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RESEARCH

Climate change impacts and seasonality changes on beef cattle in Brazil

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Abstract

Climate change, global warming, and natural resource depletion pose significant challenges to global beef cattle farming, with animal heat stress emerging as a widespread limitation. This is particularly critical in Brazil, a major global beef producer and exporter that supplies a substantial portion of the world's food. This study investigated the impact of seasonality changes on beef cattle welfare under various climate change scenarios, using the Temperature-Humidity Index (THI). Our analysis employed CMIP6 ensemble models for historical data and future projections, with a specific focus on the SSP5-8.5 scenario. The research focused on Brazil's most productive cattle farming regions. Historically, the North and Mid-West regions exhibited the highest THI values, mostly between September and December. Projections show low values of THI anomaly in the short-term (2021–2040). However, the medium-term (2041–2060) reveals a significant increase in THI anomalies in the Mid-West and North, with some regions approaching 30 days per month of extreme THI (values > 94). The long-term (2061–2080) represents the worst-case scenario, with high THI anomalies persisting year-round across most of Brazil. States like Acre, Amazonas, Goiás, Mato Grosso, Pará, and Rondônia are projected to experience 28–31 days per month of extreme THI during critical periods (September-December), while Paraná remains relatively low. The findings underscore an urgent need for robust adaptation strategies, including genetic improvement, integrated crop-livestock systems, and precision livestock farming technologies, alongside national mitigation efforts, to ensure the long-term viability and sustainability of Brazilian beef production.

Keywords Animal welfare · Heat stress · Livestock · Food security · Ruminant animals · Temperature-humidity index

Introduction

Climate change and extreme weather events affect various sectors (Ferreira et al. 2021, 2023) and regions globally, but their impacts are not uniformly distributed, making regional assessments essential. Simultaneously, with population growth, the demand for animal products is projected to increase, especially in developing countries. This necessitates scaling and optimizing livestock production in response to climate change (Wankar et al. 2024). Beef cattle farming is a cornerstone of Brazilian agribusiness and holds a prominent position on the world stage. Brazil boasts the largest commercial cattle herd globally, representing about 12% of the world's total, leads beef exports, and ranks second worldwide in production volume (ABIEC 2025). Brazil's beef industry primarily relies on pasture-fed cattle (Millen et al. 2011), which makes them highly susceptible to adverse environmental conditions (Wankar et al. 2024).

Recent studies highlight the increasing importance of sustainability in animal production. This presents a multifaceted concern, given the paradox among climate change, growing demand for animal-derived foods, animal welfare, sustainability, technological innovations, and environmental issues associated with high food production demands (Andrade

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et al. 2024; Silveira et al. 2024). The connection between the environment and animal welfare is primarily established through providing an adequate and controllable environment for the animals (Li et al. 2023). Animal productivity peaks under specific environmental conditions. When air temperature and relative humidity fall below or rise above their respective thermal comfort thresholds, efficiency and, consequently, profitability, are compromised. This occurs because nutrients are diverted to maintain a safe body temperature (Baumgard & Rhoads 2012).

Outside their thermoneutral zone, homeothermic animals respond to heat stress by increasing heat loss and reducing heat production in an attempt to prevent an increase in body temperature (Thornton et al. 2021). Metabolic responses include increased respiration and sweating rates, and a decrease in feed intake. These physiological events can significantly contribute to the occurrence of metabolic disorders in heat-stressed animals (Lacetera 2019). The effects of heat stress include reduced production, reproduction, fertility, and animal welfare, as well as increased susceptibility to diseases and, in some cases, higher mortality rates (Herbut et al. 2021). This exacerbates a global scenario already facing serious food security concerns in the context of climate change. Therefore, the increasing spread of extreme heat stress risk in the future will seriously challenge the viability of raising animals outdoors, even those with higher resistance to heat stress (Ferreira et al. 2024).

In this context, climate models are vital tools for assessing the impacts of climate change. Projections from Phase Six of the Coupled Model Intercomparison Project (CMIP6) provide climate scenarios based on different Shared Socio-Economic Pathways (SSPs), and are widely used to assess climate change impacts across various sectors (Thornton et al. 2021; Zeng et al. 2022), including animal production (Ferreira et al. 2024). Using climate projections, heat stress indices can be calculated to investigate the impact of climate change on livestock across different regions and species (Berman 2019; Ferreira et al. 2024).

With the escalating impacts of climate change, animals worldwide are increasingly falling outside this optimal thermal zone. This necessitates expending additional energy for thermoregulation, which can consequently reduce the effectiveness of production processes (Joy et al. 2020; Godde et al. 2021). Therefore, when exposed to heat stress, animals struggle to dissipate sufficient heat to maintain homeothermy, leading to increases in respiration, pulse, heart rate, and body temperatures (Nardone et al. 2010; Kadzere et al. 2002). This can result in reduced feed intake, decreased reproductive efficiency, and alterations in mortality rates and immune system function (Das et al. 2016; Sejian et al. 2018). Such challenges present an additional threat to global food security, particularly in a changing climate.

As highlighted by Cheng et al. (2022), adaptation measures are crucial for sustaining the growing demand for livestock products. The relevance of these measures depends on specific climatic conditions, local production management, and the ability to ensure animal comfort and welfare. Simultaneously, mitigation strategies are vital for limiting the future intensification of climate change.

The Temperature-Humidity Index (THI) is one of the most widely adopted indices for analyzing heat stress in various productive animal species (Ferreira et al. 2024; Wankar et al. 2024). Despite their relevance, measures related to animal welfare, as well as environmental and economic factors, remain underexplored in the context of climate change (Hempel et al. 2019). This paper aims to assess the potential impacts of climate change on beef cattle welfare by examining how changes in seasonal temperature and humidity affect heat stress exposure, as indicated by the Temperature-Humidity Index (THI) and its associated thresholds for severe stress. Using CMIP6 ensemble models, we analyze historical climate data and future projections across short, medium, and long-term time frames (2021–2080), with a focus on the SSP5-8.5 scenario, which represents a business-as-usual trajectory. This approach indirectly evaluates welfare impacts by calculating the number of days per year that beef cattle experience extreme heat stress, providing critical insights into future risks to animal welfare in Brazil's major cattle farming regions. The analysis covers all of Brazil, with a specific focus on the Mid-West and Southeast, as well as the Northern states, which are vulnerable to deforestation driven by the expansion of livestock farming in the Amazon.

Material and methods

Datasets: CMIP6 climate change projections

Projections from Phase Six of the Coupled Model Intercomparison Project (CMIP6) provide climate scenarios based on different Shared Socio-Economic Pathways (SSP) (O'Neill et al. 2014, Oliveira et al. 2022). The SSP scenarios were created from long-term integrations with possible greenhouse gas emission (GGE) scenarios in the atmosphere and their impacts on climate variables. These scenarios can be used to investigate the implications of long-term climate change, aiding in the design of robust policies within complex, uncertain systems (Hall et al. 2016; Harrison et al. 2015; O'Neill et al. 2014). Their widespread use in the literature also facilitates comparison with other research findings. For this study, we constructed an ensemble model using four CMIP6 models. This ensemble represents the daily median values across these models. More information on the specific models is provided in Table 1.

Table 1 Climate models used to create the ensemble model

Model	Institution	More information
CanESM5	Canadian Centre for Climate Modelling and Analysis	Swart et al. 2019
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (GFDL)	Horowitz et al. (2018)
MPI-ESM1-2-LR	Max-Planck Institut für Meteorologie	Wieners et al. 2019
MRI-ESM2-0	Japan Meteorological Research Institute	Yukimoto et al. 2019

We evaluate the impacts of climate change on beef cattle, using historical simulations (from 1991 to 2010) and climate projections (scenario SSP5-8.5, from 2021 to 2080). The baseline period was chosen to consider the most recent climatology (20-years) and the availability of data from the climate models. The scenario SSP5-8.5 is considered as a pessimist scenario, with a higher increase of temperature by the end of the century, compared to other scenarios. The projections were divided into short- (2021–2040), medium- (2041–2060) and long-term (2061–2080). The key variables used in this methodology are daily temperature (tas) and near-surface relative humidity (hurs). These datasets will be used to calculate the Temperature-Humidity Index (THI), as detailed in Section 2.3.

Study area: Brazil

Brazil is divided in five geographical regions: North, South, Southeast, Center-West, and Northeast, which contains 26 states and 1 Federal District. Given the country's large territorial extension, both animal production practices and thermal environments vary significantly across these regions.

In 2024, Brazil maintained its status as the largest holder of the commercial beef cattle herd globally, estimated at 194 million head (11.6% of the world's herd) (ABIEC 2025). In the same year, 39.27 million heads of beef cattle were slaughtered, marking a substantial 15.2% increase from the previous year (IBGE 2025). Among the main destinations for Brazilian beef exported in 2024 (considering revenue), they were China,

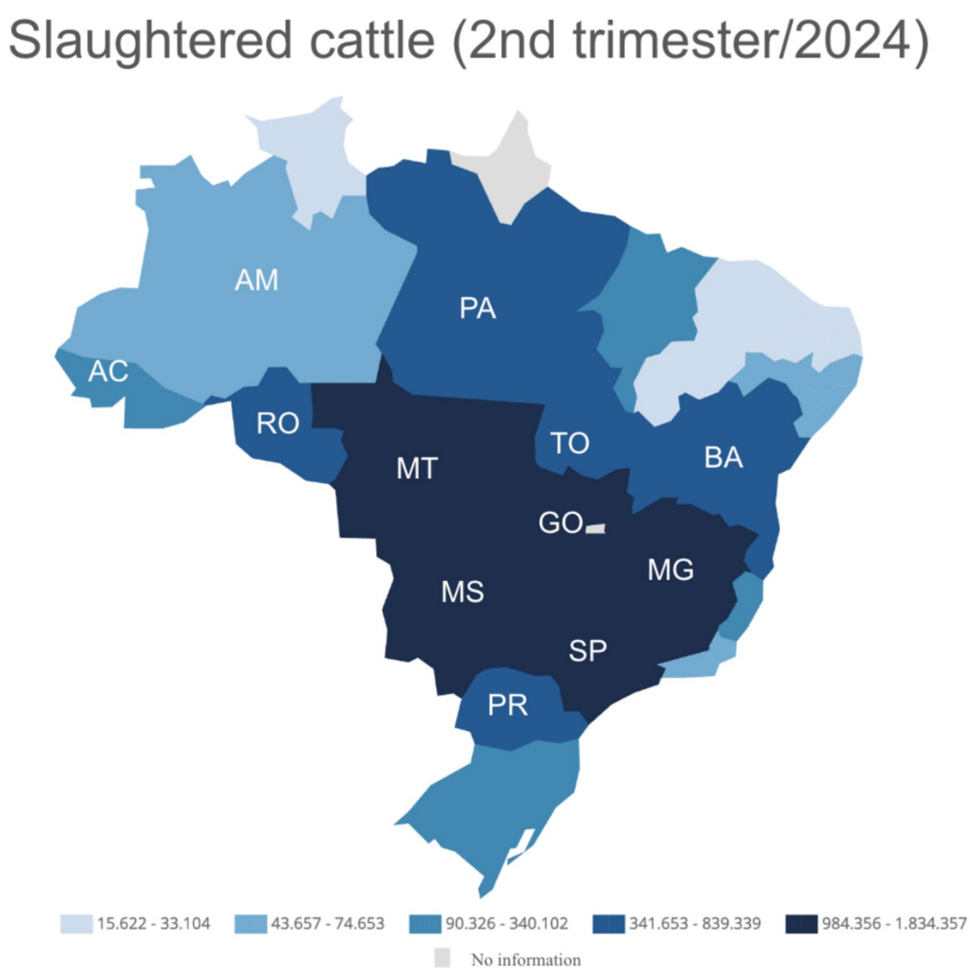

Fig. 1 Slaughtered cattle in Brazil (per state) in the second quarter of 2024. IBGE 2025

the United States and the United Arab Emirates, with 46.2%, 7.9% and 4.7%, respectively (ABIEC 2025).

Figure 1 illustrates the number of cattle slaughtered per state in the second quarter of 2024 (IBGE 2025). The states with higher total production were Mato Grosso (MT), Mato Grosso do Sul (MS), Goiás (GO) in the Mid-West, and Minas Gerais (MG) and São Paulo (SP) in Southeast. For strategic research purposes, we also evaluated states like Tocantins (TO, North), Bahia (BA, Northeast) and Paraná (PR, South) due to their significant productivity. Additionally, Amazonas (AM), Acre (AC), Pará (PA) and Rondônia (RO) in the North region were included because they encompass parts of the Amazon rainforest, making them vulnerable to deforestation driven by the expansion of livestock farming in Brazil.

Projections from the Organisation for Economic Co-operation and Development (OECD 2023) indicate continued growth in global beef production over the next ten years, reaching a record of 77.8 million tonnes by 2032. Among major global producers, Brazil is projected to experience the fifth-highest growth, at 4.52%. The OECD also anticipates that global beef consumption will reach 77.6 million tonnes by 2032, a 5.68 million tonnes increase from 2023. This rise is primarily attributed to population growth, as per capita beef consumption is expected to remain relatively stable at 5.91 kg/year.

Temperature humidity index (THI)

Various methods exist to evaluate the risk of heat stress in production animals. These often include thermal indices that combine ambient temperature and relative humidity measurements to quantify an animal's thermal comfort or discomfort (Oliveira et al. 2022; Cesca et al. 2021; Herbut et al. 2018). The thermal environment, encompassing air temperature, humidity, and air movement, is a primary climatic factor influencing animal production (Ames 1980). Animals typically exhibit optimal performance and minimal energy expenditure within a specific thermal neutral zone (Nardone et al. 2010). When an animal experiences an individual stressor, its phenotypic response is called acclimation (Nardone et al. 2010).

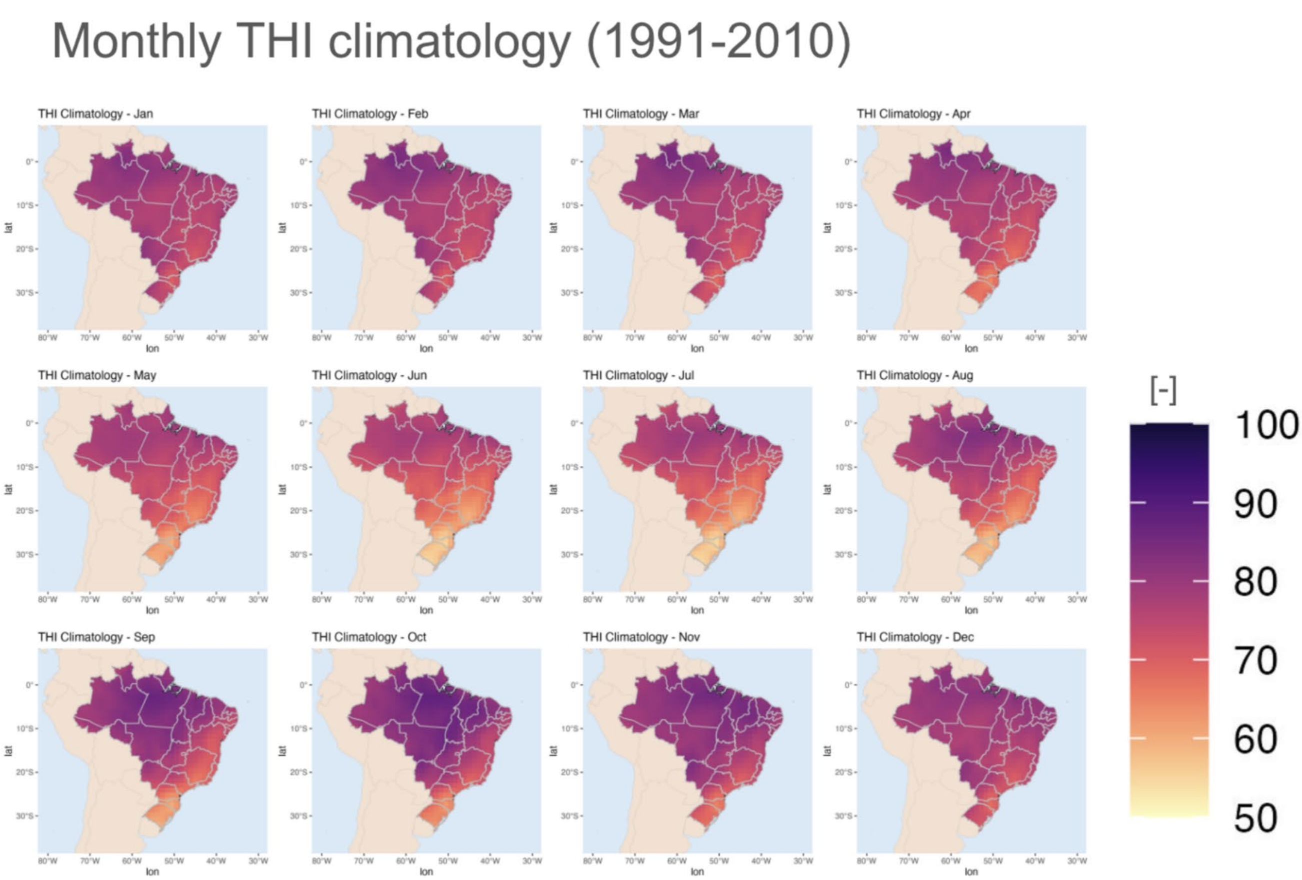

Fig. 2 Monthly THI climatology, from 1991 to 2010, in Brazil

The environmental conditions inducing heat stress can be quantified using the Temperature-Humidity Index (THI), which combines ambient temperature and relative humidity (NRC 1971). The THI is calculated as follows:

$$THI = (1.8 * T + 32) - [(0.55 - 0.0055 * RH) * (1.8 + T - 26)] \tag{1}$$

where T is the air temperature (°C), RH is the relative humidity (%) and THI is the Temperature-humidity index.

The THI has been widely applied in studies globally to identify thermal stress in livestock (Andrade et al. 2022; Kang et al. 2020; North et al. 2023; Ferreira et al. 2024). It is important to note that THI thresholds vary by animal species, as each possesses different mechanisms for coping with high temperatures and humidity. For beef cattle, literature (Mader et al. 2006; Valente et al. 2015) indicates the onset of a moderate stress level at THI 72, high stress at 82, and extreme stress at 94. The THI extreme stress onset level (> 94) was used to evaluate the impact of climate change on livestock in Brazil. We calculated the number of days experiencing extreme stress for beef cattle based on historical simulations and future projections from CMIP6 data. This data was used to construct a climatology of days with extreme stress for each time-slice.

Results and discussions

Seasonality changes of THI

We assessed the impact of climate change on beef cattle heat stress by calculating the Temperature-Humidity Index (THI) monthly for the historical period of 1991 to 2010 (Fig. 2). Our analysis revealed significant spatial and temporal variability in THI across Brazil. Consistently, the North and Mid-West regions exhibited the highest THI values, while the South experienced the lowest. This pattern aligns with the established temperature and relative humidity gradients across South America. Notably, between September and December, the North and Mid-West regions frequently recorded THI values exceeding 80, indicating high thermal stress. These months typically coincide with a prolonged dry season in these areas, characterized by high air temperatures and low relative

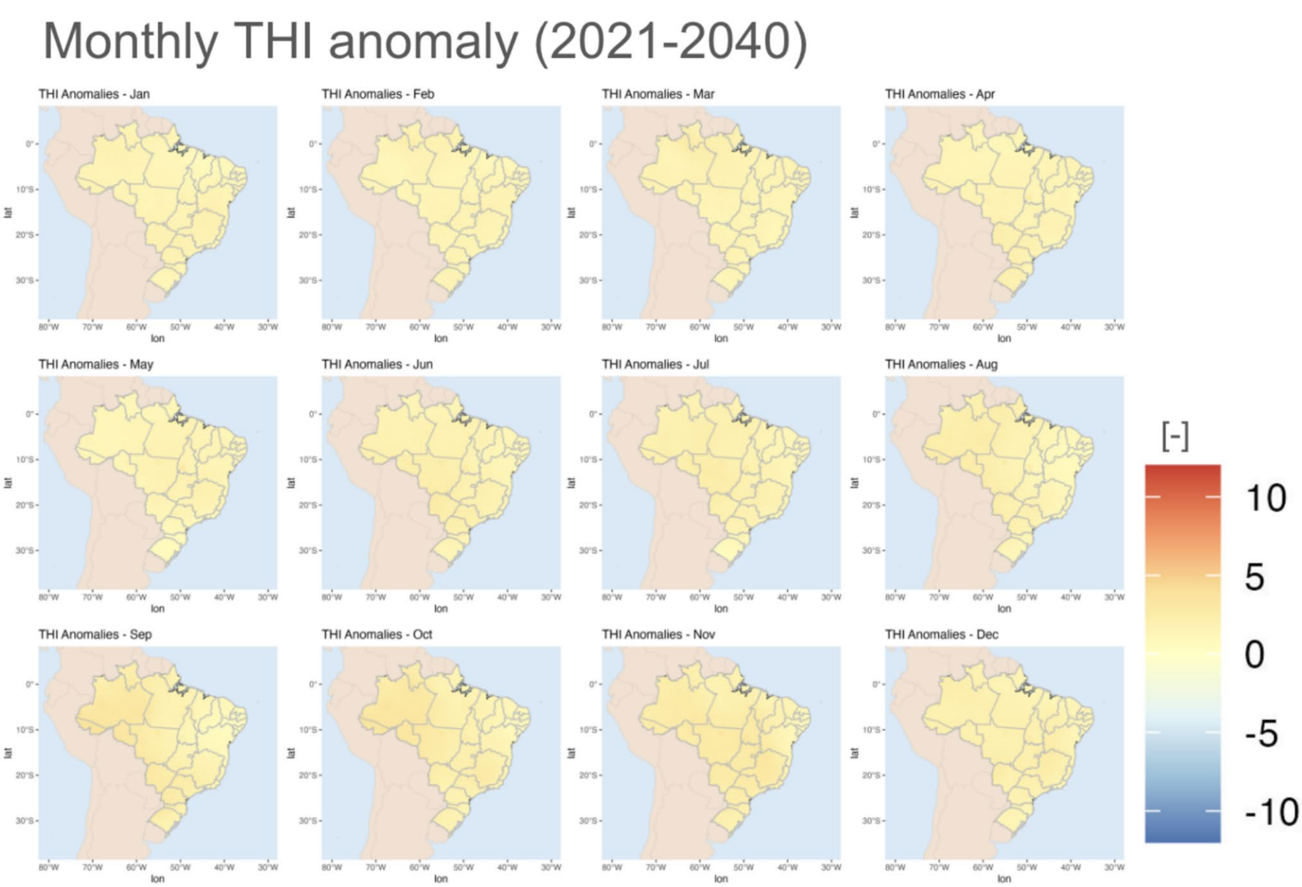

Fig. 3 Monthly THI anomaly, considering the short-term period simulations from 2021 to 2040, in Brazil

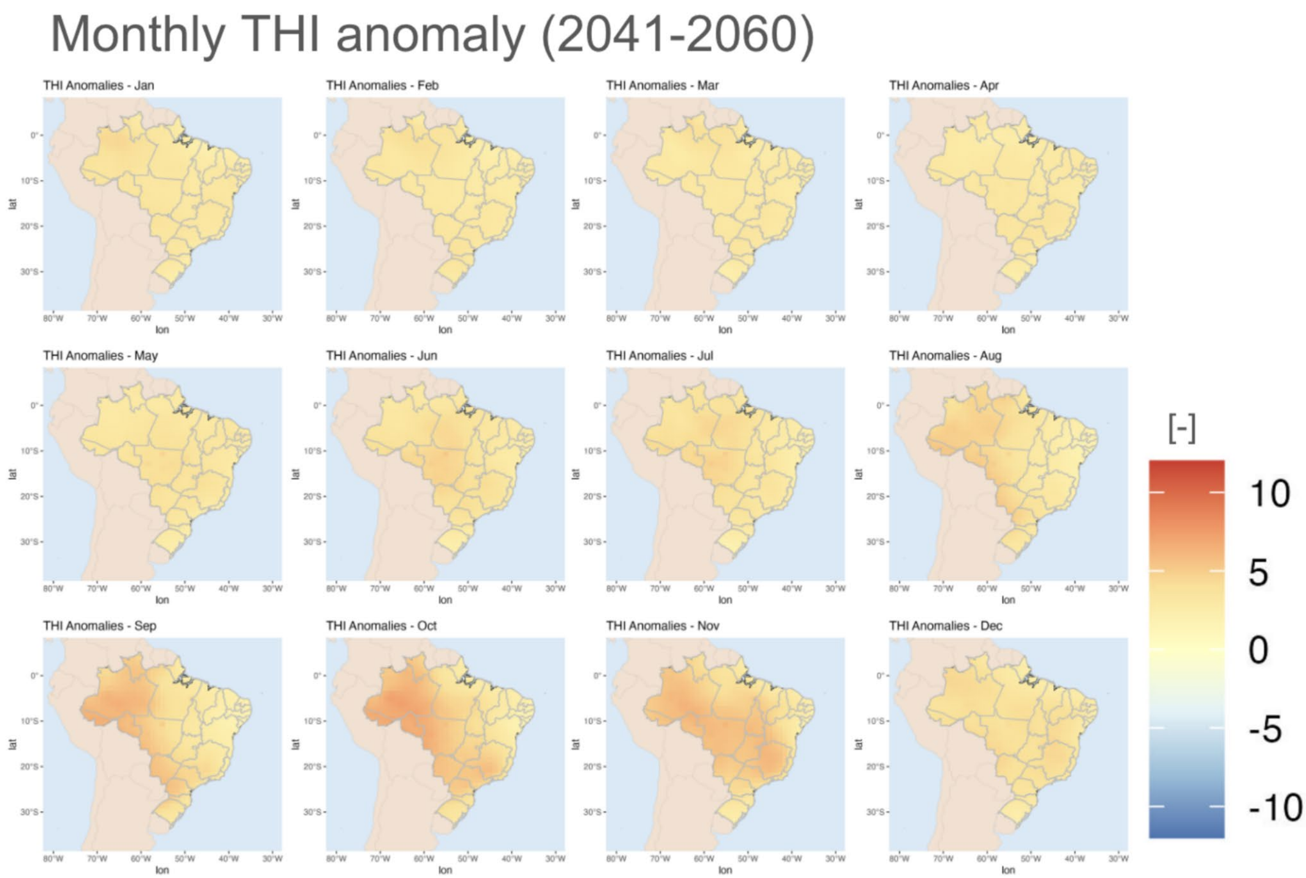

Fig. 4 Monthly THI anomaly, considering the medium-term period simulations from 2041 to 2060

humidity. It's important to recall that the Mid-West region, home to major beef-producing states like Mato Grosso (MT), Mato Grosso do Sul (MS), and Goiás (GO), is particularly affected by these conditions.

This section presents the anomalies (the difference between future and historical simulated climatology) for the short-term (Fig. 3), medium-term (Fig. 4), and long-term (Fig. 5) periods. Figure 3 shows that in the short-term (2021–2040), the THI anomaly is very small, indicating minimal changes in the index when compared to the historical period.

In the medium-term (Fig. 4), the months of January to May show a small increase in the THI anomaly, and this increase is observed across the entire Brazilian territory. From June onwards, a more significant increase in the THI anomaly is identified in the Mid-West and North regions, spreading to the South and Southeast regions around September to November. Therefore, the most critical period for increasing THI anomalies occurs between September and November.

Figure 5 shows the highest THI occurrence compared to the short and medium-term projections. This indicates a significant increase in the THI towards the end of the century, aligning with projected increases in temperature and changes in relative humidity. Consequently, the 2061–2080 time-slice represents the worst-case scenario, when the North and Mid-West regions are projected to be the most severely affected, experiencing substantial THI increases. However, it's important to note that all regions will be strongly impacted in this time-slice, including the Southeast and parts of the South and Northeast of Brazil. Moreover, under this scenario, elevated THI anomalies are projected to persist across different months, based on climatological values.

Climate simulations for three future scenarios (2050, 2075, and 2100) were conducted by Silveira et al. (2026) to identify key characteristics that could strengthen ruminants' adaptive response to climate change. According to the authors, ruminants raised in the Southern Hemisphere are projected to exhibit an increase in rectal temperature as a physiological response to new climatic conditions. Furthermore, the authors emphasize that the degree of phenotypic plasticity in beef cattle will be a determining factor for the species' adaptation to climate changes.

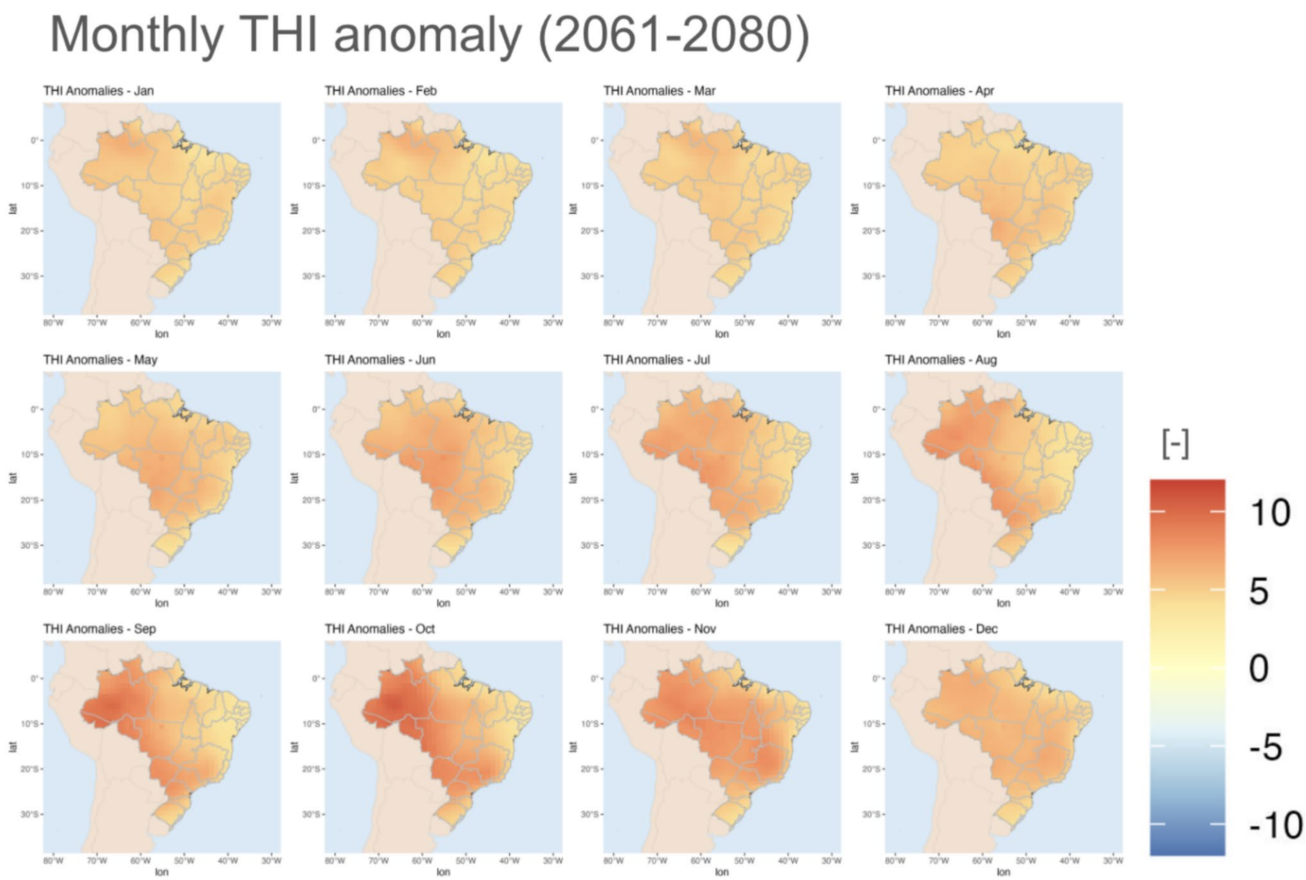

Fig. 5 Monthly THI anomaly, considering the long-term period simulations from 2061 to 2080

Number of days with extreme THI

To quantify the impact of climate change on beef cattle, we calculated the number of days with extreme THI, meaning values of THI exceeding the threshold of 94. Figure 6 below illustrates the monthly climatology of the number of days per month with extreme THI (*ndaysTHI*) for the historical period (1991–2010).

Figure 6 illustrates that the North and Mid-West regions historically experience the highest number of days with extreme THI (*ndaysTHI*) between September and November. October stands out as particularly critical, showing the highest prevalence of days with high temperatures and low relative humidity. It's important to note that the period from August to November is characterized by prolonged dry spells in these regions. These harsh climatic conditions can negatively impact these animals, leading to respiratory problems and a deterioration of their local environment. Recommended mitigation measures include providing shade, implementing integrated crop-livestock systems (ICLS), and utilizing sprinklers (Liu et al. 2024; Rodrigues et al. 2023).

Figures 7, 8, and 9 present the monthly anomalies of *ndaysTHI* (number of days with extreme THI). Figure 7 shows that in the 2021–2040 period, when compared to the historical period, some regions in the states of Amazonas and Pará are affected by extreme THI for most of the year (August to March). This pattern was also observed in the 2041–2060 period, but with even higher values (approaching 30 days per month with extreme THI) in some regions between August and March. The 2041–2060 time-slice also highlights a large central area of Brazil being affected by extreme THI. This widespread impact extends to states such as Mato Grosso, Mato Grosso do Sul, Goiás, Tocantins, Roraima, among others.

Figure 9 shows the monthly anomaly of *ndaysTHI* for the 2061–2080 period. Under this scenario, most areas of Brazil could be affected by extreme THI at different times of the year. The sole exception is the southern region of Brazil, where *ndaysTHI* is projected to remain relatively low throughout the century according to climate projections. Generally, the months of September to December will continue to be the most critical for animal welfare, although *ndaysTHI* is projected to increase across the entire year when compared to the historical period.

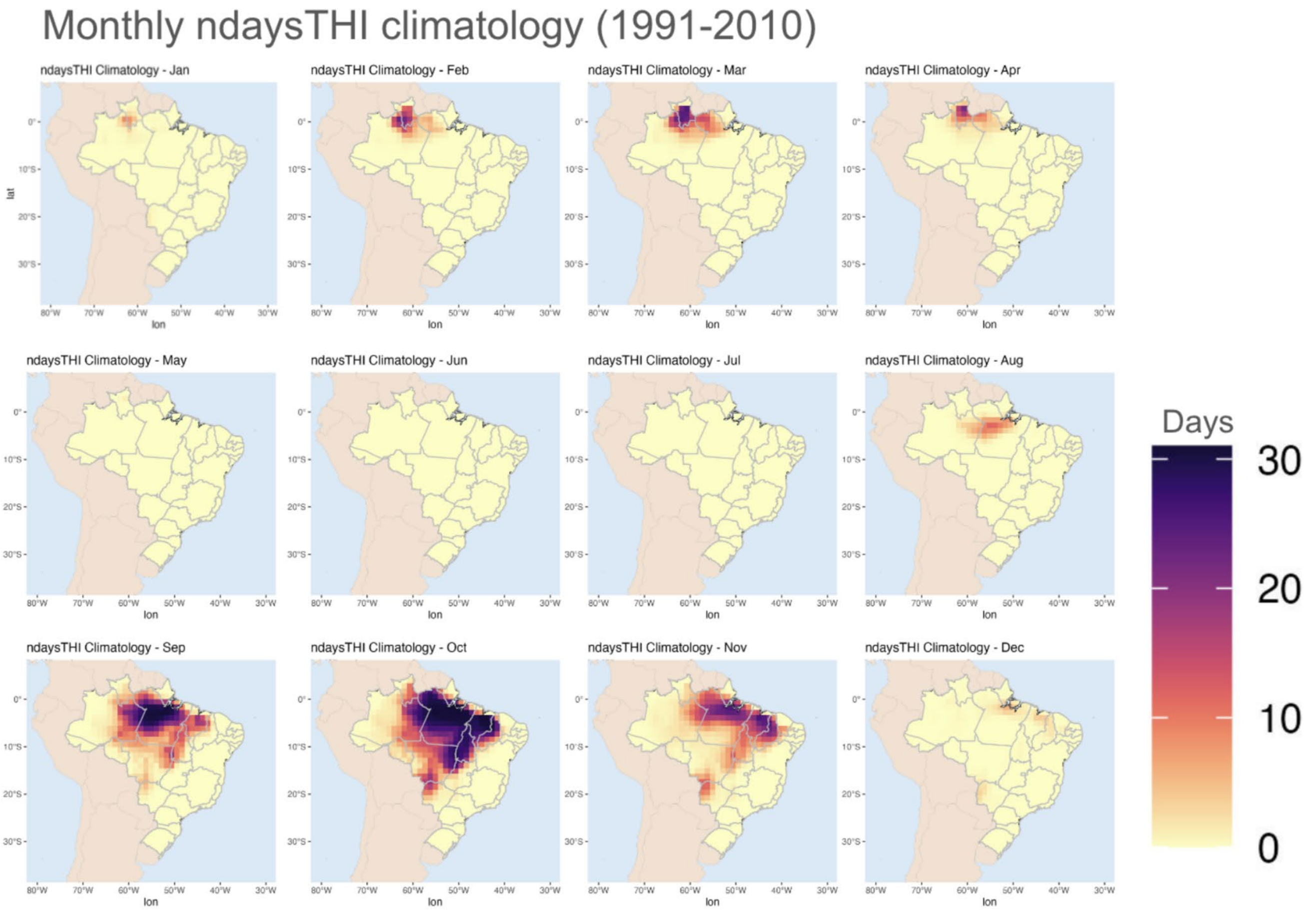

Fig. 6 Monthly climatology of the number of days with extreme THI (*ndaysTHI*), from 1991 to 2010

Our findings align with McIntosh et al. (2023), who used the THI to evaluate the impact of global warming on animal production systems in regions of Baja California, Mexico. The authors identified a risk of heat stress during summer and emphasized the importance of adopting management strategies to reduce the thermal load on domestic animals, particularly in northern Baja California, as an essential measure for maintaining productivity.

Currently, we observe in Brazil a trend of livestock expansion into Amazonian regions. However, this study indicates that expanding beef-cattle activities into these areas will not be advantageous in the long term, primarily due to the severe impact of extreme THI on animal production. In this context, one adaptation measure could involve shifting beef cattle production towards the South of Brazil and parts of the Northeast region, where the number of days with extreme THI (*ndaysTHI*) remains relatively low compared to other regions. It's crucial to highlight, however, that these aforementioned regions lack the sufficient land area to accommodate Brazil's entire beef cattle production. Therefore, this underscores the need for more efficient and widespread adaptation measures. Among these adaptation strategies, we can include animal genetic improvement and the implementation of integrated crop-livestock systems (ICLS), among others. Furthermore, it's essential that mitigation measures be applied nationwide to minimize GGE and reduce climate change impacts.

Extreme THI per state

We calculated the number of days per month with extreme THI for each state. It's worth noting, however, that for larger states, this analysis might underestimate the total number of extreme THI days. This is because, in some cases, only a portion of the state is severely affected by high THI, while other parts are not. Figure 10 shows the number of days with extreme THI for various Brazilian states. The monthly average values are presented for each time-slice: 1991–2010, 2021–2040, 2041–2060, and 2061–2080. The 90th percentile is also indicated to represent the worst-case scenario.

For the periods 2021–2040 and 2041–2060, the largest increase in the number of days with extreme THI was observed in Rondônia, with an increase of 17 and 27 days,

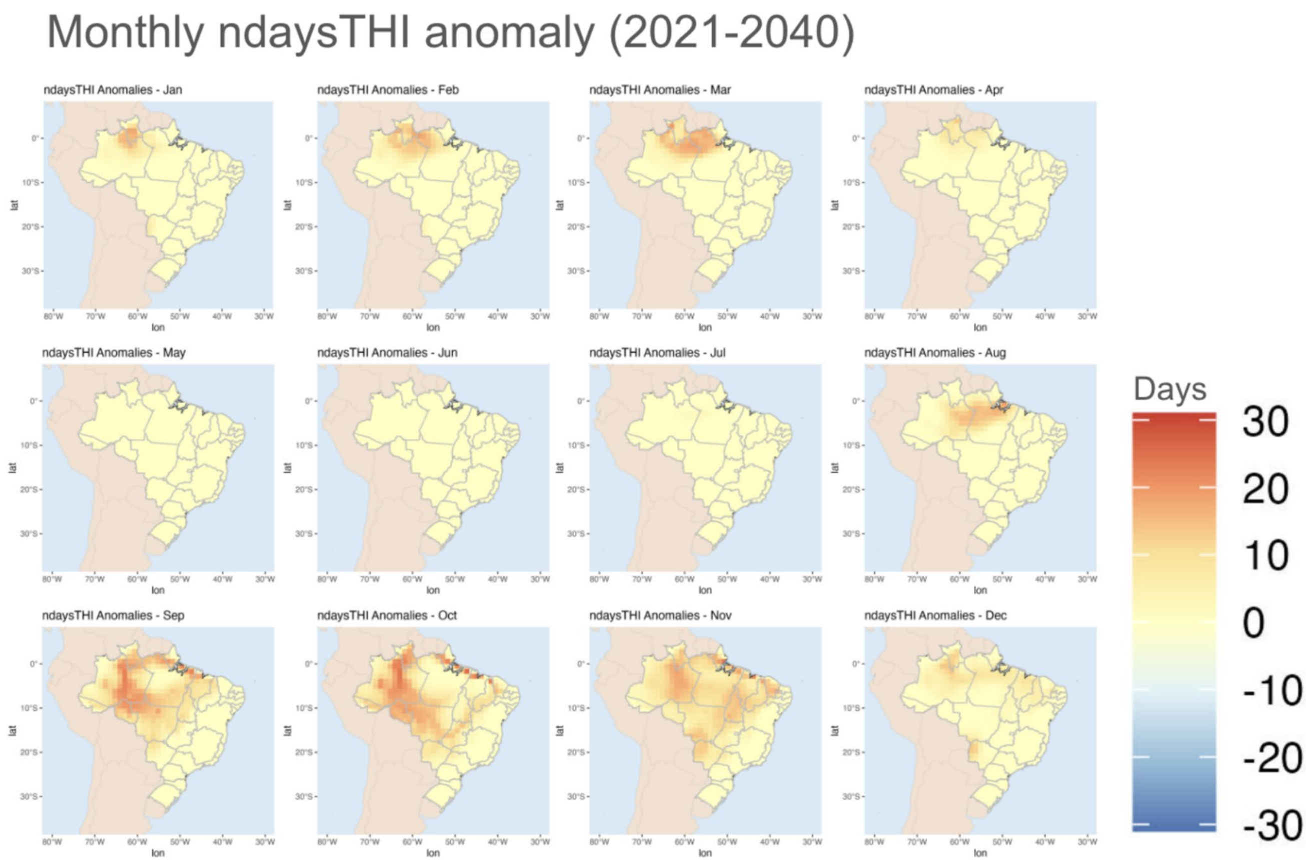

Fig. 7 Monthly anomaly of the number of days with extreme THI (*ndaysTHI*), considering the short-term period simulations from 2021 to 2040

respectively, during the 31-day month of October, reaching 31 days with extreme THI.

Considering the 2061–2080 scenario, the state of Acre (AC) may experience an increase in *ndaysTHI* between August and December, peaking at 31 days with extreme THI in October by the end of the century. In Amazonas (AM), the *ndaysTHI* increase is lowest in June (7 days) and highest in November (28 days), compared to the historical period. This state is projected to have some of the highest *ndaysTHI* values, exceeding 15 days with extreme THI in nine months of the year, with all days between September and November tending to extreme THI. In Bahia (BA), the most significant increase in *ndaysTHI* occurs between November and December, with a peak of about 16 days in November. For the state of Goiás (GO), the highest values are found between September and November, with a peak increase of up to 25 *ndaysTHI* in October compared to the historical period (resulting in approximately 30 days of extreme THI values in that month).

Under the 2061–2080 scenario, projections indicate that Mato Grosso (MT) could experience an increase in days with extreme THI between September and December, with a peak increase of around 26 days in December. It's notable that in this state, between September and October, the *ndaysTHI* value could range from 28 to 31 days. In Mato Grosso do Sul (MS), compared to the historical period, an increase in *ndaysTHI* is estimated between September and March, with a 23-day rise occurring between October and December (resulting in 24 to 27 days with extreme THI during these months). Minas Gerais (MG) is expected to experience an increase of 10 to 11 days with extreme THI in October and November. For Pará (PA), a trend of increasing in *ndaysTHI* is observed across all months of the year. Historically, Pará already had very high values of *ndaysTHI* between September and November (ranging from 12 to 26 days per month in historical simulations). As a result of climate change, high THI values are expected year-round, with extreme THI tending to occur daily between September and November. As shown in Fig. 10, among the states analyzed, Paraná (PR) stands out for its consistently low values of extreme THI days, both in the historical period and in future projections.

The states of Rondônia, Acre, and Goiás are notable because, while they didn't show high numbers of extreme heat stress days historically, they are projected to experience a significant increase in *ndaysTHI* in the future, particularly between September and November. In Rondônia, *ndaysTHI* values for the 2061–2080 period could reach high numbers between September and November (30, 31, and

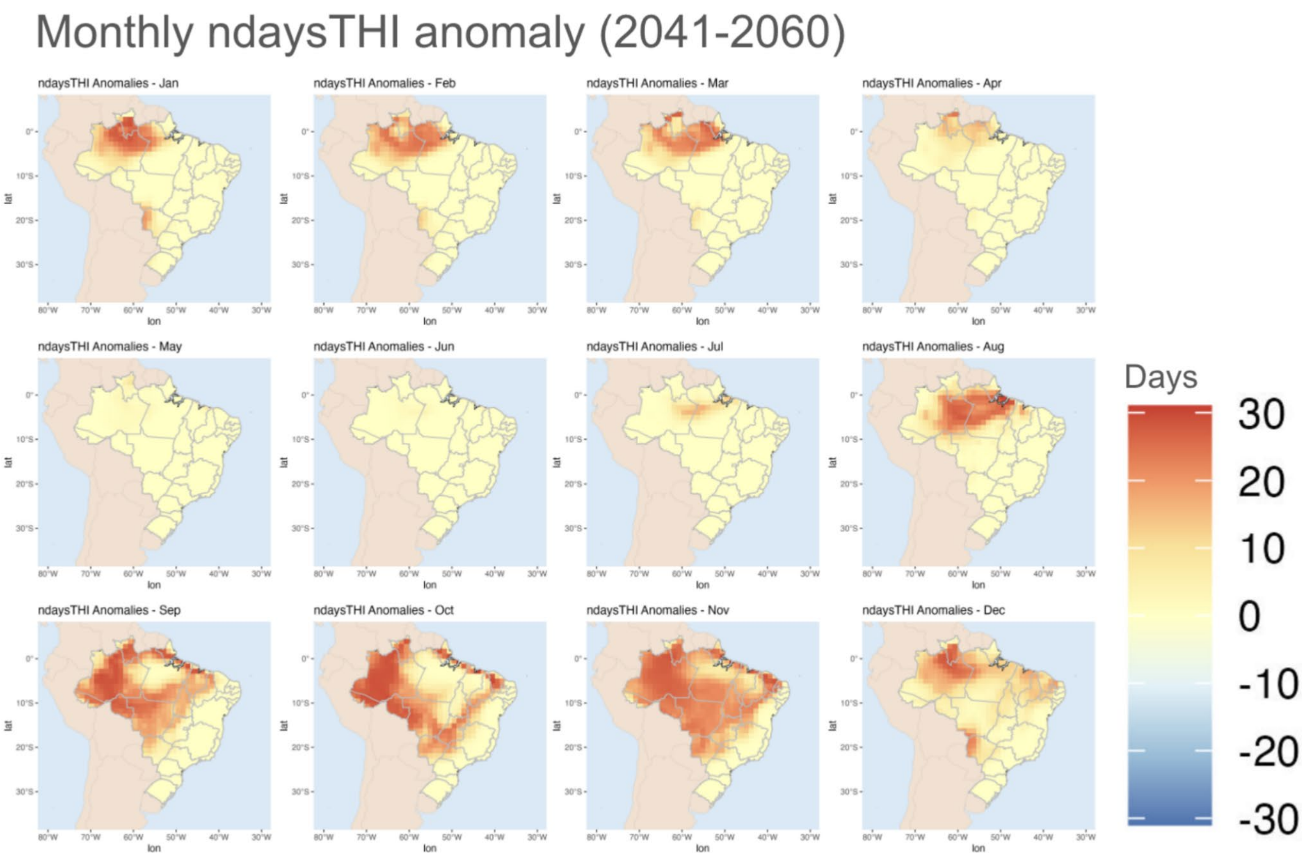

Fig. 8 Monthly anomaly of the number of days with extreme THI,, considering the medium-term period simulations from 2041 to 2060

29 days, respectively). São Paulo, along with Minas Gerais (MG) and Bahia (BA), had low *ndaysTHI* values historically but show a moderate increase in future projections. For São Paulo, this increase translates to 8 to 10 days in October and November. Finally, Tocantins, similar to Pará, already exhibited high extreme THI values in the historical period, and these values are projected to increase even further in the future. In Tocantins, the largest increase in *ndaysTHI* is found in November, with all days in October and November projected to experience extreme THI.

Therefore, we conclude that heat stress is projected to increase in the future, especially between September and December, across a great part of Brazil. It's important to note that constant, extreme heat stress can severely impact an animal's reproductive cycle, reduce feed intake and meat quality, and eventually lead to death (Silanikove 2000).

It is important to emphasize that the number of days with extreme heat stress was determined using established THI thresholds, which were applied as a proxy for assessing beef cattle welfare. This approach provides an innovative and scalable means of estimating the potential impacts of climate change on animal welfare across large spatial and temporal domains. However, this methodology has inherent limitations, as it considers only air temperature and relative humidity. In addition, the applied thresholds do not account for other critical factors influencing animal welfare, such as genetic variability, short-term weather fluctuations, nutritional status, and management practices. Despite these limitations, the results highlight the urgent need for the development of more comprehensive methodological frameworks capable of better representing animal welfare and more accurately quantifying climate change impacts, thereby offering stronger scientific support for the design and implementation of effective adaptation strategies.

Sustainable and resilient practices for livestock adaptation to climate change

Projections from various studies indicate that, with climate change, natural resource depletion, and increased GGE, beef cattle production will be a constant challenge. This challenge can only be minimized by maintaining a sustainable production and optimizing the use of natural resources (McIntosh et al. 2023; Wankar et al. 2024). We expect that extensive pasture-based systems will remain the primary production system in tropical regions, given the phenotypic plasticity of these animals (Silveira et al. 2026).

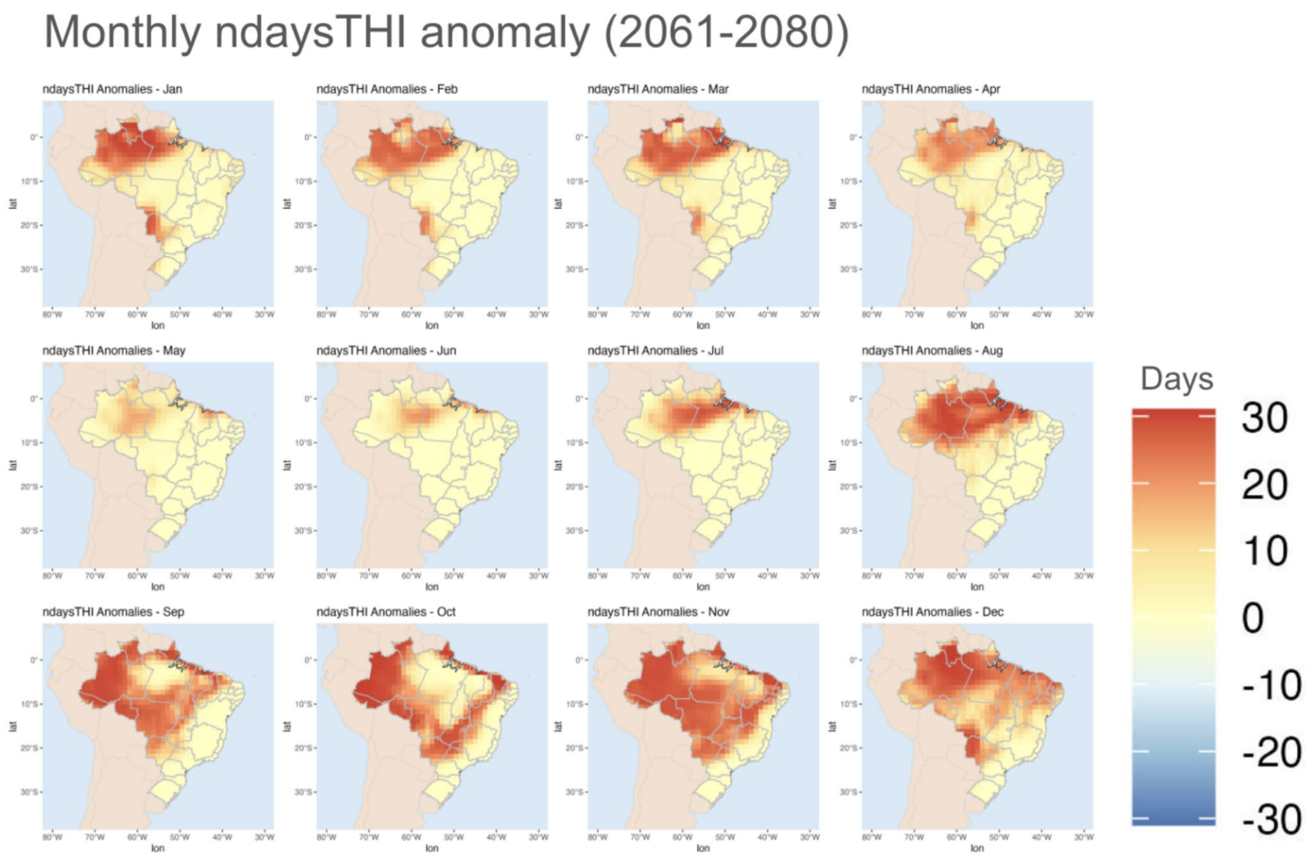

Fig. 9 Monthly anomaly of the number of days with extreme THI, considering the long-term period simulations from 2061 to 2080

Although beef cattle show significant tolerance to heat stress, it's essential to adopt climate change adaptation measures that do not contribute to the expansion of degraded areas. Key strategies include integrated crop-livestock systems (ICLS), proper pasture management, genetic selection of animals more resilient to heat stress, improving animal welfare and environmental conditions, and implementing technologies that reduce the carbon footprint of the activity. When integrated, these strategies contribute to the resilience of production systems and align Brazilian livestock farming with the Sustainable Development Goals (SDGs). We highlight that the increasing temperatures can significantly affect the performance of crops commonly used in integrated crop–livestock systems (ICLS), such as maize, soybean, sorghum, and forage grasses (Ferreira et al. 2021; Resende et al. 2019). In this context, climate warming will likely alter crop phenology, reduce yields, and increase water stress, particularly during critical growth stages (Ferreira and Miranda 2020, 2023). However, ICLS also offers adaptive advantages, including improved soil organic matter, greater water retention, and microclimate regulation, which can mitigate some negative effects of heat stress on crops (Delandmeter et al. 2024). Moreover, the adoption of heat- and drought-tolerant crop cultivars, adjustments in planting dates, crop diversification, and the use of tropical forage species better adapted to high temperatures are key adaptation strategies within ICLS (Ferreira et al. 2023).

The adoption of protocols focused on animal adaptability has become increasingly relevant in livestock production systems. This drives continuous efforts in developing more heat and disease-resistant animal breeds and lineages, especially through the use of genetically adapted resources for the specific conditions of the Southern Hemisphere (Silveira et al. 2026). Delandmeter et al. (2024) studied ICLS with the aim of ensuring high and stable yields while minimizing environmental impacts. The authors observed that moderate and light grazing intensities (pasture heights of 30 and 40 cm) resulted in the greatest increase in soil organic carbon compared to no-grazing treatments. They also noted that these improvements were accompanied by greater resilience to moderate and extreme climatic events, benefiting forage production and beef cattle weight gain. Due to its satisfactory results, ICLS has been considered a key solution for the various challenges imposed on current agriculture and livestock farming by climate change.

In this context, recovering degraded pastures in Brazil represents a promising strategy for advancing sustainable

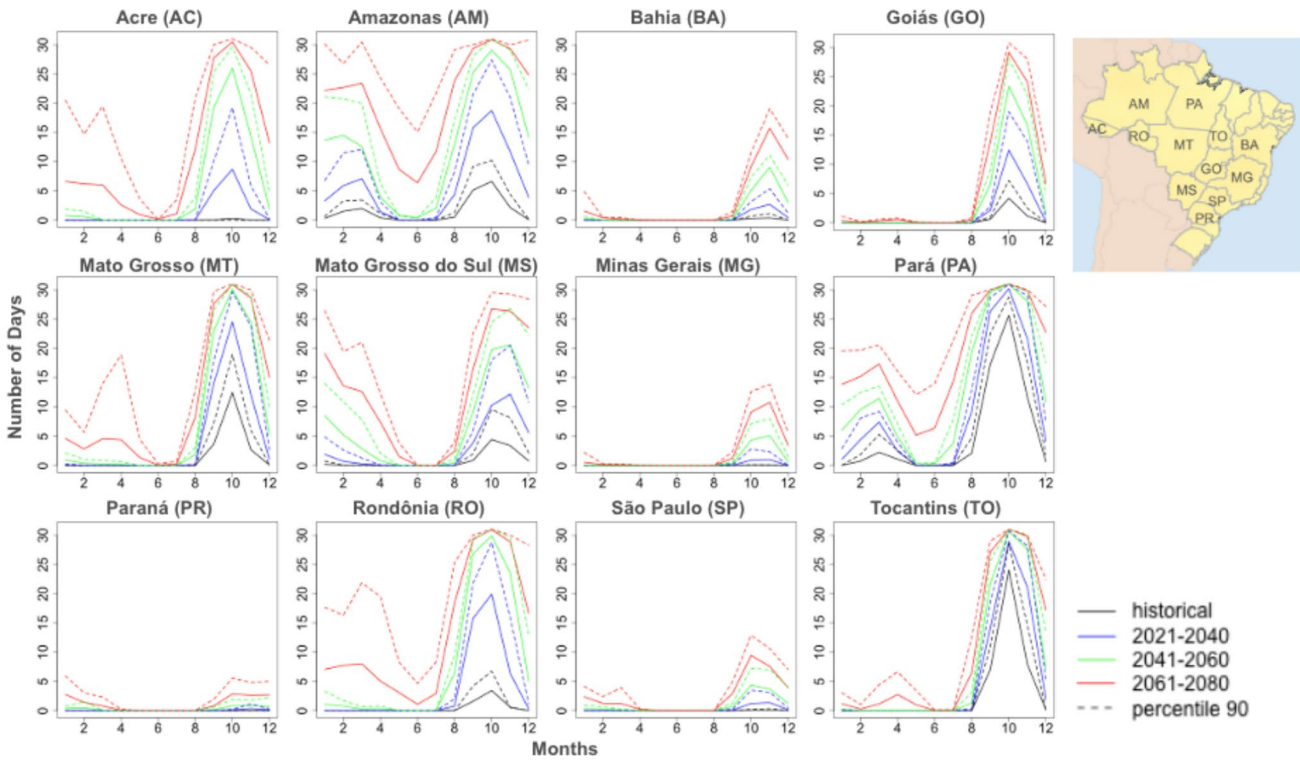

Fig. 10 Number of days with extreme THI, considering the short- (2021–2040), medium- (2041–2060) and long-term (2061–2080) simulations

agricultural practices, reconciling agricultural production with environmental conservation (Rodrigues et al. 2023). Although rising temperatures and more frequent climate extremes may limit pasture recovery, studies suggest that targeted restoration practices—such as the use of heat- and drought-tolerant forage species, improved soil management to enhance water retention and soil organic matter, and integrated crop–livestock systems—can enhance pasture resilience even under warmer climates (Volaire et al. 2014). Key benefits include improved soil quality, the generation of higher value-added products, strengthened qualification of rural labor, and job creation. Another aspect to consider is the increasing need for cooling systems, such as sprinklers for cattle; however, attention must be paid to the growing water usage and electricity costs (Ferreira et al. 2024). The alternative of more intensive integration of mechanized systems powered by renewable energy sources should also reduce costs and potential increases in GGE.

Simultaneously, water plays a fundamental role in various metabolic processes and is crucial for ensuring animal welfare. Inadequate drinking water conditions not only harm cattle welfare and health but also increase the incidence of intestinal diseases, leading to significant economic losses in livestock production (Li et al. 2023). In this context, selecting breeds more adapted to the environment becomes an essential strategy to mitigate the adverse effects of climate change. According to McIntosh et al. (2023), traditional or hybrid cattle breeds with a history of adaptation to grazing in a specific location are more likely to achieve climate change adaptation goals than breeds without such a history.

Precision livestock farming (PLF) technologies have emerged as a promising solution for sustainable livestock production (Papakonstantinou et al. 2024). Digital platforms based on big data and the Internet of Things (IoT) have shown promise in optimizing real-time monitoring of the breeding environment, animal behavior, and health. These tools, combined with predictive models, will enable responses to climate change, better management of natural resources, and improved animal welfare. The integration of automated data collection systems, such as environmental sensors and smart cameras, will allow for more comprehensive and accurate analyses of production systems. The major challenge, therefore, is to facilitate their accessibility to rural producers, ensuring wider dissemination and demonstrating their great potential (Silveira et al. 2024). The development and application of methods that link climatic data to disease occurrence should be implemented to prevent and/or control climate-associated diseases (Lacetera 2019).

However, such efforts can be compromised by unsustainable environmental practices, such as the deforestation of the Amazon for cattle ranching expansion. This intensifies climate change and, consequently, increases risks to animal and human health. Furthermore, as shown by the results obtained here, this area will suffer severely from the impacts of increased THI. It's also important to mention that this practice contributes significantly to biodiversity loss, GGE, and ecological imbalance. Additionally, by destroying large forest areas, the preservation of essential natural resources, such as the water cycle and climate regulation, is compromised, affecting both the environment and the quality of life for future generations.

Therefore, the major challenge is to ensure that innovations and sustainable strategies truly reach rural producers in an accessible and practical manner, promoting their widespread and effective adoption. Maintaining the three pillars of sustainability—economic, social, and environmental—becomes essential to enable a more efficient beef production chain that is resilient to climate change, environmentally responsible, ensures greater animal welfare, and achieves high long-term profitability. Consolidating this path requires integrated public policies, investments in technical training, and incentives for adopting sustainable technologies, ensuring that Brazilian livestock farming progresses in a way that is compatible with the SDGs and the society demands.

Conclusions

The results presented in this article indicate an increase in extreme heat stress across large areas of Brazil, primarily in the North and Mid-West regions, and mostly between September and December. The detailed findings in this research provide practical support that can contribute to adaptation policies. These policies can foster future sustainable production systems linked to the challenges of the 2030 Agenda, aligning with the Sustainable Development Goals (SDGs) such as food security, biodiversity conservation, water security, and climate change adaptation and mitigation. Equally important, effective agricultural policy is needed to enhance the climate resilience of livestock production, along with the introduction of adaptation measures that include simplifying procedures for obtaining subsidies and credit rates that will enable the adoption of favorable sustainable systems. Beyond considering future consequences, it's essential to establish actions focused on the recovery of already degraded areas, ensuring a more balanced and regenerative use of natural resources.

Given the complexity of the challenges posed by climate change to beef cattle farming, future research should delve deeper into the analysis of specific mitigation and adaptation strategies for different biomes and production systems. Integrated studies combining climate modeling, animal genomics, pasture management, and precision livestock farming technologies could offer more effective and regionalized solutions.

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Data availability Data will be shared under request.

Declarations

Conflicts of interest The authors declare no competing interests.

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References

ABIEC (2025). Associação Brasileira das Indústrias Exportadoras de Carnes [database; in portuguese] https://www.abiec.com.br/publicacoes/beef-report-2024-perfil-da-pecuaria-no-brasil/. Accessed 14 Jul 2025

Ames D (1980) Thermal environment affects production efficiency of livestock. Bioscience 30:457–460. https://doi.org/10.2307/1307947

Andrade RR, Tinôco IDFF, Damasceno FA, Oliveira CEA, Concha MS, et al. (2024) Understanding compost-bedded pack barn systems in regions with a tropical climate: a review of the current state of the art. Animals 14(12):1755. https://doi.org/10.3390/ani14121755

Andrade, R. R., Tinoco, I. D. F. F., Damasceno, F. A., Ferraz, G. A., Freitas, L. C. S., Ferreira, C. D. F. S., ... & TELES, C. G. (2022). Spatial analysis of microclimatic variables in compost-bedded pack barn with evaporative tunnel cooling. Anais da Academia Brasileira de Ciências, *94*(3), e20210226. https://doi.org/10.1590/0001-3765202220210226

Baumgard LH, Rhoads RP (2012) Ruminant nutrition symposium: ruminant production and metabolic responses to heat stress. J Anim Sci 90(6):1855–1865. https://doi.org/10.2527/jas.2011-4675

Berman A (2019) An overview of heat stress relief with global warming in perspective. Int J Biometeorol 63(4):493–498. https://doi.org/10.1007/s00484-019-01680-7

Cesca RS, Santos RC, Goes RHDTEBD, Favarim APC, Oliveira MSGD, et al. (2021) Thermal comfort of beef cattle in the state of Mato Grosso do Sul, Brazil. Cienc Agrotecnol 45:e008321. https://doi.org/10.1590/1413-7054202145008321

Cheng M, McCarl B, Fei C (2022) Climate change and livestock production: a literature review. Atmosphere 13(1):140. https://doi.org/10.3390/atmos13010140

Das R, Sailo L, Verma N, Bharti P, Saikia J, et al. (2016) Impact of heat stress on health and performance of dairy animals: a review. Vet World 9(3):260. https://doi.org/10.3390/atmos13010140

Delandmeter M, de Faccio Carvalho PC, Bremm C, dos Santos Cargnelutti C, Bindelle J, et al. (2024) Integrated crop and livestock systems increase both climate change adaptation and mitigation capacities. Sci Total Environ 912:169061. https://doi.org/10.1016/j.scitotenv.2023.169061

Ferreira NCR, Miranda JH (2020) Potential occurrence of *Puccinia sorghi* in corn crops in Paraná, under scenarios of climate change. Int J Biometeorol 64(7):1051–1062. https://doi.org/10.1007/s00484-020-01880-6

Ferreira NCR, Miranda JH (2021) Projected changes in corn crop productivity and profitability in Parana, Brazil. Environ Dev Sustain 23(3):3236–3250. https://doi.org/10.1007/s10668-020-00715-z

Ferreira NCR, Martins M, da Silva Tavares P, Chan Chou S, Monteiro A, et al. (2021) Assessment of crop risk due to climate change in Sao Tome and Principe. Reg Environ Change 21(1):22. https://doi.org/10.1007/s10113-021-01746-6

Ferreira NCR, Rötter RP, Bracho-Mujica G, Nelson WC, Lam QD, et al. (2023) Drought patterns: their spatiotemporal variability and impacts on maize production in Limpopo province, South Africa. Int J Biometeorol 67(1):133–148. https://doi.org/10.1007/s00484-022-02392-1

Ferreira CN, Andrade R, Ferreira LN (2024) Climate change impacts on livestock in Brazil. Int J Biometeorol 68(12):2693–2704. https://doi.org/10.1007/s00484-024-02778-3

Godde CM, Mason-D'Croz D, Mayberry DE, Thornton PK, Herrero M (2021) Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob Food Secur 28:100488. https://doi.org/10.1016/j.gfs.2020.100488

Hall JW, Tran M, Hickford AJ, Nicholls RJ (eds) (2016) The future of national infrastructure: A system-of-systems approach. Cambridge University Press. Available at: https://www.cambridge.org/core/books/future-of-national-infrastructure/7D4DF0295A9D8A7304E6C87204BAA0EA. Accessed 25 Jul 2025

Harrison PA, Holman IP, Berry PM (2015) Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. Clim Change 128(3):153–167. https://doi.org/10.1007/s10584-015-1324-3

Hempel S, Menz C, Pinto S et al (2019) Heat stress risk in European dairy cattle husbandry under different climate change scenarios-uncertainties and potential impacts. Earth Syst Dyn 10:859–884. https://doi.org/10.5194/esd-10-859-2019

Herbut P, Angrecka S, Walczak J (2018) Environmental parameters to assessing of heat stress in dairy cattle—a review. Int J Biometeorol 62(12):2089–2097. https://doi.org/10.1007/s00484-018-1629-9

Herbut P, Hoffmann G, Angrecka S, Godyń D, Vieira FMC, et al. (2021) The effects of heat stress on the behaviour of dairy cows–a review. Ann Anim Sci 21(2):385–402. https://doi.org/10.2478/aoas-2020-0116

Horowitz LW., Naik V, Sentman, L, et al (2018) NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6 AerChemMIP. Version 20230703. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.1404

IBGE (2025) Instituto Brasileiro de Geografia e Estatística [database; in portuguese] https://agenciadenoticias.ibge.gov.br/agencia-sala-de-imprensa/2013-agencia-de-noticias/releases/42898-2024-registra-recorde-no-abate-de-bovinos-frangos-e-suinos. Accessed 25 Jul 2025

Joy A, Dunshea FR, Leury BJ, Clarke IJ, DiGiacomo K, et al. (2020) Resilience of small ruminants to climate change and increased environmental temperature: a review. Animals 10(5):867. https://doi.org/10.3390/ani10050867

Kadzere CT, Murphy MR, Silanikove N, Maltz E (2002) Heat stress in lactating dairy cows: a review. Livest Prod Sci 77(1):59–91. https://doi.org/10.1016/S0301-6226(01)00330-X

Kang S, Da-hye KİM, Lee S, Lee T, Kyung-woo L, et al. (2020) An acute, rather than progressive, increase in temperature-humidity index has severe effects on mortality in laying hens. Front Vet Sci 7:568093. https://doi.org/10.3389/fvets.2020.568093

Lacetera N (2019) Impact of climate change on animal health and welfare. Anim Front 9(1):26–31. https://doi.org/10.1093/af/vfy030

Li B, Wang Y, Rong L, Zheng W (2023) Research progress on animal environment and welfare. Animal Research and One Health 1(1):78–91. https://doi.org/10.1002/aro2.16

Liu E, Liu L, Zhang Z, Qu M, Xue F (2024) An automated sprinkler cooling system effectively alleviates heat stress in dairy cows. Animals (Basel) 14(17):2586. https://doi.org/10.3390/ani14172586

Mader TL, Davis MS, Brown-Brandl T (2006) Environmental factors influencing heat stress in feedlot cattle. J Anim Sci 84(3):712–719.

McIntosh MM, Spiegal SA, McIntosh SZ, Sanchez JC, Estell RE, et al. (2023) Matching beef cattle breeds to the environment for desired outcomes in a changing climate: a systematic review. J Arid Environ 211:104905. https://doi.org/10.1016/j.jaridenv.2022.104905

Millen DD, Pacheco RDL, Meyer PM, Rodrigues PHM, De Beni Arrigoni M (2011) Current outlook and future perspectives of beef production in Brazil. Anim Front 1(2):46–52. https://doi.org/10.2527/af.2011-0017

Nardone A, Ronchi B, Lacetera N et al (2010) Effects of climate changes on animal production and sustainability of livestock systems. Livest Sci 130:57–69. https://doi.org/10.1016/j.livsci.2010.02.011

North MA, Franke JA, Ouweneel B, Trisos CH (2023) Global risk of heat stress to cattle from climate change. Environ Res Lett 18(9):094027. https://doi.org/10.1088/1748-9326/aceb79

NRC, NATIONAL RESEARCH COUNCIL - NRC (1971) A guide to environmental research on animals. National Academy of Sciences, Washington

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, et al. (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim Change 122(3):387–400. https://doi.org/10.1007/s10584-013-0905-2

OECD (2023). Organisation for economic co-operation and development. Agricultural Outlook 2023–2032. Available at: https://stats.oecd.org/index.aspxDatasetCode. Accessed 15 Jul 2025

Oliveira CEA, Tinôco IDFF, Damasceno FA, Oliveira VCD, Ferraz GAES, et al. (2022) Mapping of the thermal microenvironment for dairy cows in an open compost-bedded pack barn system with positive-pressure ventilation. Animals (Basel) 12(16):2055. https://doi.org/10.3390/ani12162055

Papakonstantinou GI, Voulgarakis N, Terzidou G, Fotos L, Giamouri E, et al. (2024) Precision livestock farming technology: applications and challenges of animal welfare and climate change. Agriculture (Basel) 14(4):620. https://doi.org/10.3390/agriculture14040620

Resende NC, Miranda JH, Cooke R, Chu ML, Chou SC (2019) Impacts of regional climate change on the runoff and root water uptake in corn crops in Parana, Brazil. Agric Water Manag 221:556–565. https://doi.org/10.1016/j.agwat.2019.05.018

Rodrigues, R.d.A.R., Ferreira, I.G.M., da Silveira, J.G., da Silva, J.J.N., Santos, F.M., da Conceição, M.C.G. (2023). Crop-Livestock-Forest Integration Systems as a Sustainable Production Strategy in Brazil. In: Søndergaard, N., de Sá, C.D., Barros-Platiau, A.F. (eds) Sustainability Challenges of Brazilian Agriculture. Environment & Policy, vol 64. Springer, Cham. https://doi.org/10.1007/978-3-031-29853-0_9

Sejian V, Bhatta R, Gaughan JB, Dunshea FR, Lacetera N (2018) Adaptation of animals to heat stress. Animal 12(s2):s431–s444. https://doi.org/10.1017/S1751731118001945

Silanikove N (2000) Effects of heat stress on the welfare of extensively managed domestic ruminants. Livest Prod Sci 67(1–2):1–18. https://doi.org/10.1016/S0301-6226(00)00162-7

Silveira RMF, Mcmanus C, da Siva IJO (2024) Global trends and research frontiers on machine learning in sustainable animal production in times of climate change: Bibliometric analysis aimed at insights and orientations for the coming decades. Environmental and Sustainability Indicators 26:100563

Silveira RMF, Façanha DAE, de Vasconcelos AM, Leite SCB, Leite JHGM, et al. (2026) Physiological adaptability of livestock to climate change: a global model-based assessment for the 21st century. Environ Impact Assess Rev 116:108061. https://doi.org/10.1016/j.eiar.2025.108061

Swart NC, Cole JN, Kharin VV, Lazare M, Scinocca JF, et al. (2019) The Canadian earth system model version 5 (CanESM5. 0.3). Geosci Model Dev 12(11):4823–4873. https://doi.org/10.5194/gmd-12-4823-2019

Thornton P, Nelson G, Mayberry D, Herrero M (2021) Increases in extreme heat stress in domesticated livestock species during the twenty-first century. Glob Chang Biol 27(22):5762–5772. https://doi.org/10.1111/gcb.15825

Valente ÉEL, Chizzotti ML, de Oliveira CVR, Galvão MC, Domingues SS, de Castro Rodrigues A, Ladeira MM (2015) Intake, physiological parameters and behavior of Angus and Nellore bulls subjected to heat stress. Semina: Ciências Agrárias 36(6Supl2):4565–4574.

Volaire F, Barkaoui K, Norton M (2014) Designing resilient and sustainable grasslands for a drier future: adaptive strategies, functional traits and biotic interactions. Eur J Agron 52:81–89

Wankar AK, Bhangale GN, Rindhe SN, Kumawat BL, Shafi TA (2024) Heat stress in beef cattle: climate cHange and tHe global scenario–a review. Ann Anim Sci 24(4):1093–1105. https://doi.org/10.2478/aoas-2024-0026

Wieners KH, Giorgetta M, Jungclaus J, et al (2019) MPI-M MPI-ESM1.2-LR model output prepared for CMIP6 CMIP historical. Version 20230703. Earth System Grid Federation. https://doi.org/10.22033/ESGF/CMIP6.6595

Yukimoto S, Kawai H, Koshiro T, Oshima N, Yoshida K, et al. (2019) The Meteorological Research Institute Earth System Model version 2.0, MRI-ESM2. 0: description and basic evaluation of the physical component. J Meteorol Soc Japan Ser II 97(5):931–965. https://doi.org/10.2151/jmsj.2019-051

Zeng J, Li J, Lu X, Wei Z, Shangguan W, et al. (2022) Assessment of global meteorological, hydrological and agricultural drought under future warming based on CMIP6. Atmos Ocean Sci Lett 15(1):100143. https://doi.org/10.1016/j.aosl.2021.100143