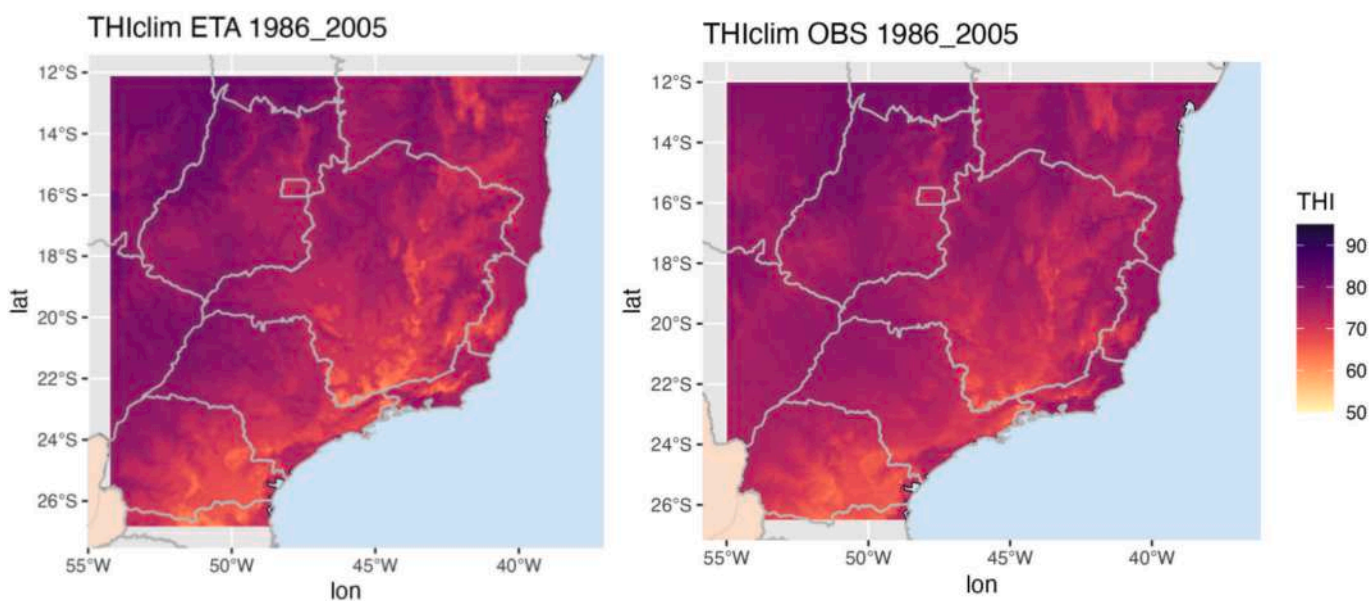

Fig. 4. THI simulated for the Historical period (Eta model) and THI calculated using observations.

THI varies according to the evaluated species.

For the general, and hair sheep category, where the extreme heat level stress were defined as 90, the *ndaysTHI* had a small increase in short- and medium-term, but reached high values (above 94 days) in the long-term analysis for the RCP4.5 scenario. In RCP8.5, the higher increase in the *ndaysTHI* for the short-, medium- and long-term were 52, 103, and 207 days, respectively. Those higher values were found in the west region of the domain.

According to the literature, hair sheep begin to show signs of heat stress (HS) with THI values starting at 78. Because hair sheep tolerate higher temperatures than wool sheep, the HS threshold in any sheep breed is more likely to begin at or below 78 units. More research is needed to determine the precise inflection point at which sheep begin to manifest HS symptoms, as has already been established in other domestic animal species (Pérez et al., 2020).

Considering the cattle-dairy and goats category, where the onset for extreme stress level was defined as 89, the higher increase in *ndaysTHI* found in RCP4.5 were 48 (in short-), 83 (medium-) and 142 days (long-term). In the RCP8.5, these values were 97, 150, 244 days, respectively. We highlight that an increase of 244 days, considering an annual calendar of 360-days, is a very worrying situation, as indicated that the animals in these categories will be under high stress levels for a great part of the year. It is noteworthy that for dairy cows housed indoors, ambient temperature and relative humidity are the main factors of heat stress, whereas for cows kept outdoors, solar radiation and wind speed are also important. Solar radiation directly increases the heat load on the cows, while wind speed affects their ability to dissipate heat through convection and evaporation (Woodward et al., 2025).

For the cattle-beef, we identified higher tolerance (onset for extreme heat stress is THI $>$ 94), therefore the *ndaysTHI* in the RCP4.5 scenario is low, even by the end of the century. Considering the RCP8.5, this number elevates by the end of the century. The results suggest that even heat-tolerant animals will face unprecedented challenges, potentially requiring new adaptation strategies. Silveira et al. (2026), using future

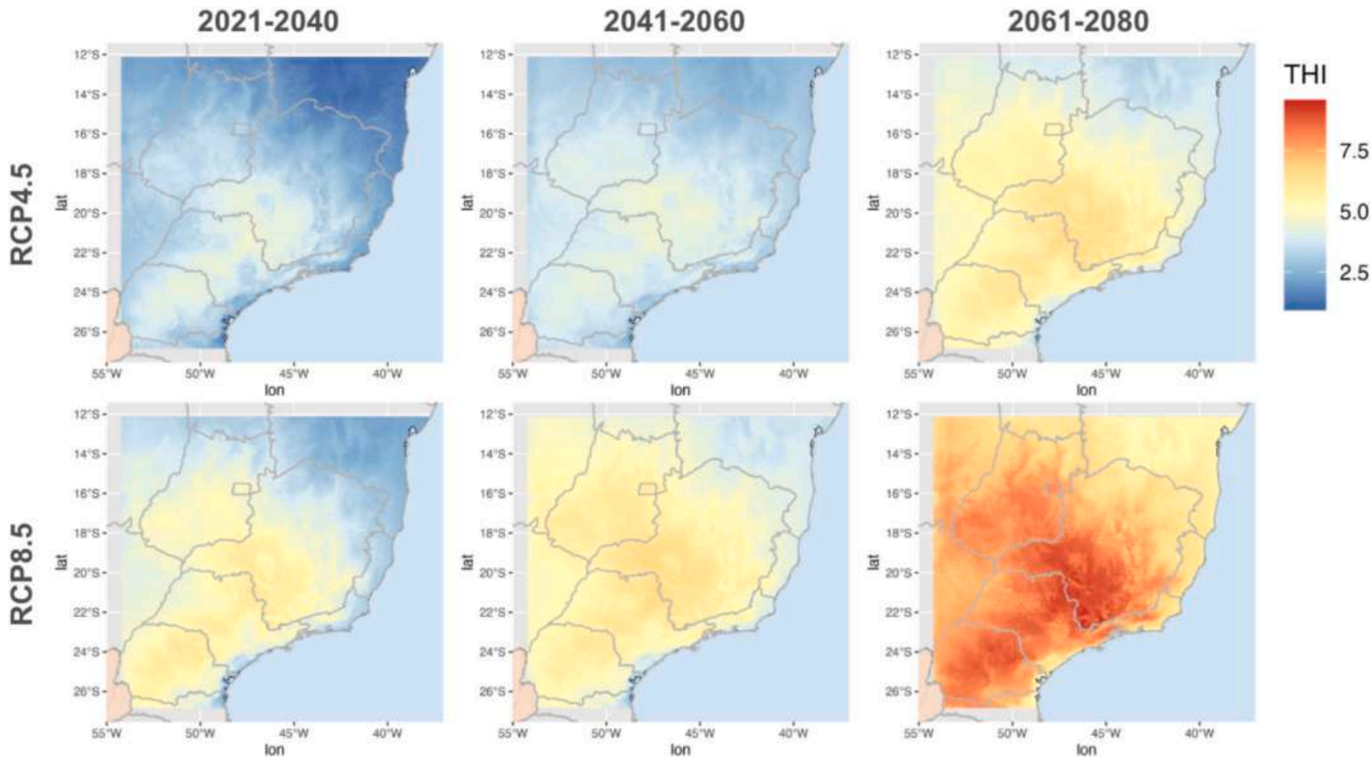

Fig. 5. THI anomalies (lines: RCP4.5 and RCP8.5; columns: 2021–2040, 2041–2060, 2061–2080).

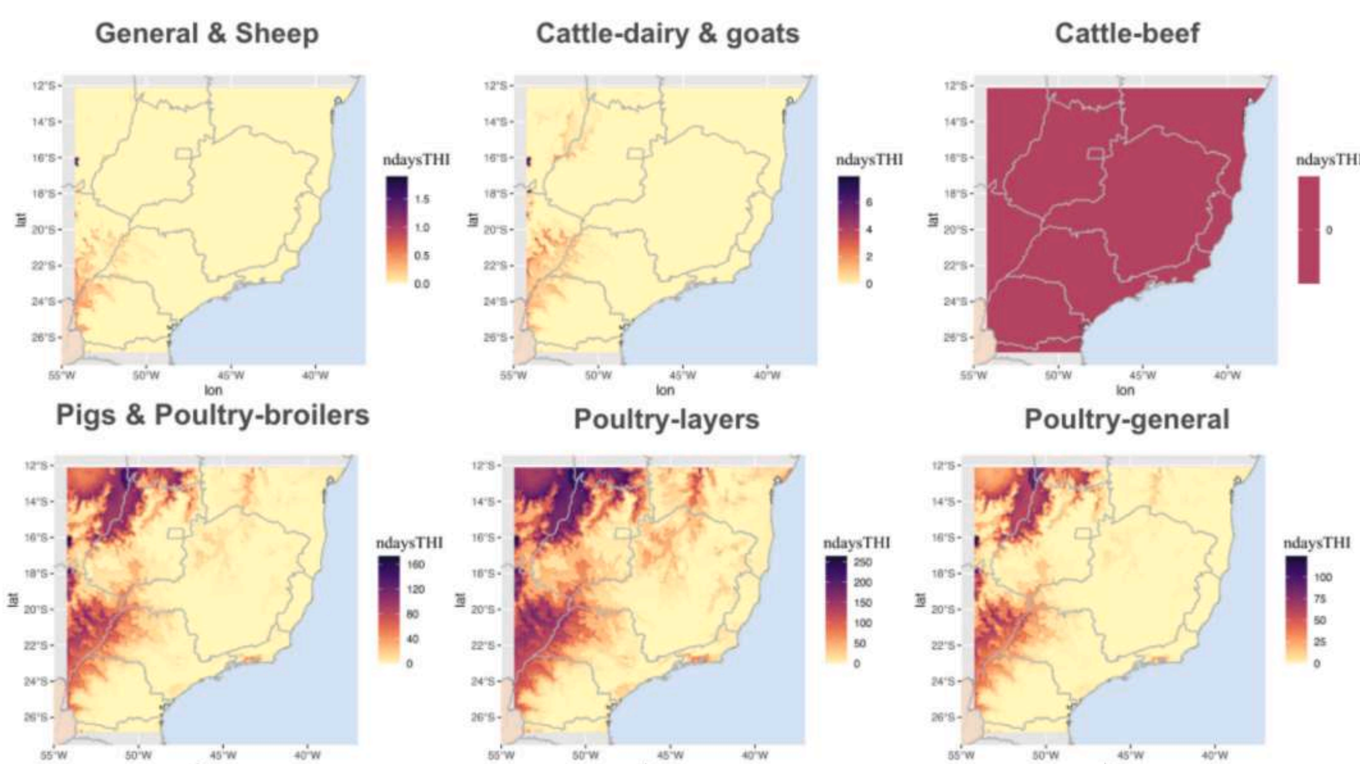

Fig. 6. Climatology of the number of days with extreme heat stress (*ndaysTHI*) for each species.

climate simulations based on the IPCC climate models (RCP4.5), evaluated the impact of climate change on the physiological responses of production animals. According to the authors, goats and beef-cattle were the only species that exhibited phenotypic plasticity, as they did not alter their respiratory rate when temperatures increased in the climate scenarios, and therefore, will not experience a significant impact on their production.

In the pig and poultry-broilers categories, the onset that represents the extreme heat stress is 84. The increase in the *ndaysTHI* were 138, 155, 207 days in RCP4.5 and 200, 240, 299 days in RCP8.5 in short-,

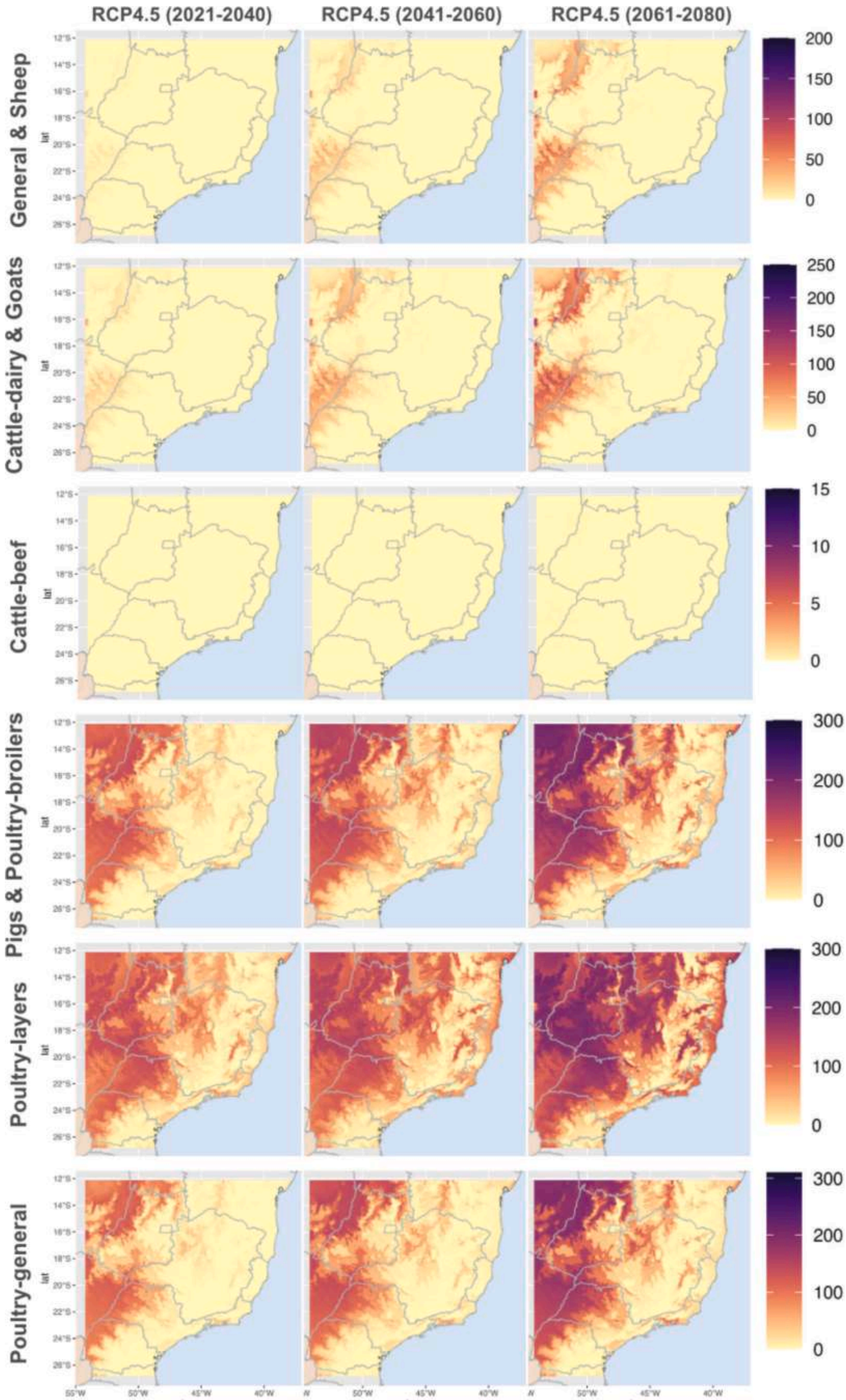

Fig. 7. Anomalies of the number of days with extreme heat stress (*ndaysTHI*) for each species, considering the RCP4.5 scenario.

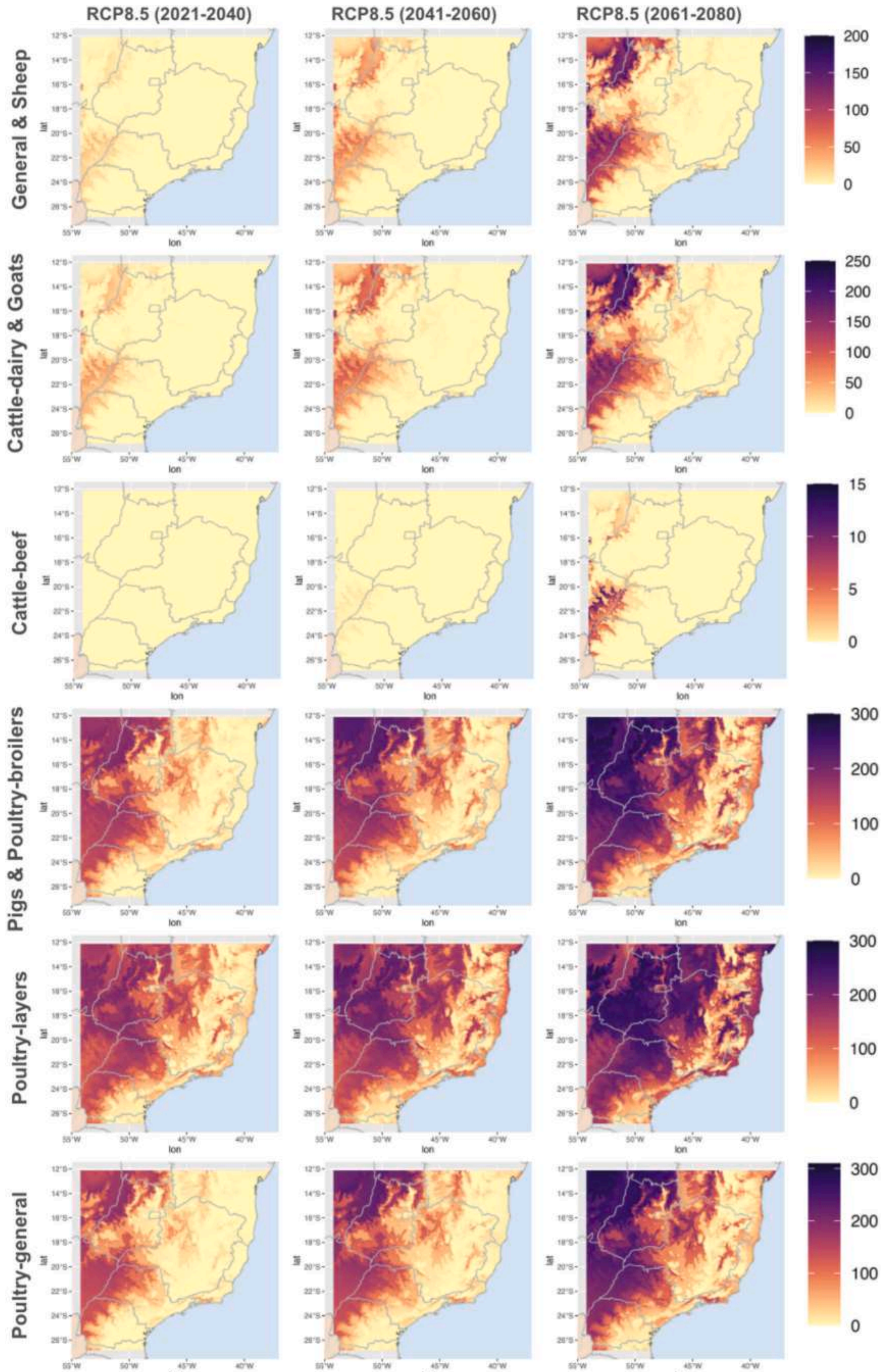

Fig. 8. Anomaly of the number of days with extreme heat stress (*ndaysTHI*) for each species, considering the RCP8.5 scenario.

medium-, and long-term, respectively. For poultry-layers, the increase in *ndaysTHI* in the RCP4.5 (RCP8.5) is up to 146 (206), 159 (239) and 209 (289) days for short-, medium-, and long-term. For poultry-general, these values are: 133 (197), 158 (238) and 206 (302) days.

From Figs. 7 and 8, we conclude that climate change will have a significant impact on livestock production, specially for poultry and pigs, as the projections indicate that great part of the study area will be heavily be impacted by extreme heat stress (e.g. RCP8.5, 2061–2080). Additionally, the results show that the west region of the study area will also be affected by the extreme heat stress for cattle-dairy, sheep and goat production and well-being. Although there are prospects for accelerated genetic improvement programs for domesticated cattle, the projected extent and spread of extreme heat stress risk in the future suggest that extensive livestock systems in some tropical regions may become unviable unless significant advances in heat tolerance are achieved in these animals. Also, advances in environmental technology, such as cooling systems, are also essential to reduce the impact of heat stress on livestock. Furthermore, poultry and swine already face considerable challenges related to heat stress in many of the regions where they are currently raised (Thornton et al., 2021).

Fig. 9 shows the average values of *ndaysTHI*, extracted for each state in the study region.

We highlight that this analysis is an overview of the changes in time, and caution is necessary to evaluate these results, as the spatial average in larger states may smooth the higher values simulated. As an example, we can mention the state of MG, where the west part is heavily affected by the increase of *ndaysTHI* for different species, but the east side does not indicate this severe increase. Another highlight is the state of GO, which has a great part of the state affected by the increase of *ndaysTHI*, especially for the species: pigs and poultry-broilers, poultry-layers and poultry-general. In light of this scenario, the poultry and swine industry faces an urgent need to intensify its production systems, as animals will not withstand high temperatures in environments lacking environmental enrichment strategies (Silveira et al., 2026).

Fig. 10 shows the seasonality of *ndaysTHI*, for each species, states, scenario and time-slice. The abbreviations DJF, MAM, JJA and SON stands for the summer, autumn, winter and spring seasons in the South Hemisphere.

The results indicate that most species do not suffer from extreme heat stress in the historical period during the autumn (MAM) and winter (JJA). Using climate change scenarios we identify that mostly pigs and poultry, which currently are not vulnerable to heat stress during MAM and JJA (according to Historical baseline), may suffer from the heat-stress in future. This stress is projected to be higher over time, and higher in the RCP8.5 scenario.

During hotter seasons, such as spring (SON) and summer (DJF), the *ndaysTHI* will increase, potentially reaching values near 90 days (eg. poultry-layers), which represents the full season in the analysis. From Fig. 10, we can also observe a greater impact in Goias, indicating a strong need for adaptation strategies to address climate change challenges in livestock systems. These strategies are discussed in section 3.4.

This study demonstrates that heat stress conditions in Brazil will continue to increase until the end of the current century and is in agreement with other works developed to date (Pereira et al., 2018; Ferreira et al., 2024). This result also corroborates the study by Silveira et al. (2026), who found that dairy farming will be the activity most susceptible to heat stress in the coming decades in the Southern Hemisphere. According to the same authors, ruminant animals raised in the Southern Hemisphere will increase their rectal temperature as an adaptive response to climate change.

3.4. Sustainable and resilient strategies for animal production in climate change scenarios

Livestock systems are highly dynamic, and extensive, semi-intensive, and intensive production systems are expected to change significantly in the coming decades in response to factors such as shifts in the demand for different types of animal-based foods and the effects of climate change (Thornton et al., 2021). The adoption of animal adaptability strategies is becoming increasingly relevant in livestock production systems, with ongoing efforts to develop breeds and lineages of domestic animals that are more resilient to heat stress and diseases, especially using locally adapted resources from the Southern Hemisphere (Silveira et al., 2026).

Although beef cattle exhibit a considerable tolerance to heat stress, it remains essential to adopt adaptation measures to climate change that avoid contributing to the expansion of degraded areas. At the same time, food production in Brazil, the world's largest exporter of beef and soy, has accounted for a significant share of the country's greenhouse gas emissions. Most of these emissions are directly associated with deforestation for the conversion of native vegetation into pasture, representing Brazil's main source of carbon released into the atmosphere.

Key strategies include integrated crop–livestock systems (ICLS), sustainable pasture management, genetic selection of animals with greater resilience to heat stress, improvements in animal welfare and housing conditions, and the adoption of technologies that mitigate the carbon footprint of livestock production. It is also important to mention that ICLS systems have been used in some regions of Brazil for dairy cattle.

It is important to emphasize that grazing-based systems remain the

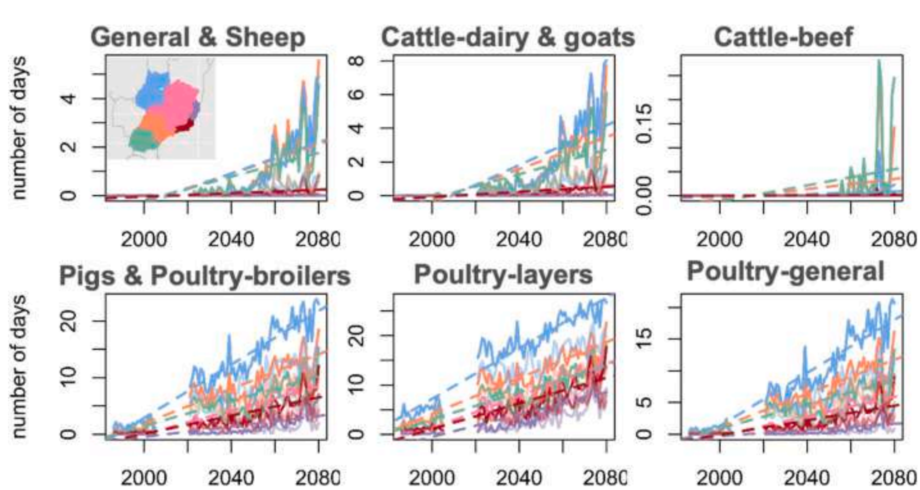

Fig. 9. Number of days with extreme heat stress (*ndaysTHI*) for each species, for each state. Transparency was added to represent the RCP4.5, while "normal"colors represent the RCP8.5.

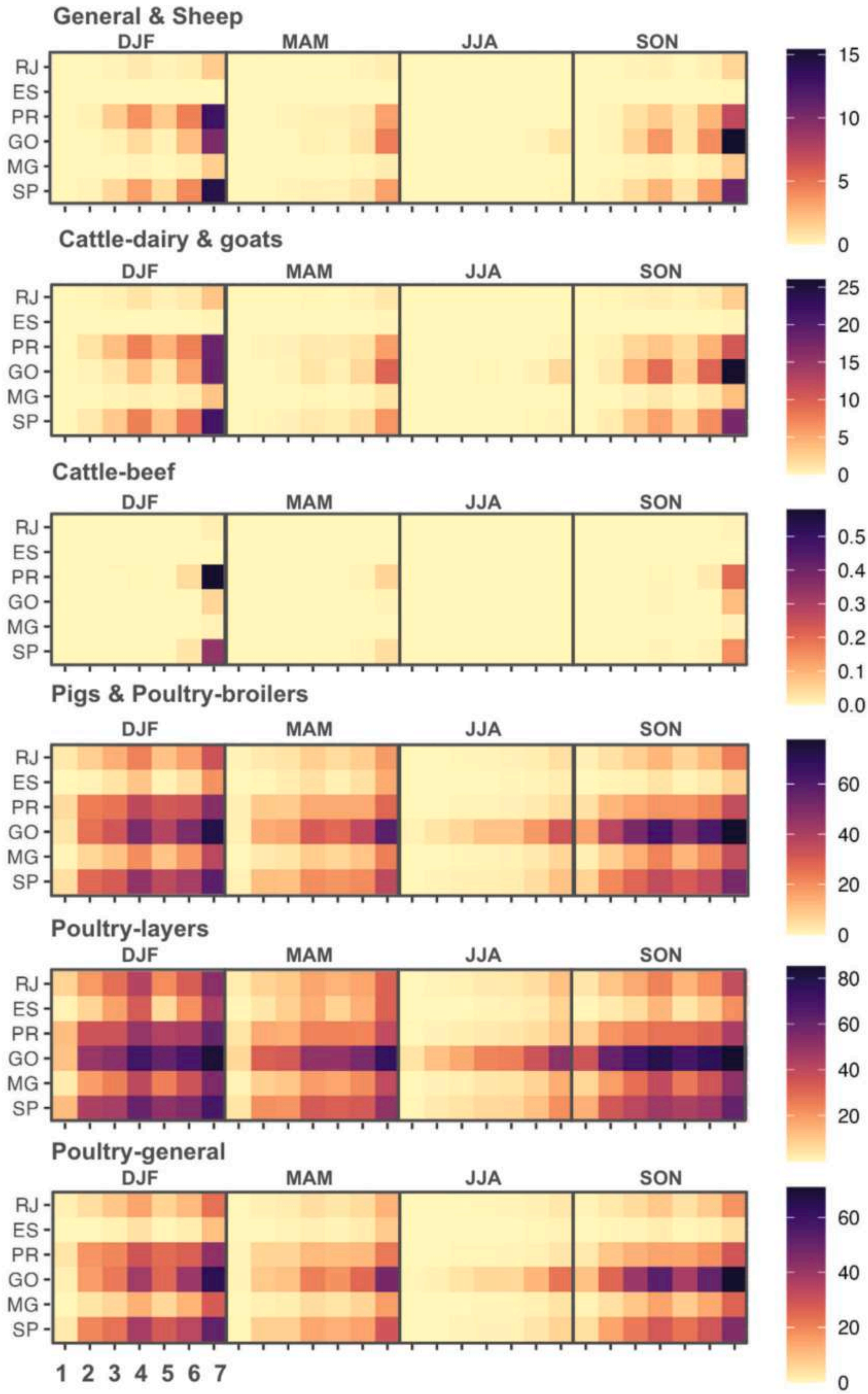

Fig. 10. Seasonality of number of days with extreme heat stress (*ndaysTHI*) for each species. Column 1 indicates the Historical period; columns 2, 3 and 4 represent the short-, medium- and long-term for RCP4.5; and columns 5, 6 and 7 represent the short-, medium- and long-term for RCP8.5.

predominant feeding strategy in Brazilian livestock production, particularly for beef cattle (Alves et al., 2024). Most herds are raised under extensive or semi-intensive conditions, with animals spending long periods exposed directly to ambient climatic conditions (Barsotti et al., 2024). As a result, heat stress represents a major constraint to productivity and animal welfare in pasture-based systems, reinforcing the relevance of adaptation strategies that operate at the pasture–animal–environment interface (Hendriks et al., 2025). In this context, the provision of natural shade through trees plays a central role in reducing solar radiation, ambient temperature, and animal body heat load, thereby mitigating heat stress and improving animal welfare (Li et al., 2025). Silvopastoral systems, which integrate trees, pastures, and livestock, are particularly effective in enhancing resilience to climate change by improving the microclimate, sustaining forage quality, and maintaining productivity. In addition to their adaptation benefits, silvopastoral systems can contribute to greenhouse gas mitigation through carbon sequestration and improved nutrient and energy use efficiency, supporting both environmental sustainability and climate-smart livestock production (Brunetti et al., 2025).

According to dos Reis et al. (2025), the expansion of ICLS in degraded pasture areas in Brazil has the potential to generate highly positive economic impacts. The authors also note that the ICLS demonstrates superior economic performance, particularly in the long term, as evidenced by more favorable viability indicators such as higher internal rates of return and profitability indexes. In the Cerrado biome, where the state of *Goiás* is located, the gross profit per hectare would be higher compared to traditional livestock farming. Although these systems require greater initial investments per hectare, they offer shorter payback periods and higher profitability.

Heat stress reduces productive efficiency and negatively affects the environment. Chen et al. (2025) developed mathematical models showing a decline of up to 8.6% in milk yield and an increase of 0.8% to 6.6% in enteric methane (CH_4) emission intensity in dairy cows exposed to thermally stressful conditions, thereby compromising production efficiency and exacerbating environmental impacts. This increase in methane emissions occurred because milk production fell more rapidly than methane production. Although feed efficiency (methane production) may improve slightly, production efficiency (methane intensity) worsens, increasing the environmental cost per unit of milk.

In some regions of Brazil, such as the Southeast and Central-West, the compost-bedded pack barn (CBP) has proven promising and has been adopted by several producers as a measure to mitigate the effects of heat stress in dairy cattle (Andrade et al., 2024). The adoption of Free Stall and CBP confinement facilities with closed sides and evaporative cooling systems has been used to improve the microclimate of these facilities (Vega et al., 2022). However, it has been observed that, when opting for the CBP, greater attention is needed to bedding management due to increased relative humidity. Therefore, it is advisable to provide a larger bedding area per animal, with a recommendation of 14 m^2 per cow. However, this type of cooling still poses a significant challenge for litter management, as its moisture content increases significantly. Therefore, the adoption of CBP with open sides and fans in the bedding area, combined with the use of sprinklers only in the feeding alley, has shown superior results (Oliveira et al., 2022; Vega et al., 2022).

Savian & Holden (2025) presented a study on the Life Cycle Assessment (LCA) of an integrated, large-scale organic egg production system in Brazil. The authors highlighted feed production, especially organic corn and soy, as the main environmental activity, while manure management similarly influences impacts such as acidification and climate change. The integrated system demonstrated greater eco-efficiency compared to analogous systems, both national and international, described in the literature.

Another important point to highlight is that, in addition to adopting modern technologies to improve the indoor environment of livestock facilities, there is also a need to pursue housing systems that foster the sustainability of animal production, a demand reinforced by the current sustainability trend emphasized by consumers. According to Galama et al. (2020), a large proportion of dairy farmers have chosen housing systems that allow animals to express their natural behavior, maintain thermal comfort, reduce ammonia and greenhouse gas emissions, and enable waste recycling.

One aspect to consider is that, due to climate change, the demand for climate control systems is expected to increase, requiring attention to rising water and electricity costs. The broader adoption of mechanized systems powered by renewable energy sources is also likely to reduce both costs and potential increases in greenhouse gas emissions that would otherwise result from the use of fossil fuels (Ferreira et al., 2024). Sustainable agricultural practices, improved energy systems, and more efficient water use are essential to enhance the resilience and efficiency of the interconnection between food production, energy use, and water resource management (Karri et al., 2026).

When implemented in a complementary manner, these strategies enhance the resilience of production systems and align Brazilian livestock farming with the United Nations Sustainable Development Goals (SDGs).

3.5. Limitations and methodological challenges

The vulnerability of livestock to heat stress varies according to species, genetic potential, life stage, nutritional status and production system (pasture or confinement). To improve sustainability and resilience in productive systems, there is a greater tendency to use intensive confinement systems, especially for dairy cattle in the lactation phase, using Compost Barn or Freestall type facilities (Andrade et al., 2024; Pinheiro et al., 2021).

The THI heat stress categories used in this study were adopted as guidelines. It should be noted that defining ranges for heat stress categories can be somewhat arbitrary, as heat stress depends not only on the predominant climate and the THI formulation, but also on the practices employed to manage heat stress, which determine the microclimate, as well as the animal's breed, how well-adapted it is to the climate, and its physiological state (Lallo et al., 2018).

Considering the differences in sensitivity to ambient temperature and relative humidity among species, a variety of equations have been proposed for calculating the THI, with different weightings of dry-bulb temperature (Tdb) and relative humidity (RH). Some indices incorporate RH through the wet-bulb temperature (Twb) index, others use dew point temperature (Tdp), or they use RH directly. In these equations, the reference values are not always the same. The formulas generally apply to specific situations; for example, some are more suitable for hot-humid environments, others for hot-dry environments. The THI is typically classified into categories that indicate the level of heat stress. However, the definitions of these levels vary among the different indices and authors (Mader et al., 2006; Thom, 1959).

Other indices that account for other climatic variables may need to be further explored in the context of global climate change. Some examples are the Black Globe Humidity Index (BGHI) and the Comprehensive Climate Index (CCI) (Zanetoni et al., 2019; Yan et al., 2021). However, we highlight that this study stands out for its pioneering and innovative nature, providing valuable insights into the magnitude of climate change impacts by simulating future climate scenarios using high-resolution projections from the Eta Regional Climate Model, and thus offering a comprehensive perspective on animal adaptability.

4. Conclusions

The climate projections used in this study were generated by the Eta Regional Climate Model. The simulations, with a 5-km resolution, reproduced historical spatial patterns of air temperature and relative humidity with high accuracy, reflecting a high capability to represent the Temperature-Humidity Index (THI) in the study region, which is crucial to evaluate the current and future impacts on livestock production.

Overall, all species are projected to experience an increase in heat stress (measured by the number of days with extreme THI - *ndaysTHI*) by the end of the century, especially under the RCP8.5 scenario. The northwestern region of the assessed area shows the most critical projections, with the greatest increase in the number of days with extreme THI, although this intensification varies across species.

This research provides insights into eco-efficiency, offering guidance for sustainable practices in Brazil that can be adapted and implemented in other countries. Future work could include mapping climate risk zones for different species and production systems (intensive and extensive) at the regional scale, to inform local public policies. Additionally, replicating the methodology in other tropical and subtropical areas and countries is recommended to enble comparison of vulnerabilities and adaptation strategies across different climate contexts.

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Declaration of competing interest

Declare conflicts of interest or state "The authors declare no conflicts of interest".

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Data availability

Data will be made available on request.

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