Environmental Impact Assessment Review 116 (2026) 108061

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

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

Physiological adaptability of livestock to climate change: A global model-based assessment for the 21st century

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ARTICLE INFO

Keywords:
Climate adaptation
Poultry
Heat stress
Climate projections
Ruminant animals
Genetic resources

ABSTRACT

Rising global temperatures and the growing world population create a paradox that compromises food security and hinders efforts to achieve the Sustainable Development Goals (SDGs) of zero hunger and climate action by 2030 Agenda. Global-scale studies are necessary to assess climate change scenarios in the livestock industry. Meteorological data and adaptive responses of animals reared in different countries around the world were used to show that animals in the thermal environment of the Northern Hemisphere must display a wider range of thermoregulatory responses than animals in the Southern Hemisphere. Subsequently, future climate simulations were performed based on conservative IPCC RCP4.5 climate models to project the impact of climate change on physiological responses of sheep, goats, dairy and beef cattle, pigs, poultry and quails, and identify key traits to strengthen the adaptative response to future climatic conditions. Results showed that ruminant animals in the Northern Hemisphere will be most impacted by climate change in the three climate scenarios of 2050, 2075, and 2100, with a predicted increase in respiratory rate of up to 68 % compared to animals in the Southern Hemisphere. Ruminant animals reared in the Southern Hemisphere will increase their rectal temperature as an adaptive response to climate change. It was also found that dairy cattle farming will be the most susceptible activity to heat stress in the coming decades in the Southern Hemisphere, and goats and beef cattle are the animals that will be less impacted by climate change due to phenotypic plasticity. Quails and laying hens will be the most susceptible animals to climate change, with respiratory rates expected to increase by up to 40 beats per minute by 2100. It is concluded that the adoption of animal adaptability protocols is becoming an increasingly relevant topic in livestock production systems in the Northern Hemisphere, with ongoing efforts to develop breeds and lines of domestic animals more resistant to heat stress and diseases, especially using resources locally adapted to the conditions of the Southern Hemisphere, where strategies should be based on the selection and crossbreeding to increase animal production and ensure food security for the growing population by the end of

Abbreviations: Air temperature, (AT, °C);; Alanine aminotransferase, (ALT, U l^{-1}); Albumin, (ALB, g dl^{-1}); Aspartate aminotransferase, (AST, U l^{-1}); Cholesterol, (CHO, mg dl^{-1}); Coat surface temperature, (CST, °C); Cloaca temperature, (CT, °C); Coat thickness, (COT, mm); Cortisol, (CO, g dl^{-1}); Creatinine, (CRE, mg dl^{-1}); Glucose, (GLU, mg dl^{-1}); Globulin, (GLO, mg dl^{-1}); Hair density, (HAD, hair cm^{-2}); Hair diameter, (HD, μm); Hair length, (HL, mm); Heart rate, (HR, beats min^{-1}); Hemoglobin concentration, (HC, g dl^{-1}); Max, maximum;; Mean corpuscular volume, (MCV, fl); Min, minimum; Rectal temperature, (RT, °C); Relative humidity, (RH, %); Respiratory rate, (RR, breaths min^{-1}); Red blood cell count, (RBC, $\times 10^6$/μL); Standard deviation, (SD); Sweat rate, (SR, g/m^2/s); Sustainable Development Goals, (SDGs).

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https://doi.org/10.1016/j.eiar.2025.108061
Received 19 April 2025; Received in revised form 19 June 2025; Accepted 20 June 2025
Available online 4 July 2025

the century. For the poultry industry, intensifying the production system is needed and urgent since animals will not withstand high temperatures in systems with no environmental enrichment strategies. Finally, the conservation of locally adapted genetic resources will be essential to preserve biodiversity, strengthen ecosystem resilience, and address food security challenges in the face of climate change.

1. Introduction

The impact of climate change on food production is a global concern for current livestock systems, especially in developing countries, where the demand for food is increasing due to the growing population and the need to raise living standards (Shi and Yin, 2021). For instance, Emediegwu and Ubabukoh (2023) reported that a 1 °C increase in temperature will lead to a 9.7 % reduction in global beef production in the coming decades. Predictions are even more pessimistic for some areas of Asia, Africa, and South America, where extensive or rangeland pasture-based systems predominate (Nardone et al., 2010).

The direct effects of climate change on food production are related to the increase in average temperatures and in the frequency of heat waves which can cause heat stress in animals, especially in breeds that have been genetically selected for decades focusing on productive performance rather than adaptive traits (Carabaño et al., 2019), causing health, reproductive, and livestock welfare problems. Indirect effects are related to the impact of a changing climate on soil fertility, rainfall distribution and its consequences on pasture and crop growth as well as the spread of pathogens and vectorial diseases. All of which are globally threatening the livestock sector (Nardone et al., 2010). These direct and indirect effects are modulated by different factors, such as geographic location, characteristics of animal species, intensity and level of exposure to extreme events (Weiskopf et al., 2020).

Climate projections predict that the global average temperature can increase by up to 6.4 °C by the end of this century (Solomon et al., 2007; Van Vuuren et al., 2008), but these models are improbable and overestimated. Studies have reported that more conservative projections are more "realistic" in predicting the impact of climate change on temperature by 2100, mainly due to human intervention in mitigating climate change (Hausfather et al., 2022; Scafetta, 2024). These conservative models consider increases of up to 3 °C by the end of the century. Hence, animals will struggle to adapt to climate conditions due to climate change's indirect and direct effects.

The scientific community has been discussing adaptability in production animals intensively in recent years, in order to identify measures that could guide farmers and the industry in terms of infrastructure, sector organization, breeding and selection objectives to reduce the effect of climate change on the animals and mitigate the impact of the sector on climate change. When focusing on heat stress, it is complex to model adaptability in a simple approach, as it is multifactorial (Silveira et al., 2024). An animal adapted to its environment is the one that maintains homeothermy in a thermally stressful environment (Façanha et al., 2020; Lima et al., 2022), while maintaining satisfactory productive and reproductive levels (Carabaño et al., 2019). From a thermodynamic point of view, it is expressed as the ability to balance heat gains and losses in the organism regardless of the environmental condition (Silva de Farias et al., 2020).

This adaptive capacity is closely linked to the concept of phenotypic plasticity, which is defined as the ability of a single genotype to express different phenotypes in response to environmental variations (Oostra et al., 2018; Lima et al., 2022). In the context of livestock production under climate change, phenotypic plasticity refers to the capacity of animals to modulate physiological (e.g., respiratory rate and rectal temperature), morphological (e.g., coat and hair characteristics), behavioral, hematological, and biochemical responses in order to maintain homeostasis under heat stress conditions. This biological flexibility is a key determinant of resilience, enabling certain species to better cope with environmental fluctuations and thereby reducing the negative impacts of heat stress on productivity, health, and animal welfare.

In this context, recent studies have identified thermal stress adaptation biomarkers, which are defined as any measurable phenotypic trait—whether physiological, morphological, hematological, or biochemical—that exhibits a consistent, sensitive, and biologically meaningful response to thermal environmental variation, contributing to the animal's ability to maintain homeostasis under heat stress conditions. For instance, rectal temperature, mean corpuscular volume, and white blood cells have been identified as adaptive biomarkers in Brahman bulls (Silveira et al., 2023), while hematological parameters have been reported as robust biomarkers of thermotolerance in Spanish goats (Silveira et al., 2024).

Although heat stress physiology in animals reared in tropical and temperate regions have been widely documented (De Vasconcelos et al., 2019; de Vasconcelos et al., 2020a; Silveira et al., 2024), information on the impacts of global changes on heat stress events in livestock production of sheep, goats, dairy and beef cattle, pigs, poultry, and quails is still scarce, especially how climate change will require adaptive responses of these animals, since it is known that animals in the Southern Hemisphere responded differently than animals in the Northern Hemisphere, and vice versa, due to the differences between temperate and tropical climates and specific characteristics of the animals. But how will this happen? What adaptive mechanisms will be used by animals in each hemisphere? What is the impact of climate on the adaptive mechanisms in dairy and beef cattle, poultry, sheep, pigs, and goats? How will farm animals respond to climate change by 2100? Which livestock crops are most susceptible to heat stress, and which ones have shown phenotypic plasticity to cope with these changes in 2100?

The objectives of the present study were twofold: (i) to evaluate the impact of the thermal environment on the adaptive physiological responses of farm animals in both hemispheres; and (ii) to project the impacts of climate change on livestock production for sheep, goats, dairy and beef cattle, pigs, poultry, and quails using future climate simulations based on conservative RCP4.5 models. It was hypothesized that climate change will increase animals' respiratory rate and rectal temperature, leading to heat stress. This physiological burden is expected to elevate basal metabolic energy demands, diverting energy from productive functions to thermoregulation and maintenance. Consequently, this process may reduce livestock productivity worldwide, with greater impacts anticipated for animals reared in the Southern Hemisphere.

In the long term, the results of this research provide essential practical support for the development of adaptation policies in global livestock systems, contributing to food security and the sustainability of animal production in the face of climate change. The identification of more resilient species, such as goats and beef cattle, and the urgency of specific strategies for more vulnerable sectors, such as poultry and dairy farming, allow for targeted efforts in management, genetic improvement, and the conservation of animal genetic resources. Thus, this study offers a scientific foundation for the development of more efficient, resilient, and environmentally sustainable animal production systems, in alignment with the Sustainable Development Goals.

2. Material and methods

2.1. Databases

The databases used in this study were collected by trained technicians in four research groups from the institutions *Universidade Federal*

Rural do Semiárido (UFERSA-RN), *Universidade Estadual Vale do Acaraú* (UVA-CE) and *Universidade Federal da Paraíba* (UFPB-PB), all located in the Northeast of Brazil – Semiarid region. All projects were submitted and approved by the University Ethics Committee on the Use of Animals (CEUA) of their respective educational institutions. Additional information such as number of animals, species, months of collection, country of collection, Koppen's climate classification and animal breed from the twelve databases used in this study are presented in Table 1. Management information (feeding, diet composition, health and reproduction), and the description of the facilities of the 12 databases are described in Supplementary Material 1.

2.2. Data collection

Meteorological variables and thermoregulatory, morphological, hematological, biochemical and hormonal responses were collected in the different experiments. The description of the methodology and analysis of the collection is described in Supplementary Material 2.

2.3. Statistical methods

The statistical methods were organized into four steps, using different multivariate analysis techniques and machine learning models. Fig. 1 presents an explanatory diagram of each step, while Supplementary Material 3 describes each analysis in detail, including the models adopted and their respective assumptions.

3. Results

3.1. Impact of thermal environment on the adaptive responses

The evaluation of the impact of thermal environment on the adaptive responses of production animals is presented in Tables 2, 3 and 4. Ruminant animals reared in the Northern Hemisphere presented a greater impact of thermal environment on thermoregulatory responses [Italian Massese ewes ($r^2 = 0.64$; $p < 0.001$); Spanish Canaria ewes ($r^2 = 0.29$; $p < 0.001$); Spanish Majorera goats ($r^2 = 0.52$; $p = 0.001$); and Spanish Palmera goats ($r^2 = 0.46$; $p = 0.001$)]. The opposite was observed for ruminant animals reared in the Southern Hemisphere [Brazilian Morada Nova ewes ($r^2 = 0.02$; $p = 0.018$), Brazilian Bahman bulls ($r^2 = 0.25$; $p = 0.001$); Brazilian cows ($r^2 = 0.31$; $p < 0.001$) and Sindi cows ($r^2 = 0.06$; $p = 0.08$)]. It was also discovered that among farm animals, poultry are more susceptible to heat stress than ruminant animals, regardless of the hemisphere [pullets ($r^2 = 0.90$; $p < 0.001$); chickens ($r^2 = 0.81$; $p < 0.001$) and quails ($r^2 = 0.93$; $p < 0.001$ – Table 2)]. Out of the monogastric animals, the thermal environment showed low impact on the thermoregulatory responses only for piglets ($r^2 = 0.15$; $p = 0.002$). All thermoregulatory responses were influenced by the thermal environment ($p < 0.001$), except for rectal temperature in ruminant animals reared in the Southern Hemisphere and piglets.

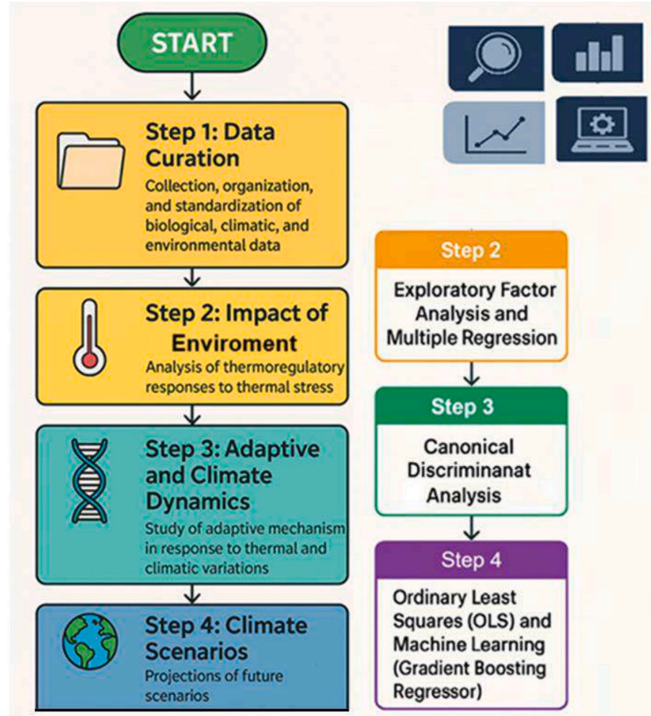

Fig. 1. Statistical analysis design.
Step 1: Involves the tabulation, organization, and standardization of biology, productive, and environmental data; ***Step 2:*** Analyzes adaptive responses and identifies phenotypic biomarkers using exploratory factor analysis and multiple regression; ***Step 3*:** Defines the adaptive profile of different animals across both hemispheres through canonical discriminant analysis; and ***Step 4*:** Projects future scenarios based on statistical models (OLS) and machine learning (Gradient Boosting Regressor).

3.2. Identification of phenotypic biomarkers associated with adaptation

The impact of the thermal environment on coat morphological traits, hormonal profile, serum biochemistry and hematological variables was generally low among species from both hemispheres (Tables 3, 4, and 5). However, key insights regarding these adaptive traits include: *1)* Coat morphological traits: Hair density was the only common variable that had an impact of the thermal environment ($p < 0.001$); *2)* Hormonal

Table 1
General database information.

Database	Hemisphere	Animals	Breed	Location	Animals (n)	Data collection period	Koppen's Climate classification
1	North	Ewes	Massese	Italy	159	24 months	Csa
2	South	Ewes	Morada Nova	Brazil	120	36 months	BSh
3	North	Ewes	Canaria	Spain	23	12 months	Csa
4	North	Goats	Majorera	Spain	30	24 months	Csa
5	North	Goats	Palmera	Spain	20	24 months	Csa
6	South	Dairy cows	Girolando	Brazil	15	12 months	BSh
7	South	Dairy cows	Sindi	Brazil	15	12 months	BSh
8	South	Beef cattle	Brahman	Brazil	63	12 months	Aw
9	South	Pullets	Hy-Line White	Brazil	288	56 days	BSh
10	South	Laying hens	Hy-Line White	Brazil	270	174 days	BSh
11	South	Quails	European	Brazil	648	21 days	As
12	South	Piglets	Agroceres	Brazil	64	37 days	As

Csa – Hot-summer mediterranean climate.
BSh – Hot semi-arid climate.
Aw – Tropical savanna climate with dry winter.
As – Tropical savanna climate with dry summer.

Table 2
Assessment of the environmental impact on the adaptive traits of farm animals in temperate environments.

Databases	Models		Unstandardized coefficients		Standardized coefficients			Collinearity Statistics	
			B	Error	B	t	*p*-Value	Tolerance	VIF
Italian Massese ewes	Thermoregulatory responses ($r^2 = 0.64$; $p < 0.001$)	(Constant)	12.27	3.00		4.08	< 0.001		
		CST	0.15	0.01	0.51	10.11	< 0.001	0.44	2.26
		RT	−0.47	0.07	−0.23	−6.34	< 0.001	0.84	1.19
		RR	0.001	0.001	−0.12	−1.83	0.07	0.28	3.56
		HR	0.02	0.001	0.45	8.62	< 0.001	0.41	2.42
Spanish Canaria ewes	Thermoregulatory responses ($r^2 = 0.29$; $p < 0.001$)	(Constant)	7.90	4.29		1.82	0.07		
		RR	0.02	0.002	0.55	9.30	< 0.001	0.97	1.02
		RT	−0.25	0.11	−0.12	−2.28	0.02	0.97	1.02
	Morphological traits ($r^2 = 0.02$; $p = 0.019$)	(Constant)	1.18	0.35		3.38	< 0.001		
		COT	−0.95	0.22	−0.25	−4.24	< 0.001	0.82	1.22
		HAD	0.001	0.001	−0.08	−1.44	0.15	0.87	1.14
		HL	0.02	0.02	0.08	1.39	0.16	0.83	1.20
		HD	−24.92	3.26	−0.43	−7.65	< 0.001	0.91	1.09
	Adaptive traits ($r^2 = 0.26$; $p < 0.001$)	(Constant)	0.01	0.25		0.04	0.97		
		RR	−0.02	0.001	−0.40	−7.72	< 0.001	0.99	1.01
		COT	0.95	0.20	0.25	4.72	< 0.001	0.93	1.08
		HAD	0.001	0.001	0.18	3.27	< 0.001	0.93	1.08
Spanish Majorera Goats	Thermoregulatory responses ($r^2 = 0.52$; $p = 0.001$)	(Constant)	−5.59	1.42		−3.93	< 0.001		
		RT	−0.07	0.04	−0.07	−2.07	0.04	0.95	1.06
		RR	0.001	0.001	0.06	1.79	0.07	1.00	1.00
		HR	−0.01	0.001	−0.15	−4.31	< 0.001	0.91	1.10
		CST	0.30	0.01	0.67	20.46	< 0.001	0.96	1.05
	Morphological traits ($r^2 = 0.06$; $p = 0.001$)	(Constant)	0.75	0.14		5.35	< 0.001		
		COT	−0.07	0.12	−0.03	−0.54	0.59	0.97	1.03
		HL	0.001	0.001	0.03	0.61	0.54	0.80	1.26
		HD	−13.04	2.88	−0.22	−4.53	< 0.001	0.95	1.06
		HAD	0.001	0.001	−0.08	−1.47	0.14	0.83	1.20
	Adaptive traits ($r^2 = 0.32$; $p < 0.001$)	(Constant)	−2.32	1.16		−2.01	0.05		
		CST	0.18	0.01	0.52	12.76	< 0.001	1.00	1.00
		ND	−12.70	2.37	−0.22	−5.36	< 0.001	0.99	1.01
		RT	−0.07	0.03	−0.10	−2.37	0.02	0.99	1.01
Spanish Palmera goats	Thermoregulatory responses ($r^2 = 0.46$; $p = 0.001$)	(Constant)	3.06	2.92		1.05	0.30		
		RT	−0.23	0.07	−0.12	−3.15	< 0.001	1.00	1.00
		RR	0.01	0.001	0.18	4.53	< 0.001	0.98	1.02
		HR	−0.02	0.001	−0.27	−6.62	< 0.001	0.92	1.09
		CST	0.23	0.02	0.52	12.84	< 0.001	0.93	1.07
	Morphological traits ($r^2 = 0.04$; $p = 0.014$)	(Constant)	0.77	0.16		4.91	< 0.001		
		COT	−0.13	0.10	−0.07	−1.22	0.22	0.95	1.06
		HL	0.001	0.001	0.03	0.49	0.62	0.87	1.15
		HD	−7.14	2.46	−0.17	−2.90	< 0.001	0.94	1.06
		HAD	0.001	0.001	−0.06	−1.01	0.31	0.88	1.13
	Adaptive traits ($r^2 = 0.27$; $p < 0.001$)	(Constant)	3.69	2.28		1.61	0.11		
		CST	0.13	0.01	0.47	9.43	< 0.001	0.99	1.01
		RT	−0.18	0.06	−0.15	−3.10	< 0.001	0.99	1.02
		HAD	−5.33	2.10	−0.13	−2.53	0.01	0.98	1.02

Rectal temperature (RT, °C); respiratory rate (RR, breaths min^{-1}), coat surface temperature (CST, °C), heart rate (HR, breaths min^{-1}), coat thickness (COT, mm); hair length (HL, mm); hair diameter (HD, μm); hair density (HAD, hair cm^{-2}).

profile: Thyroid hormones were important for the bovine species in the adaptive profile; *3*) Hematological profile: Erythrocyte morphology was important in all databases; and *4*) Serum biochemistry panel: The variables responsible for liver and kidney function are important adaptive responses used by ruminant animals under heat stress conditions in tropical regions.

3.3. Adaptive profile

The thermoregulatory responses of ruminant animals differ between those reared in the Northern and Southern Hemispheres (Fig. 2AB). Additionally, birds presented different thermoregulatory responses compared to ruminant animals, regardless of the hemisphere. Among the variables accessed, rectal temperature followed by respiratory rate were the most important for distinguishing animals by hemisphere (Fig. 3A) and for differentiating animal species by hemisphere (Fig. 2B). When animals were classified based on species and hemisphere, 77.5 % were correctly assigned to their group of origin. Notably, more than 85 % of the monogastric animals from the Southern Hemisphere and ruminants from the Northern Hemisphere were correctly classified in their origin group. However, when the twelve databases were evaluated, only 37.7 % of the cases were correctly classified in their group of origin (Fig. 2B), with similarities between species, but not by hemisphere. For example, unlike laying hens, pullets and quails presented similar thermoregulatory mechanisms. As for ruminants, two groups are observed according to hemisphere, on the right side (northern hemisphere) and on the left side (southern hemisphere).

3.4. Climate change scenarios and their impact on adaptive responses

The impact of climate change according to the climate scenarios for the next decades for animals reared in the Northern and Southern hemispheres is presented in Figs. 3 and 4. It can be seen that animals from the Northern hemisphere ($r^2 = 0.14$; $p < 0.001$) will be more impacted by climate change in the three climate scenarios (2050, 2075, and 2100) when compared to animals from the Southern hemisphere ($r^2 = 0.53$; $p < 0.001$). Specifically, it is expected that animals from the Northern hemisphere will present a 68.05 % increase in respiratory rate in 2100 when compared to animals from the Southern hemisphere (Fig. 3). This relationship is inverse for rectal temperature, as animals

Table 3
Assessment of the environmental impact on the adaptive traits of farm animals in tropical environments.

Databases	Models		Unstandardized coefficients		Standardized coefficients			Collinearity Statistics	
			B	Error	B	t	*p*-Value	Tolerance	VIF
Brazilian Morada Nova ewes	Thermoregulatory responses ($r^2 = 0.02$; $p = 0.02$)	(Constant)	0.99	2.59		0.38	0.70		
		RT	−0.04	0.07	−0.03	−0.54	0.59	0.94	1.07
		RR	0.01	0.001	0.15	2.85	< 0.001	0.94	1.07
	Morphological traits ($r^2 = 0.02$; $p = 0.02$)	(Constant)	−0.24	0.40		−0.60	0.55		
		COT	0.31	0.61	0.03	0.51	0.61	0.97	1.03
		HL	0.001	0.001	0.10	1.71	0.09	0.93	1.08
		HAD	0.22	0.10	0.12	2.14	0.03	0.99	1.01
		HD	−9.97	4.58	−0.12	−2.18	0.03	0.92	1.08
	Hormonal profile ($r^2 = 0.13$; $p < 0.001$)	(Constant)	0.22	0.19		1.19	0.24		
		T_4	−0.13	0.03	−0.25	−4.31	< 0.001	1.00	1.00
		T_3	0.23	0.06	0.24	4.23	< 0.001	1.00	1.00
	Serum biochemical profile ($r^2 = 0.03$; $p < 0.001$)	(Constant)	−0.09	0.61		−0.15	0.88		
		GLU	0.02	0.001	0.37	6.01	< 0.001	0.88	1.14
		COL	0.001	0.001	−0.03	−0.48	0.63	0.76	1.32
		TRI	0.01	0.001	0.06	1.07	0.29	0.97	1.03
		URE	0.001	0.001	0.001	0.07	0.95	0.92	1.08
		CRE	0.41	0.15	0.18	2.73	0.01	0.75	1.33
		TPR	−0.07	0.06	−0.07	−1.05	0.30	0.84	1.19
		ALB	−0.08	0.09	−0.05	−0.90	0.37	0.96	1.04
		AST	−0.01	0.001	−0.24	−3.87	< 0.001	0.91	1.10
		ALT	0.01	0.01	0.11	1.74	0.08	0.83	1.20
	Hematological variables ($r^2 = 0.15$; $p < 0.001$)	Constant	0.17	0.61		0.27	0.79		
		RBC	0.09	0.03	0.21	2.64	< 0.001	0.57	1.76
		MCV	−0.03	0.01	−0.21	−2.74	< 0.001	0.57	1.76
	Adaptive profile ($r^2 = 0.63$; $p < 0.001$)	Constant	−1.34	0.31		−4.27	< 0.001		
		GLU	0.03	0.00	0.46	6.25	< 0.001	0.81	1.23
		CRE	0.71	0.12	0.44	5.88	< 0.001	0.81	1.24
		AST	0.00	0.00	−0.13	−2.00	0.05	0.98	1.02
Brazilian Girolando cows	Thermoregulatory responses ($r^2 = 0.31$; $p < 0.001$)	(Constant)	2.81	5.04		0.56	0.58		
		RT	−0.03	0.14	−0.03	−0.25	0.80	0.76	1.32
		RR	−0.04	0.01	−0.54	−4.84	< 0.001	0.76	1.32
	Hematological variables ($r^2 = 0.15$; $p < 0.001$)	(Constant)	0.75	1.28		0.58	0.56		
		HE	0.00	0.00	0.12	0.80	0.43	0.50	2.00
		MCV	0.36	0.12	0.51	2.96	< 0.001	0.39	2.55
		HG	−0.30	0.10	−0.40	−3.03	< 0.001	0.68	1.48
	Serum biochemical profile ($r^2 = 0.033$; $p < 0.001$)	(Constant)	3.04	1.31		2.33	0.02		
		TPR	−0.30	0.16	−0.21	−1.84	0.07	0.64	1.56
		ALB	0.14	0.14	0.12	1.00	0.32	0.64	1.55
		CHO	0.00	0.00	0.05	0.41	0.69	0.49	2.02
		GLU	0.00	0.00	0.13	1.17	0.25	0.74	1.35
		TRI	0.00	0.01	0.04	0.35	0.73	0.60	1.66
		AST	0.01	0.01	0.16	1.38	0.17	0.66	1.51
		ALT	−0.04	0.01	−0.34	−2.81	0.01	0.58	1.71
		URE	−0.01	0.01	−0.13	−1.08	0.29	0.60	1.66
		CRE	−0.77	0.24	−0.43	−3.25	< 0.001	0.49	2.03
	Hormonal profile ($r^2 = 0.28$; $p < 0.001$)	(Constant)	−1.71	0.60		−2.86	0.01		
		T_3	0.75	0.42	0.18	1.77	0.08	0.99	1.01
		T_4	0.67	0.14	0.48	4.74	< 0.001	0.99	1.01
	Adaptive profile ($r^2 = 0.58$; $p < 0.001$)	(Constant)	0.59	0.58		1.02	0.31		
		RR	−0.03	0.01	−0.41	−4.18	< 0.001	0.68	1.47
		CRE	−0.55	0.17	−0.31	−3.33	< 0.001	0.79	1.27
		T_4	0.34	0.13	0.24	2.64	0.01	0.81	1.23
		AST	0.01	0.01	0.20	2.34	0.02	0.87	1.15
Brazilian Sindi cows	Thermoregulatory responses ($r^2 = 0.31$; $p < 0.001$)	(Constant)	11.81	6.32		1.87	0.07		
		RT	−0.29	0.16	−0.19	−1.78	0.08	0.99	1.01
		RR	−0.02	0.02	−0.13	−1.24	0.22	0.99	1.01
	Hematological variables ($r^2 = 0.15$; $p < 0.001$)	(Constant)	−2.48	1.86		−1.33	0.19		
		HC	0.00	0.00	0.00	−0.01	0.99	0.40	2.52
		MCV	0.43	0.18	0.38	2.37	0.02	0.40	2.52
	Serum biochemical profile ($r^2 = 0.20$; $p = 0.04$)	(Constant)	−1.80	1.59		−1.13	0.26		

(*continued on next page*)

Table 3 (*continued*)

Databases	Models		Unstandardized coefficients		Standardized coefficients			Collinearity Statistics	
			B	Error	B	t	*p*-Value	Tolerance	VIF
		TPR	0.29	0.16	0.24	1.85	0.07	0.63	1.59
		ALB	−0.02	0.23	−0.01	−0.07	0.94	0.64	1.55
		CHO	0.00	0.00	−0.04	−0.31	0.76	0.56	1.78
		GLU	−0.01	0.00	−0.23	−1.93	0.06	0.78	1.28
		TRI	−0.01	0.02	−0.07	−0.57	0.57	0.77	1.31
		AST	0.00	0.01	0.10	0.75	0.46	0.55	1.81
		ALT	0.00	0.02	−0.02	−0.16	0.87	0.51	1.96
		URE	0.01	0.01	0.13	0.98	0.33	0.59	1.68
		CRE	−0.05	0.25	−0.02	−0.22	0.83	0.84	1.19
	Hormonal profile ($r^2 = 0.28$; $p < 0.001$)	(Constant)	−0.96	0.63		−1.51	0.13		
		T_3	0.65	0.41	0.17	1.58	0.12	0.99	1.01
		T_4	0.03	0.17	0.02	0.20	0.84	0.99	1.01
	Adaptive profile ($r^2 = 0.78$; $p < 0.001$)	(Constant)	13.40	5.41		2.48	0.02		
		MCV	0.33	0.11	0.29	2.97	< 0.001	0.83	1.21
		RT	−0.51	0.14	−0.33	−3.57	< 0.001	0.93	1.07
		TPR	0.35	0.13	0.29	2.78	0.01	0.77	1.30
		T_3	0.89	0.35	0.24	2.58	0.01	0.96	1.04
		URE	0.01	0.00	0.19	2.01	0.05	0.88	1.13
	Thermoregulatory responses ($r^2 = 0.25$; $p = 0.001$)	(Constant)	2.99	2.34		1.28	0.20		
		RR	0.04	0.01	0.26	3.70	< 0.001	0.74	1.35
		RT	−0.11	0.06	−0.12	−1.92	0.06	0.99	1.01
		SR	0.001	0.001	0.15	2.09	0.04	0.74	1.35
	Hormonal profile ($r^2 = 0.07$; $p < 0.001$)	(Constant)	−0.38	0.19		−1.99	0.05		
		T_3	−0.03	0.06	−0.04	−0.58	0.57	0.76	1.31
		T_4	0.001	0.001	0.26	4.09	< 0.001	0.95	1.05
		CO	0.001	0.001	0.08	1.17	0.24	0.77	1.29
	Morphological traits ($r^2 = 0.08$; $p < 0.001$)	(Constant)	1.20	0.32		3.69	< 0.001		
		COT	0.23	0.24	0.06	0.96	0.34	0.93	1.08
		HL	−0.05	0.02	−0.17	−2.61	0.01	0.87	1.15
		HAD	0.001	0.001	−0.05	−0.75	0.45	0.99	1.01
		HD	−18.39	7.65	−0.15	−2.40	0.02	0.94	1.07
	Adaptive traits ($r^2 = 0.14$; $p < 0.001$)	(Constant)	6.04	2.28		2.65	0.01		
		T_4	0.001	0.001	0.22	3.77	< 0.001	0.98	1.02
		HL	−0.05	0.02	−0.18	−2.97	< 0.001	0.91	1.10
		HD	−17.36	7.36	−0.14	−2.36	0.02	0.94	1.06
Brazilian Brahman bulls		RT	−0.13	0.06	−0.14	−2.35	0.02	0.98	1.02

Triiodothyronine (T_3, μg dl $^{-1}$), thyroxine (T_4, μg dl $^{-1}$); cortisol (CO, g dl $^{-1}$); rectal temperature (RT, °C); respiratory rate (RR, breaths min $^{-1}$), sweat rate (SR, g/m^2/s), coat surface temperature (CST, °C), heart rate (HR, breaths min $^{-1}$), red blood cell count (RBC, $\times 10^6$/μL), hemoglobin concentration (HC, g dl $^{-1}$), mean corpuscular volume (MCV, fl); glucose (GLU, mg dl $^{-1}$); cholesterol (CHO, mg dl $^{-1}$); triglycerides (TRI, mg dl $^{-1}$); total protein (TPR, g dl $^{-1}$); urea (URE, mg dl $^{-1}$); creatinine (CRE, mg dl $^{-1}$); albumin (ALB, g dl $^{-1}$); aspartate aminotransferase (AST, U l $^{-1}$); alanine aminotransferase (ALT, U l $^{-1}$); coat thickness (COT, mm); hair length (HL, mm); hair diameter (HD, μm); hair density (ND, hair cm $^{-2}$).

from the Southern Hemisphere will increase rectal temperature by 0.035 °C ($r^2 = 0.10$; $p < 0.001$), while animals from the Northern Hemisphere are expected to increase RT by 0.025 °C ($r^2 = 0.10$; $p < 0.001$) ($\mathbf{\Delta}_{RT} = 0.01$ °C; Fig. 4).

Figs. 5 and 6 show the impact of climate change in three climate scenarios for ruminant animals reared in the Southern and Northern hemispheres, respectively. In the Northern hemisphere, sheep will have an increase of 15 movements per minute ($r^2 = 0.56$; $p < 0.001$), while goats will have a smaller increase in respiratory rate ($r^2 = 0.18$; $p < 0.0001$). In the Southern hemisphere, dairy farming is predicted to be the most susceptible activity to heat stress in the coming decades ($r^2 = 0.25$; $p < 0.0001$) with a predicted increase in RR of up to 4 breaths per minute ($r^2 = 0.24$; $P < 0.001$), followed by sheep and dual-purpose cattle ($r^2 = 0.10$; $p < 0.01$). Interestingly, beef cattle will not be affected by climate change in either of the three scenarios (Fig. 6), indicating a degree of phenotypic plasticity. A similar response was observed in goats reared in the Northern Hemisphere (Fig. 5).

The impact of climate change on poultry, quails, and piglets across the climate scenarios is shown in Fig. 7. Laying hens ($r^2 = 0.56$; $p < 0.001$) and quails ($r^2 = 0.89$; $p < 0.001$) will be more susceptible to heat stress than pullets ($r^2 = 0.36$; $p < 0.001$). By 2100, laying hens and quails are expected to experience an increase in respiratory rate of up to 40 beats per minute.

4. Discussion

4.1. Overview

Understanding how climate change affects animal production systems across the globe is fundamental for ensuring future food security and sustainability. Understanding how climate change affects animal production systems around the world is critical to ensuring future food security and sustainability. This study presents a novel and comprehensive approach to assessing the impact of climate change on animal production systems at a global scale, considering the adaptive responses of different species of production animals in both Northern and Southern hemispheres. Using a broad and diverse database, with physiological, morphological, hematological, biochemical and hormonal information from production animals, the study combined these variables with local meteorological data and conservative climate projections, which allowed the simulation of future scenarios of heat stress. The main distinguishing feature of this study is its ability to integrate multivariate

Table 4
Assessment of the environmental impact on the adaptive traits of monogastric animals.

Databases	Models		Unstandardized coefficients		Standardized coefficients			Collinearity Statistics	
			B	Error	B	t	*p*-value	Tolerance	VIF
Brazilian Pullets	Thermoregulatory response ($r^2 = 0.90$; $p < 0.001$)	(Constant)	16.75	3.17		5.29	< 0.001		
		CT	0.001	0.001	−0.11	−3.36	< 0.001	0.71	1.40
		RR	−0.14	0.08	−0.05	−1.78	0.08	0.97	1.03
		STWF	−0.16	0.03	−0.39	−6.10	< 0.001	0.20	5.02
		STF	−0.18	0.02	−0.52	−8.21	< 0.001	0.20	4.95
Brazilian laying hens	Thermoregulatory response ($r^2 = 0.81$; $p < 0.001$)	(Constant)	36.77	4.03		9.13	< 0.001		
		STWF	−0.14	0.03	−0.32	−4.38	< 0.001	0.21	4.74
		STF	−0.17	0.04	−0.31	−4.35	< 0.001	0.21	4.66
		CT	−0.64	0.10	−0.26	−6.15	< 0.001	0.60	1.66
		RR	0.001	0.00	−0.14	−3.00	< 0.001	0.47	2.12
Quails	Thermoregulatory response ($r^2 = 0.93$; $p < 0.001$)	(Constant)	28.98	0.07		435.09	< 0.001		
		RR	0.07	0.001	0.97	72.73	< 0.001	1.00	1.00
		CT	0.00	0.001	0.001	0.27	0.79	1.00	1.00
Piglets	Thermoregulatory response ($r^2 = 0.15$; $p = 0.002$)	(Constant)	21.81	22.65		0.96	0.33		
		RR	0.09	0.03	0.36	3.48	0.001	0.88	1.13
		RT	−0.19	0.58	−0.03	−0.33	0.74	0.88	1.13

Cloaca temperature (CT; °C); surface temperature with feathers (STWF, °C); surface temperature without feathers (STF, °C), respiratory rate (RR, breaths min^{-1}), Rectal Temperature (RT; °C).

analyses and artificial intelligence techniques to discriminate adaptive patterns by species and hemisphere, in addition to identifying phenotypic biomarkers related to thermotolerance, such as hair density, erythrocyte morphology, thyroid hormones, and hepatorenal variables. This allowed us to predict the physiological responses of each species to rising global temperatures, with emphasis on the greater vulnerability of birds (with an increase of up to 40 respiratory movements per minute) and ruminants in the Northern Hemisphere, which showed up to 68 % increase in respiratory rate. On the other hand, beef cattle and goats demonstrated phenotypic plasticity, being less affected. Finally, the magnitude of the expected physiological changes in different species and regions was quantified, proposing specific sustainable strategies for each hemisphere based on the data obtained. The innovation of the study lies both in its integrated and global methodological approach as well as in its practical implications for management, genetic improvement, and formulation of public policies for the sustainability of livestock farming to face climate change.

4.2. Impact of thermal environment on adaptive responses of animals

The impact of the thermal environment on the adaptive responses of animals is strongly influenced by both the production system and the animals' genetic background. In this study, the modeling focused exclusively on ruminants raised in semi-extensive and extensive systems, and monogastric species managed under intensive confinement systems—both representing the predominant production models worldwide. In pasture-based systems, particularly in tropical and semi-arid regions, ruminants are more exposed to direct solar radiation, high ambient temperatures, and humidity, which impose substantial thermal stress (de Vasconcelos et al., 2020b). However, these animals often exhibit greater genetic adaptation to harsh environments due to historical processes of natural selection (Freitas Silveira et al., 2021). In contrast, the thermal comfort of animals (ruminants and monogastrics) in intensive systems relies heavily on environmental control technologies such as ventilation, cooling, and thermal insulation (Guesine et al., 2023a; Garcia et al., 2023). While these technologies mitigate external thermal loads, they may simultaneously exacerbate the accumulation of metabolic heat due to high stocking densities and elevated productivity levels (Guesine et al., 2023b). Therefore, the relationship between heat stress and production systems is highly complex and context-dependent. The physiological responses analyzed in this study primarily represent ruminants managed under semi-extensive and extensive systems and monogastrics raised in intensive production systems.

The lower impact of the thermal environmental on animals' thermoregulatory responses in tropical regions (Sothern Hemisphere) can be attributed to natural selection, through which animals have adapted to high temperatures via morpho-anatomical, physiological, molecular, hormonal, and hematological modifications (Freitas Silveira et al., 2021; Hansen, 2004; Sejian et al., 2018). Some studies have already indicated these adaptative modifications. Anatomo-physiological adaptations include cattle with a higher proportion of zebu ancestry, which possess coat characteristics more favorable for heat dissipation in tropical climates (Façanha et al., 2015), as well as a greater density of sweat glands compared to exotic breeds (Hansen, 2004). From a physiological standpoint, Brahman bulls mainly rely on increased sweating rate to dissipate heat (Freitas Silveira et al., 2021). At the genetic level, the HSP-70, 80, and 90 genes have been identified as genetic biomarkers associated with thermotolerance in production animals (Sejian et al., 2018).

This explanation for the adaptation of animals reared in the Southern Hemisphere based on natural selection is corroborated by the use of databases of animals reared in semi-arid equatorial regions of Brazil used here (database of dairy cows and Morada Nova sheep), in which it is demonstrated that the impact of the thermal environment on thermoregulatory responses was relatively low. However, within the three databases in these regions, Girolando cows which have taurine blood in their breed composition (De Vasconcelos et al., 2019) showed a greater impact of thermal environment compared to Sindi cows and Morada Nova sheep, which are both genetic resources locally adapted to equatorial tropical conditions (Leite et al., 2018).

It is worth mentioning that "*locally adapted breeds*" are those that display the ability to adapt to high temperatures associated with other factors such as nutritional stress and disease resistance, but with unaffected reproductive and productive traits (Ferreira et al., 2020). Other studies with different species of ruminant animals carried out in different semiarid regions of the world show the adaptability of locally adapted animals to tropical climatic conditions (Camerro et al., 2016; Façanha et al., 2019). It is worth mentioning that climatic factors interfere with the adaptive responses of locally adapted animals, but they are more efficient in managing heat dissipation. Ferreira et al. (2020) demonstrated that locally adapted goats have a dynamic pattern of body heat exchange efficiency, with individual variability, in which some animals are more efficient in exchanging heat than others. However, throughout the day, the herd as a whole has an efficient heat

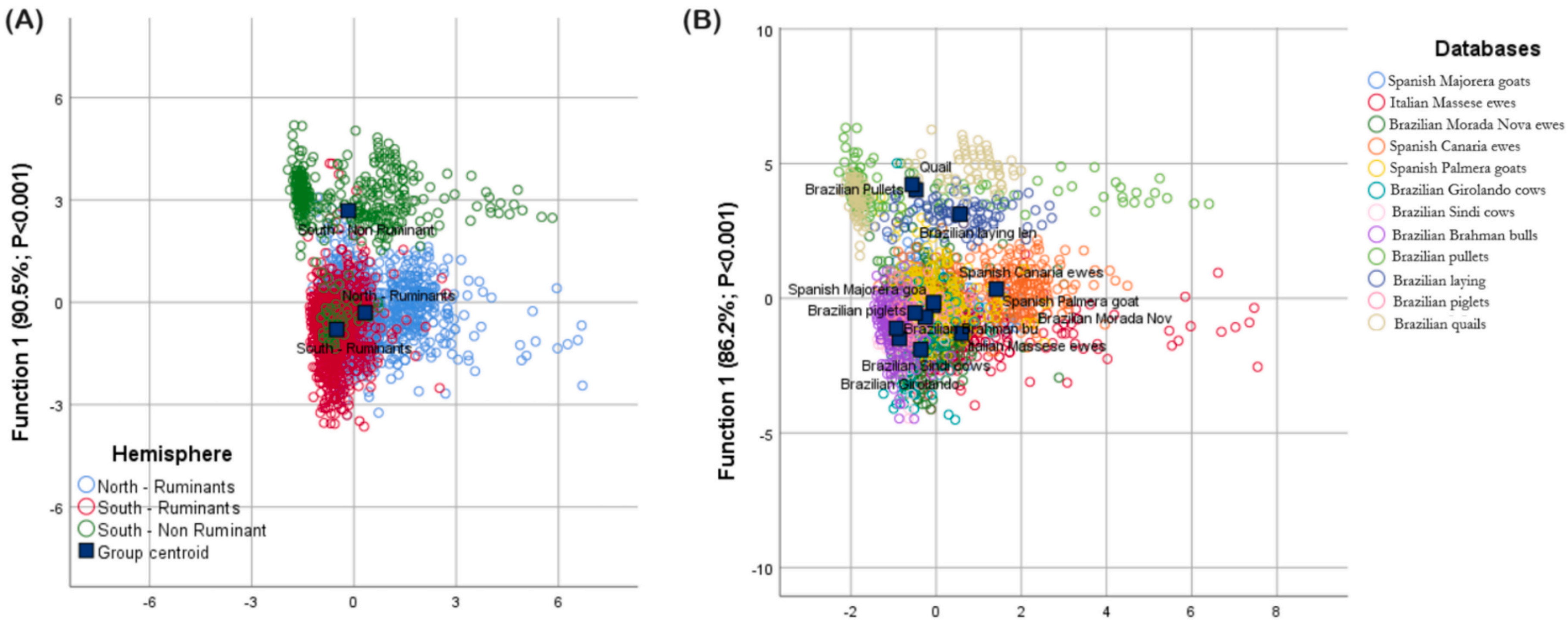

Fig. 2. Biplot of canonical discriminant analysis considering the thermoregulatory responses of farm animals.

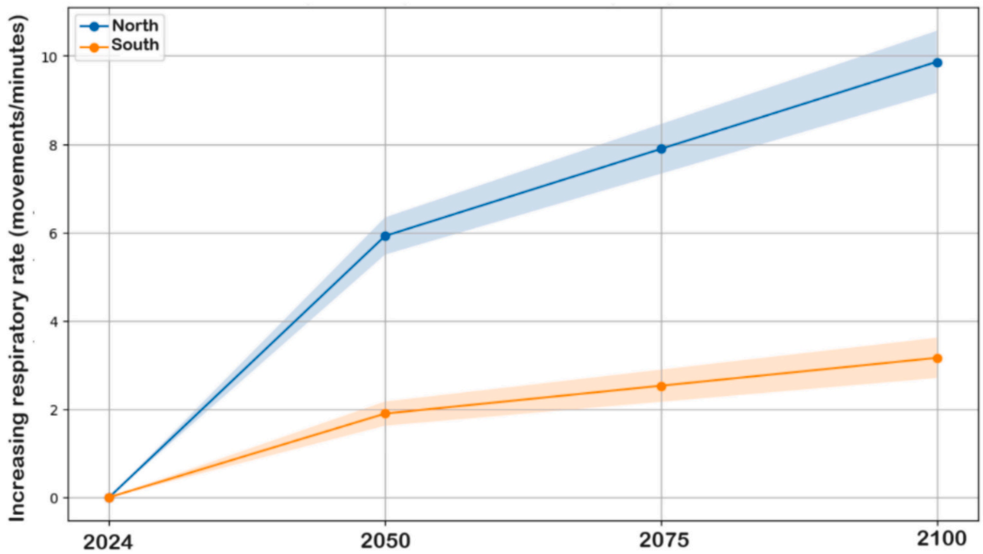

Fig. 3. Impact of environmental temperature on respiratory rate in ruminant animals around the world according to hemisphere.

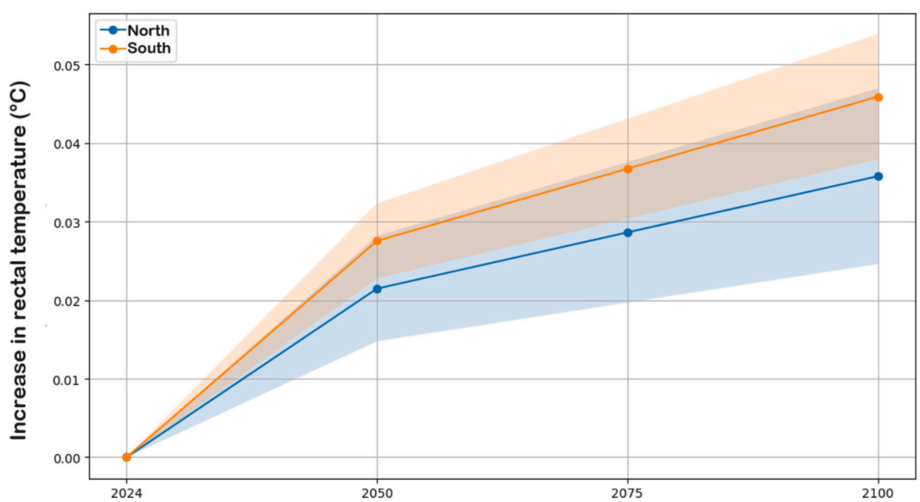

Fig. 4. Impact of environmental temperature on rectal temperature in ruminant animals around the world according to hemisphere.

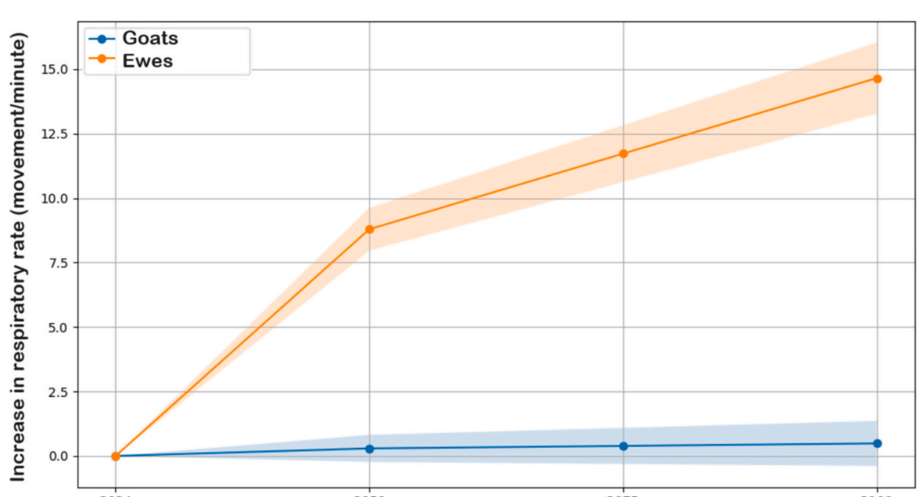

Fig. 5. Impact of increase in ambient temperature on the respiratory rate of small ruminant animals in the coming decades in a temperate region.

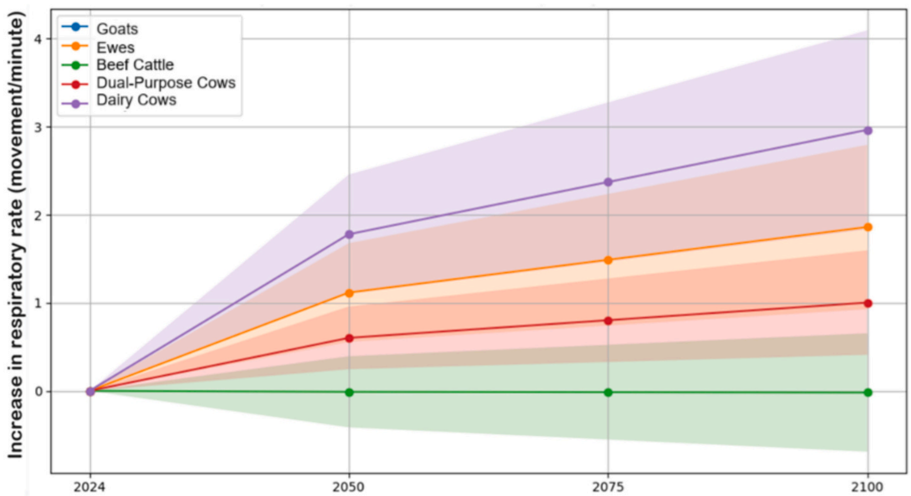

Fig. 6. Impact of ambient temperature on the respiratory rate of ruminant animals in the coming decades in a tropical region.

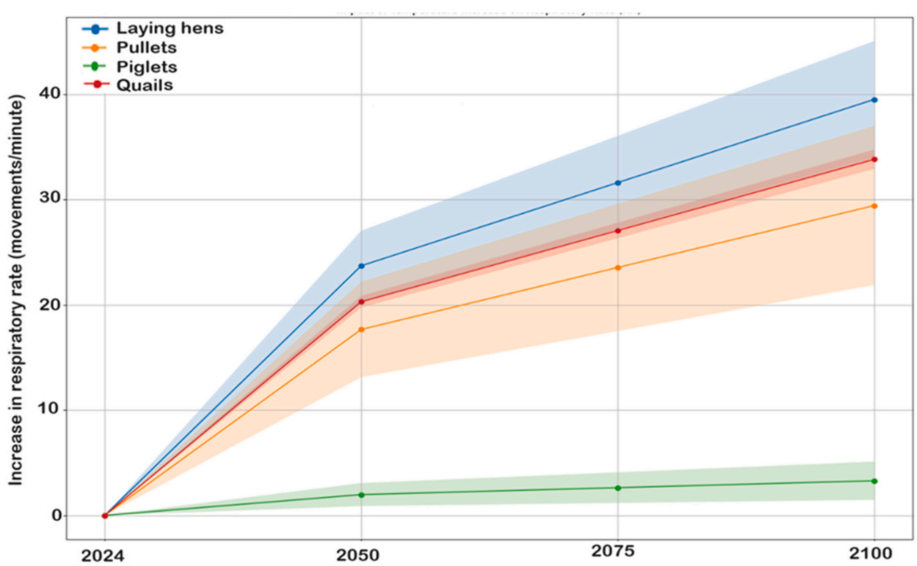

Fig. 7. Impact of increase in ambient temperature on respiratory rate in monogastric animals in the coming decades in a tropical region.

dynamic in a semi-arid equatorial environment. In a complementary study using the same animals, Façanha et al. (2020) showed the rhythm of heat dissipation mechanisms, particularly respiratory rate, rectal temperature and sweating, as adaptive mechanisms to high temperatures.

Despite the importance of these locally adapted genetic resources, data show that many of them are at risk of extinction. Of the 7616 animal breeds, 20 % are at risk of extinction, and nearly one breed is becoming extinct monthly. Among these animals, chickens, pigs and cattle are the animal species that have shown the highest percentages of extinction risk, which is more pronounced in developed countries (Northern Hemisphere) (FAO, 2007). Some authors attribute this loss of biodiversity to current livestock production practices, which prioritize mainly the productivity of animal production and economic returns, at the expense of traditional production systems (Rojas-Downing et al., 2017).

The introduction of animal genetic resources from temperate region countries (Northern Hemisphere) into tropical regions (Southern Hemisphere) demonstrates how sensitive these breeds are too high temperatures. This has been an alternative to increase the productivity of locally adapted breeds, since they generally show lower productive performance (Freitas Silveira et al., 2021). However, the successful use of these genetic resources in tropical regions is only possible in an intensive system, as it is the case in Brazilian poultry farming, where almost 70 % of the production system is in negative pressure sheds. This system can reduce thermal stress without compromising meat quality compared to the positive pressure system (Sakamoto et al., 2024).

Another example is the use of the Holstein breed in the composition of the breed Girolando, which even with an increase in productivity, shows a reduction in animal adaptation compared to locally adapted breeds (De Vasconcelos et al., 2019; de Vasconcelos et al., 2020b), which is justified by the inverse relationship between milk production and climate adaptation. On the other hand, rearing purebred Holstein animals in intensive systems in tropical regions results in a loss of milk production of up to 21 % due to heat stress (Garcia et al., 2015). Brito et al. (2021) reported significant achievements in the dairy cattle industry almost doubling milk production in the last five decades (Simões et al., 2021). However, this progress was followed by the loss of genetic diversity and the deterioration of essential biological mechanisms (health, resilience, robustness, well-being, and longevity) in dairy cattle breeds (Brito et al., 2021). In the small ruminant industry, specifically for beef production, the animals are more resistant and reared extensively mainly in tropical regions of the world (Southern Hemisphere) even with the use of exotic breeds to increase production (Silveira et al., 2024).

It is important to highlight that thermal stress is strongly modulated by production systems. Animals reared in extensive or pasture-based systems, especially in tropical and semi-arid regions, are more exposed to direct solar radiation, high ambient temperatures, and variable humidity (de Vasconcelos et al., 2020a). However, these animals often show greater genetic adaptation to such environments due to natural selection (Freitas Silveira et al., 2021). In contrast, animals in intensive systems rely heavily on environmental control technologies (e.g., ventilation, cooling, and insulation) to mitigate heat stress. While these systems can buffer the thermal load, they also concentrate metabolic heat due to high animal densities and productivity levels. Consequently, the relationship between thermal stress and production systems is complex and context-dependent. Therefore, the modeling performed here primarily reflects animals reared in semi-intensive and extensive systems, given the absence of data from fully confined systems, particularly in the Northern Hemisphere—a limitation acknowledged in this study.

4.3. Identification of phenotypic biomarkers

The identification of phenotypic biomarkers associated with the climatic adaptation of animals is important for inclusion in breeding programs, aiming at the selection of adapted animals, as shown in the results. The morphology of erythrocytes represented by the mean corpuscular volume is a hematological parameter that indicates the average size of red blood cells (RBCs), being sensitive to heat stress, and considered as one of the main hematological key parameters in the evaluation of cattle adaptation to heat stress (Habibu et al., 2018).

The importance of the thyroid hormones thyroxine (T_4) and triiodothyronine (T_3) lies in their calorigenic role, that is, they are regulate global metabolic processes that affect the metabolism of fats, carbohydrates and proteins, in order to control obligatory thermogenesis (Façanha et al., 2013). Therefore, when an animal is under heat stress, there is a change in the hypothalamic-pituitary-thyroid axis, reducing its thyroid activity and, consequently, the animal's metabolic rate. Therefore, these endocrine changes allow for the balance of organic functions related to thermoregulation. However, they can compromise animal production and growth (Sejian et al., 2018).

Other studies have already mentioned hair density an adaptive trait to be adopted in protocols for assessing the adaptability of farm animals (Façanha et al., 2013). For instance, ruminant animals have less dense coats in warmer seasons of the year, with shorter and more laid hair (Façanha et al., 2019, 2023). Now, studies are focused on the transcriptomic profile of the skin to reveal genes that are associated with thermoregulation (Pantoja et al., 2024).

The importance of renal metabolism and liver function variables as a secondary response to heat stress explains phenotypic biomarkers related to adaptation since when animals are under heat stress, they reduce feed intake, which leads to changes in metabolism to maintain homeothermy (Freitas Silveira et al., 2021). These two biological systems are interconnected and play crucial roles in the response of animals to heat stress, especially in extreme heat conditions, acting synergistically in the regulation of acid-base and electrolyte balance, control of gluconeogenesis, blood flow, and oxidative stress (Reece, 2015).

4.4. Adaptive profile of ruminant and monogastric animals

Few studies have evaluated the adaptive profile of farm animals, considering phenotypic data on a global scale. The differentiation of the adaptive mechanisms in ruminant animals reared in both hemispheres can be explained by the distinct strategies these animals used for heat dissipation, which are influenced by differences in their anatomical, physiological, behavioral and physiological traits. In addition, the climate of the Northern Hemisphere has a greater impact on these adaptive responses compared to the climate of the Southern Hemisphere, as shown by the results. An interesting study evaluating the profile of two populations of Brazilian and Italian goats corroborates the present findings. The findings of this study indicate that the Italian goat population uses adaptive mechanisms which are distinct from the Brazilian goat population, which is attributed to the anatomical, physiological, genetic and physiological characteristics, and mainly to the lower temperature values, although with greater temperature oscillation in the Northern Hemisphere. In the Southern Hemisphere, animals are subjected to prolonged heat throughout the year. The authors also reinforce that the adaptive profiles of the animals are different, in which the Italian Garfagnina population uses T_3, CST, COR, T_4, GGT, HD, GLO, HL and PCV and the Brazilian Azul population uses PRT, MCV, PCV, ALB, T_4, ST, HL, RBC, TRI, and GGT (Ribeiro et al., 2015) as an adaptive response to achieve homeostasis.

The differentiation of adaptive mechanisms between ruminants and monogastric animals is explained not by climatic factors, but by physiological, morphological and metabolic factors, as indicated in the canonical discriminant analysis. It is known that the body temperature of birds is higher than that of ruminant animals (41.5×39.5 °C) because birds have a higher metabolism, especially smaller birds such as quails, and these animals generate more internal heat, resulting in a higher body temperature. Birds also grow rapidly, which requires a high metabolic rate and, therefore, greater heat production. Another important factor is that birds are smaller and have a larger body surface area in relation to volume, which leads to greater heat loss. Therefore, in order to compensate for this loss and maintain homeostasis, they maintain a higher body temperature. Birds also have efficient temperature regulation mechanisms, such as the ability to control blood flow in order to dissipate or conserve heat. Furthermore, their digestive system is simpler and more efficient than that of ruminants, which involves microbial fermentation, a process that generates less heat (Proszkowiec-Weglarz, 2022).

4.5. Impact of climate change on animal production

Several studies indicate that heat stress will compromise food production, but the present study was the first to quantify how physiological changes will occur in animals according to climate change. However, animal production (eggs, milk, and meat) was not used based on climate data, which would make comparisons difficult. The use of respiratory rate, a gold standard measure for assessing heat stress - as it is one of the main mechanisms that trigger heat stress (Ferreira et al., 2023; Silva de Farias et al., 2020) - allowed us to successfully observe the animal response to climate scenarios. The increases observed in respiratory rate, especially in animals reared in the Northern Hemisphere, will certainly impact the diversion of energy intended for production to maintenance (basal metabolism) (Lima et al., 2022). This greater impact of heat stress on ruminant animals in the Northern Hemisphere in 2100 is justified by the greater impact of climate on the thermoregulatory responses of animals and by their adaptive characteristics already discussed in this study.

The increase in rectal temperature of animals reared in the Southern Hemisphere in 2100 can be viewed as an evolutionary mechanism of these animals in response to high temperatures. For many years, the increase in rectal temperature was thought to be a response to heat stress due to the higher heat load. Still, the results demonstrate that it may be an adaptive strategy that animals will use to increase the temperature in the body core due to high temperatures. Further studies are needed to confirm these findings. However, it was recently reported that sustainable animals are those that are efficient in converting feed into animal products, being clinically healthy and adapted to the environment, using the sweating rate as the main mechanism of heat dissipation (lower respiratory rate). Early animals with heavy carcasses and high carcass yield had higher rectal temperature than non-sustainable animals (high respiratory rate). In addition, the authors also pointed to rectal temperature as a phenotypic biomarker for selecting these animals (Silveira et al., 2023).

4.6. Impact of climate change on ruminant animals

Dairy farming was the most susceptible livestock activity to heat stress in climate change scenarios in the Southern Hemisphere, with an HR increase of up to 4 beats per minute in 2100, which is justified by the fact that it is a livestock activity with the highest production of metabolic heat for milk production. The impact of climate change will not be as pronounced in these animals, but it is necessary to consider the data from Girolando cows with an average production of 12 l of milk day^{-1}, which is considered low production. Cows with higher milk production will certainly have a greater impact, as demonstrated in a study by da Silva et al. (2010), who carried out climate change projections for 2100 and confirmed that both the optimistic and pessimistic scenarios will demonstrate that there will be negative impacts on dairy farming in semiarid regions. The authors reinforce that the greatest impact of heat stress will be on animals more specialized for the dairy sector, with production levels around 30 kg of milk $^{-1}$ day $^{-1}$.

Sheep farming was an activity predicted to be heavily impacted by heat stress in the Southern Hemisphere, with respiratory rates increasing by up to 12 beats per minute by the end of the century, which will certainly impact meat production. Such results are corroborated by a study that used temperature limits established for sheep, and modeled temperature increases of 1 °C and 3 °C relative to the historical baseline, estimating that 2.1 million potential lambs are lost annually due to heat stress alone, which will increase to 2.5 and 3.3 million, respectively, as temperatures rise in Australia - Southern Hemisphere (Van Wettere et al., 2024).

Goats and beef cattle were the only species that showed phenotypic plasticity, as they did not change their respiratory rate when temperatures rose in the climate scenarios, and therefore will not have a significant impact on animal production. These results align with previous studies that report goats as an animal model to be studied for climate change research due to their advantages over other production systems (Silveira et al., 2024). This is explained by the fact that goats have a unique ability to employ phenotypic plasticity, besides facing multiple stresses such as low-quality feed (nutritional stress). In addition to being superior to cattle and sheep in digesting dry matter and recycling nitrogen, they have a superior ability to dissect feces and concentrate urine, presenting smaller body size, greater feed conversion efficiency, and resistance to diseases (Nair et al., 2021). All these attributes lead some authors to call goats the "Animal of the Future" (Ramachandran and Sejian, 2022). Recently, Rahimi et al. (2022) suggested replacing dairy cows with goats as an alternative to ensure milk production and support the resilience of dairy production in drylands of northern sub-Saharan Africa.

The plasticity of beef cattle occurs because they are animals adapted to tropical climatic conditions. Furthermore, they use sweating rate as the main route of heat dissipation and not respiratory rate (Freitas Silveira et al., 2021), so there was no activation of respiratory thermolysis. However, it is known that the use of a single database of a single breed is incipient to reach general conclusions, even though several studies confirm this adaptive mechanism of zebu bulls reared in tropical conditions (Camerro et al., 2016; de Melo Costa et al., 2018).

4.7. Impact of climate change on monogastric animals

Studies have shown that birds production will be the most impacted by climate change by the end of the century (Rahimi et al., 2021), which corroborates with the present results. However, the magnitude of the 40-beats-per-minute increase in respiratory rate is justified because birds do not have sweat glands like mammals, which are the main route of heat dissipation at high temperatures (Silva de Farias et al., 2020). This increase is concerning and will certainly compromise egg production and may even lead to the death of these animals if mitigation measures such as environmental management and intensification of the production system are not adopted to reduce heat stress. The greater impact of the thermal environment on laying hens compared to pullets is justified by the metabolic activity due to the greater feed intake of these animals for egg production.

Pig farming, alongside with poultry farming, are the most susceptible livestock chains to heat stress due to climate change. However, the low increase in the respiratory rate of piglets is justified because, at this stage of the production system, these animals are still more tolerant to heat stress.

4.8. Sustainable strategies for animal production over the different climate scenarios

The results reinforce the significant impact of climate change on animal production, a topic that should be investigated in the coming decades to develop sustainable strategies in order to mitigate the effects of the thermal environment on animal production. It should be noted that there is no single general strategy for all livestock production systems, but these should be based on two terms: animal welfare and sustainability. These keywords are important in livestock policy due to the growing public concern on the treatment of farm animals and the environment, especially in an era of climate change.

The livestock industry is not yet ready to face and adapt to these new challenges, especially in underdeveloped and developing countries – located mainly in the Southern Hemisphere, since not even the breeding conditions in European stables are adequate to the welfare requirements of the species (Martinez and von Nolting, 2023). Given the predictions of an increasing global population by the end of the century, the progressive increase in awareness of animal welfare, and the impact of climate change on the thermoregulatory responses of animals reported here, the adoption of sustainability strategies to improve these issues by the end of the century is necessary, but they should be distinct between hemispheres as follows:

1) Northern Hemisphere: Livestock systems in this hemisphere, mainly the European continent and North America, developed from the second half of the last century, and currently protein production exceeds human demand, providing food security and protection at a relatively low economic cost to the population (Simões et al., 2021). However, this expansion was only possible through genetic selection focused on production rates, mainly with dairy cattle, pigs, and poultry, and investment in intensification through technologies and installation typologies in order to control the thermal environment. Therefore, animals are able to express their maximum genetic potential, which ensures food security in this hemisphere. However, other problems have emerged, such as fertility problems, locomotion problems, heat stress, and reduced animal welfare rates (Brito et al., 2021). Thus, it is inferred that these issues should be corrected in the future with the inclusion of adaptability biomarkers to incorporate or give greater emphasis to traits related to animal welfare, health, resilience, longevity, and environmental efficiency, always seeking balance with production. New phenotyping technologies, traits which are closer to biology, and genetic and genomic evaluation methods will continue to be developed and should be targeted at specific production systems (Brito et al., 2021), mainly using large-scale phenotyping in an era of livestock 4.0 on highly technologically prepared farms as is characterized by the livestock industry in the Northern Hemisphere, especially in North America and Europe.
2) *Southern Hemisphere:* This hemisphere is home to underdeveloped and developing countries, mainly in Africa and Latin America. Livestock production systems in this hemisphere are generally characterized by low/medium production and are not highly technical, and do not use family labor (Silveira et al., 2023). Therefore, in

order to meet the demand for animal products in the face of population growth, it will be necessary to intensify animal production, especially in monogastric animals (poultry and pigs) – the main source of protein consumed due to price – since the genetics used are all imported from the Northern Hemisphere, as is the case of Brazil, and these animals are not adapted to tropical conditions, as reported in the present study.

Rearing laying hens in sheds with no air conditioning will not be possible since the predicted increase of 40 beats per minute in respiratory rate will certainly lead to the death of these animals. The elaboration of research lines in research centers in the Southern Hemisphere should be encouraged to develop productive and adapted poultry and swine lines through crossbreeding with local genetic resources and imported genetic material. In addition, for laying hens, production systems such as free-range and cage-free are already being implemented to promote animal welfare. This shift has been largely driven by social pressure, which has significantly influenced egg consumption patterns, moving away from caged toward cage-free alternatives (Gautron et al., 2021). This trend represents a global movement in laying hen management.

For dairy cattle farming, crossbreeding, genetic selection to increase the production of local breeds, and intensification of the production system are the main sustainable alternatives for facing climate change. The adoption of productive and adapted breeds in the production system, such as the medium-production Girolando breed reared in a pasture system, has shown to be a viable option for sustainable production in times of climate change, as has the Sindi breed. Although crossbreeding and genetic improvement are, without a doubt, solutions frequently highlighted for boosting livestock productivity and adaptation in the face of climate change, it is crucial to understand that these approaches demand a delicate balance with biodiversity conservation and ethical considerations. The unchecked replacement of local breeds with high-producing exotic varieties can lead to serious consequences, such as genetic erosion, which is the irreversible loss of valuable traits uniquely adapted to specific environments, and a significant reduction in overall ecosystem resilience (Silva et al., 2025). That is the main reason why breeding programs must prioritize the preservation of local genetic resources. Furthermore, they should encourage sustainable crossbreeding strategies—meaning those that aim to increase productivity without compromising the rich and essential tapestry of biodiversity (Silveira et al., 2024). Achieving this balance is not merely an ethical obligation; it is, in fact, a fundamental strategy for ensuring the long-term resilience of livestock systems as they confront the challenges posed by climate change (Hoffmann, 2010).

For small ruminants and beef cattle, the extensive system based on tropical pastures appears and will continue to be the main production system in tropical regions given the phenotypic plasticity of these animals. The adoption of silvopastoral systems is an alternative which can be used by producers of dairy and beef cattle, sheep and goats to provide shade for the animals (improving thermal comfort) and increase the farm's net revenue from the sale of wood. Lemes (2021) state that this system improved animal welfare and productive performance in beef cattle production systems in Brazil and Cai et al. (2025) reported that crop and livestock recovery system can potentially reduce greenhouse gas emissions in agriculture by more than 40 % in China.

5. Methodological difficulties, restrictions, and limitations

Assessing the impact of the thermal environment on the adaptive responses of animals is complex when working with different databases collected in different regions of the world, as these responses vary according to the thermal environment. Therefore, to carry out this assessment, a systematic methodology was developed with multivariate models which standardized the thermal environment as a dependent variable and whose main result was the rejection of the initial hypothesis of this study, that the thermal environment of the Southern Hemisphere would have a greater impact on the adaptive responses of animals. Subsequently, using another systematic approach once again, but this time a combination of regression models with a machine learning algorithm, it was possible to simulate future climate scenarios based on conservative climate models to project the conditions of the impact of climate change on the livestock industry of sheep, goats, dairy and beef cattle, poultry and swine reared in the two hemispheres of the planet Earth. However, this study presents some limitations. It is known that the number of databases is low in order to represent both hemispheres, but this is justified by the difficulty of combining several databases collected with the same methodology in different regions of the world, in addition to the cost of laboratory analyses and data collection. A second limitation is that this study does not have a database of ruminant and monogastric animals in fully confined systems, which does not fully represent livestock production systems in the Northern and Southern (non-ruminant) hemispheres. It is worth noting the absence of data from large producing regions of global importance, such as Australia, China and India, in addition to the lack of data in fully confined production systems, such as the ones adopted in the USA. This gap may have consequences on the representativeness of the results.

Another aspect worth highlighting is the consideration of only a single climate scenario, such as RCP4.5. Although it is a useful approach for forecasts, considering multiple scenarios (such as RCP2.6 or RCP8.5) would have provided a broader analysis platform on the set of relevant impacts. Additionally, while temperature and humidity are the two main psychometric properties of air that impact heat stress, focusing solely on them can be limiting. It would be interesting to also include other manifestations (changes in precipitation patterns, long-lasting droughts, extreme weather events, and heat waves) on the systems. These aspects usually present interactions and can have similar or even more relevant effects on production systems.

Another important consideration is the common assumption that the relationships between variables and their observed impacts are linear, which can be questioned since biological systems usually have non-linear or adaptive responses to changes. Ignoring this complexity can lead to underestimation or overestimation of the impacts. Another important factor is the genetic adaptation of the breeds and species considered. It was used the current breed base, but these animals will certainly undergo a process of adaptability as global temperatures increase. However, this limitation is found in all studies of this nature since it is not possible to model the genetic base of animals through adaptability.

It was also not considered the incorporation of mitigation technologies and strategies, i.e., the modeling did not include the adoption rate or effectiveness of measures such as shading, cooling, strategic nutrition, and adapted management that can be adopted by farmers to reduce heat stress in the coming years. Finally, it is important to highlight that a major limitation in studies that use climate scenario models to predict heat stress in production animals is the lack of a robust validation of the results with empirical data. Although the models are based on real climate and physiological data, they often simplify the complexity of the animals' biological responses, which include physiological, behavioral, and productive adaptations to heat as already mentioned. In addition, validation requires long-term data from different production systems to verify whether the projections adequately reflect real conditions.

As with other empirical models, real-world livestock systems are significantly more complex than any single model can fully represent. There is substantial heterogeneity in the various pathways through which climate change affects the adaptive responses of animals, making it virtually impossible for a single model to address all questions, capture every interaction, or account for all uncertainties involved (Emediegwu and Ubabukoh, 2023). Nevertheless, this study stands out for its pioneering and innovative character, providing valuable insights into the magnitude of environmental impacts on the physiological responses of livestock, identifying phenotypic biomarkers related to adaptation, and simulating future climate scenarios—thus offering a comprehensive and unprecedented perspective on livestock adaptability on a global scale.

6. Conclusion

The present assessment suggests that animals reared in the Northern Hemisphere are more productive, but they are and will continue to be the most impacted by climate change. Therefore, adopting animal adaptability protocols is becoming a gradually more relevant topic in livestock production systems, with ongoing efforts to develop breeds and lines of domestic animals with greater resistance to heat and diseases, especially using resources locally adapted to the conditions of the Southern Hemisphere. The search for a balance between animal production and adaptability is a premise for these livestock systems to face climate change scenarios. A review of selection criteria in genetic improvement programs is suggested, with the inclusion of phenotypic biomarkers such as hematological characteristics, coat morphology, renal and hepatic metabolism, and thyroid hormones to improve the adaptability of these animals. In the Southern Hemisphere, ruminant animals, particularly those reared in hotter regions, will be slightly impacted by climate change, but they will need to use trait-based selection strategies and crossbreeding to increase animal production, in order to ensure food security by the end of the century for the increasing population. For monogastric animals, intensification of the production system is crucial and urgent, as the animals will not be able to withstand high temperatures. Finally, the conservation of locally adapted genetic resources and the protection of their natural habitats are also essential to maintaining the biodiversity and resilience of the world's ecosystems, ensuring food security today and in the future.

By the end of the century, the development of a more sustainable livestock sector capable of withstanding the challenges posed by climate change will require continuous innovation across various areas of animal production, particularly in genetics. This progress will depend on the synergistic involvement of farmers, researchers, policymakers, and consumers, all working toward the common goal of ensuring global food security. Government programs to support and incentive livestock produc.

tion—especially targeting small-scale farmers and research centers in the Southern Hemisphere—will be essential, given the limited purchasing power of famers and the low levels of investment in research in these regions. The integration of these strategies into national livestock development plans, rural extension programs, and climate adaptation agendas will be crucial to enable the transition toward more resilient and sustainable livestock systems in both hemispheres. Furthermore, future research should deepen the understanding of the relationship between thermoregulatory responses and productive performance in order to strengthen strategies aimed at ensuring food security now and in the future.

Funding

São Paulo Research Foundation (FAPESP, grant ID: 2022/14250-8 and 2023/16733-9) that provided a researcher fellowship to 1 st author.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors utilized ChatGPT to improve readability in specific sections of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the publication's content.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no conflicts of interest.

Acknowledgements

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108061.

Data availability

Data will be made available on request.

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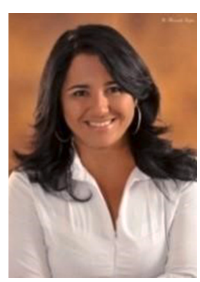

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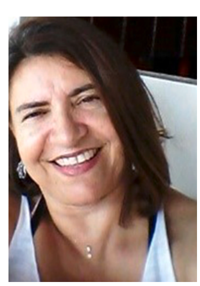

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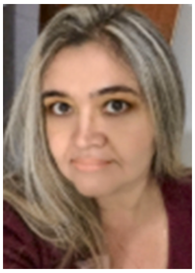

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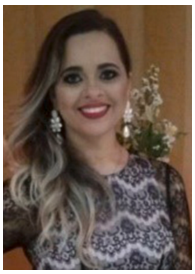

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