



Cut-off value of body surface temperature and assessing heat stress in dairy cows

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ABSTRACT

Heat stress has a significant impact on the health and productivity of dairy cows, making early and accurate detection essential for effective welfare management. The aim of this study was to determine cut-off values of body surface temperature across different anatomical regions, measured by infrared thermography (IRT), to distinguish cows under heat stress from those in thermoneutral conditions. The research was conducted on a Holstein-Friesian farm in the Vojvodina region, with 200 total measurements collected during spring and summer. The identified cut-off values were as follows: 36.06 °C for the eye, 32.2 °C for the ear, 33.6 °C for the nose, 37.3 °C for the forehead, 35.8 °C for the whole head, 35.1 °C for the abdomen, 36.6 °C for the udder, 32.3 °C for the front limb, 33.5 °C for the hind limb, and 35.95 °C for the whole body. All values demonstrated satisfactory to high discriminative power (AUC = 0.71–0.95) for identifying cows under heat stress. These thresholds enable early identification of thermal load and timely interventions. Although body surface temperature is a sensitive and non-invasive indicator, its application requires contextual interpretation and integration with other physiological parameters. The results support the development of automated systems for continuous monitoring and prevention of heat stress, contributing to more sustainable dairy farming practices under changing climatic conditions.

Keywords: cow, infrared thermography, body surface temperature, heat stress

ИЗВОД

Топлотни стрес негативно утиче на здравље и продуктивност млечних крава, те је рано и прецизно препознавање ових стања кључно за ефикасно управљање добробити. Циљ ове студије је био да се утврде граничне (cut-off) вредности површинске температуре тела за различите анатомске регије, мерене инфрацрвеном термографијом (IRT), које омогућавају диференцијацију крава у топлотном стресу од оних које нису под стресом. Истраживање је спроведено на фарми холштајн-фризијских крава у Војводини током пролећно-летњег периода, а укупно је анализирано 200 мерења у десет регија тела. Добијене cut-off вредности су: 36.06 °C за око, 32.2 °C за уво, 33.6 °C за нос, 37.3 °C за чело, 35.8 °C за целу главу, 35.1 °C за абдомен, 36.6 °C за виме, 32.3 °C за предње екстремитете, 33.5 °C за задње екстремитете и 35.95 °C за цело тело. Све вредности су показале задовољавајућу до високу дискриминативну моћ (AUC = 0.71–0.95) за идентификацију крава у топлотном стресу. Идентификација ових прагова омогућава рану детекцију термалног оптерећења и правовремене интервенције. Иако површинска температура представља осетљив и неинвазиван индикатор, њена примена захтева интеграцију са другим физиолошким параметрима и контекстуализацију према условима средине. Ови резултати пружају основу за развој аутоматизованих система за мониторинг и превенцију топлотног стреса у условима климатских промена.

Кључне речи: краве, инфрацрвена термографија, температура површине тела, топлотни стрес

1. Introduction

Heat stress represents a significant challenge in modern livestock production, particularly in dairy cattle, where adverse climatic conditions directly affect animal health, welfare, and production performance (Cincović et al., 2023; Giannone et al., 2023; Azevedo et al., 2024). With the ongoing rise in global temperatures and the increasing frequency of heatwaves, accurate identification and monitoring of heat stress have become essential for improving farm management systems (St-Pierre et al., 2003). Climate change-induced extremes on farms, the growing consumer

demand for healthy animal-derived products, and the search for novel animal-based indicators of stress capable of being monitored through information technologies are key reasons why heat stress in cattle has emerged as a critical issue requiring innovative detection approaches and technological solutions (Lukić, 2023; Sichoongwe, 2023; Milovanović, 2023; Nikšić et al., 2023; Čolović & Mitić, 2024). Resilience to high ambient temperatures and the measurement of its indicators represent an imperative in the process of predicting and preventing heat stress (Majkić et al., 2023).

The Temperature-Humidity Index (THI) is a widely accepted indicator that integrates ambient temperature

and relative humidity, providing an objective measure of environmental conditions in relation to heat stress in livestock (Bohmanova et al., 2007). According to most studies, THI values exceeding 72–74 indicate the onset of heat stress in dairy cows, while THI values above 78 are considered a critical threshold associated with severe effects on productivity and health (Kadzere et al., 2002; Yan et al., 2021). It has been established that there is a long-term increasing trend of the THI index in our region during almost all months of the year, with the most significant rise observed during the summer months (Cincović et al., 2017; Majkić et al., 2020).

Rectal temperature has traditionally been used to assess thermoregulation and the level of heat stress, serving as an indicator of core body temperature (Tiezzi et al., 2017). However, rectal measurement is invasive, impractical for frequent monitoring, and slower to reflect acute changes in the animal's thermal status (Mota-Rojas et al., 2021). In recent years, infrared thermography has emerged as an attractive non-invasive method for measuring surface body temperature, offering rapid and accurate assessment of the thermal state across different body regions and enabling early detection of heat stress (Salles et al., 2016; Stewart et al., 2017). Studies have demonstrated a significant positive correlation between THI and body surface temperature in cows, particularly in head regions such as the forehead and eye, which are considered reliable indicators of thermoregulatory changes (Peng et al., 2019; Kim et al., 2020). For instance, Peng et al. (2019) reported that forehead surface temperature increases with rising THI, identifying a threshold of approximately 37 °C as the onset of heat stress. Similarly, Salles et al. (2016) found that eye temperatures exceeding 37.5 °C were associated with elevated THI values >74, indicating a pronounced physiological response to heat stress. In addition to the head, other significant indicators include the udder, flank, and horns, where elevated surface temperatures have also been correlated with higher THI values and thermoregulatory strain (Ghezzi et al., 2024; Martello et al., 2016). These regions differ in thermal sensitivity, which is essential for accurate interpretation of data and for determining precise cut-off values for heat stress detection (Kim et al., 2020; Wang et al., 2023).

Defining and verifying threshold values of body surface temperature has practical implications for monitoring dairy cow welfare, as it enables the timely identification of animals experiencing thermal stress before adverse effects on health or productivity become apparent given that numerous physiological changes occur prior to the manifestation of clinical symptoms (Bang et al., 2022; Blond et al., 2024). The use of infrared thermography allows for continuous monitoring and effective intervention under high THI conditions, thereby contributing to the sustainability of livestock production systems. Although the relationship between THI and surface temperature is well documented, variations in heat stress detection thresholds persist due to multiple influencing factors (Herbut et al., 2018; Mota-Rojas et al., 2021).

The aim of this study is to examine the relationship between the THI index and the surface temperature of various body regions, and to establish temperature cut-off values indicative of heat stress in dairy cows.

2. Materials and methods

This experiment was carried out on a Holstein-Friesian cattle farm in the Vojvodina region of Serbia. Data was collected during two distinct periods: April and May, representing a thermoneutral period, and June and July, representing a heat stress period. The cows were housed in a standard free-stall system with unlimited access to water. They were fed twice daily with a total mixed ration (TMR) formulated according to established standards (NRC, 2001).

To assess heat stress, the ambient temperature-humidity index (THI) was monitored. Temperature and air humidity were measured thrice daily in three distinct periods: early morning (05:00–07:00, THI night) and mid-afternoon (13:00–15:00, THI day). The THI was calculated using a standard formula based on data provided by the Republic Hydrometeorological Service of Serbia.

We conducted 200 measurements of body surface temperature (100 from the thermoneutral period and 100 from the heat stress period). Thermal images were captured of various body parts, including the eye (EYT), ear (EAT), nose (NT), forehead (FHT), whole head (WHT), abdomen (AT), front limb (FLT), hind limb (HLT), udder (UT), and the whole body (WBT). An infrared camera (Testo 865, Germany) was used to obtain these thermograms. Each cow's thermal images were recorded with an emissivity coefficient of 0.95 from a distance of approximately 1 meter. The measurements were taken at regular time intervals during the four mentioned months.

In this study, a model incorporating continuous values of measured body temperatures and dichotomous values representing the presence of heat stress (thermoneutral period = 0; heat stress = 1) was analyzed. To determine the threshold temperatures of different body regions indicative of heat stress, a Receiver Operating Characteristic (ROC) analysis was conducted in two stages. The ability of surface temperatures from different body regions to distinguish between cows under heat stress and those in a thermoneutral period was determined using the area under the ROC curve (AUC) analysis. We then determined the cut-off threshold of body temperature, above (or below) which cases are classified as belonging to the positive class (cows under heat stress). All values below this threshold are assigned to the negative class (thermoneutral period). The inverse ROC curve method was used to illustrate the relationship among different temperature thresholds across body regions. The correlation between THI and body temperature was determined using Pearson's correlation coefficient. THI index values were specifically recorded at the moment when the cut-off value of body surface temperature was reached, above which the probability of cows being exposed to heat stress increases. Statistical analyses were performed using the SPSS software package (USA).

3. Results and Discussion

THI values were from 58 to 69 in the thermoneutral period and from 70 to 82 during the heat stress period. Body surface temperatures were measured across different anatomical regions of dairy cows during thermoneutral and heat stress periods, taking into account both the intensity of heat stress

(mild, moderate to severe) and the stage of lactation. During exposure to increasing heat stress, surface temperatures across all body regions rose noticeably. Eye temperature increased from 32.7 °C in the thermoneutral period to 37.5 °C during mild heat stress and reached 38.6 °C under moderate heat stress. Ear temperature showed a sharp rise from 22.5 °C to 35.5 °C and further to 36.6 °C, indicating high sensitivity. Nose temperature increased gradually from 32.9 °C to 35.2 °C and then 37.4 °C. Forehead temperature climbed from 29.6 °C to 36.1 °C and reached 38.3 °C under moderate stress. Whole head temperature followed a similar trend, rising from 33.2 °C to 36.6 °C and then 38.6 °C. Abdomen temperature exhibited one of the steepest increases, from 33.5 °C to 36.9 °C and further to 37.9 °C. Udder temperature rose from 30.5 °C to 36.9 °C and peaked at

39.5 °C. Front limb temperature increased from 29.9 °C to 34.8 °C and reached 37.9 °C, while hind limb temperature followed a similar pattern, rising from 28.7 °C to 34.5 °C and then to 38.4 °C. Finally, whole-body surface temperature reflected the overall thermal load, increasing from 28.8 °C in thermoneutral conditions to 35.7 °C with mild heat stress, and peaking at 37.7 °C under moderate heat stress.

A positive and statistically significant correlation was found between the THI index and the surface temperature of various body regions, with the following correlation coefficients: 0.82 for the eye, 0.92 for the ear, 0.75 for the nose, 0.81 for the forehead, 0.86 for the whole head, 0.88 for the abdomen, 0.93 for the udder, 0.64 for the front limb, 0.62 for the hind limb, and 0.79 for the whole body. The results are presented in Table 1.

Table 1.
Relation between THI and body surface temperature

Body surface	Correlation with THI over time	THI values at which the surface temperature cut-off points were identified
Eye	0.82 ($p < 0.001$)	73
Ear	0.92 ($p < 0.0001$)	69
Nose	0.75 ($p < 0.001$)	76
Forehead	0.81 ($p < 0.001$)	72
Whole head	0.86 ($p < 0.0001$)	70
Abdomen	0.88 ($p < 0.0001$)	71
Udder	0.93 ($p < 0.0001$)	68
Front limb	0.64 ($p < 0.001$)	76
Hind limb	0.62 ($p < 0.001$)	76
Whole body	0.79 ($p < 0.001$)	74

The model based on body surface temperature successfully distinguished cows under heat stress from those in the thermoneutral zone, with the discriminative power varying by body region. The area under the ROC curve (AUC) for surface temperature of different body regions was as follows: 0.85 for the eye, 0.93 for the ear, 0.74 for the nose, 0.81 for the forehead, 0.95 for the whole head, 0.80 for the abdomen, 0.90 for the udder, 0.72 for the front limb, 0.71 for the hind limb, and 0.92 for the whole body. All AUC values were statistically significant at a minimum level of $p < 0.05$, indicating that the surface temperature of various body regions can serve as a meaningful indicator of heat stress in dairy cows.

From a practical standpoint, AUC values between 0.7 and 0.8 indicate moderate discrimination, values between 0.81 and 0.9 indicate good discrimination, and values between 0.91 and 0.99 indicate excellent discrimination between cows under heat stress and those in thermoneutral conditions. The data are presented in Figure 1.

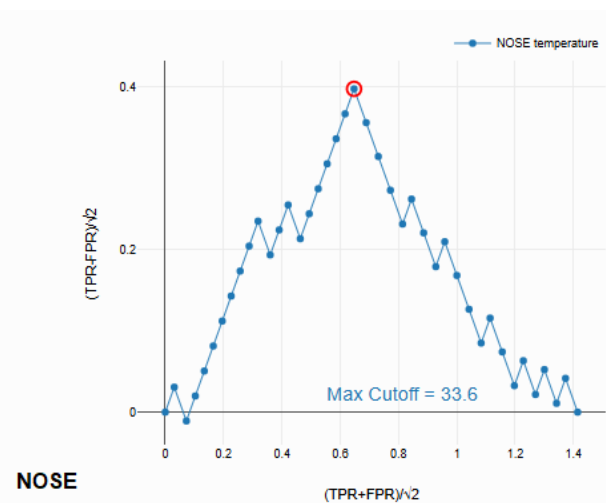
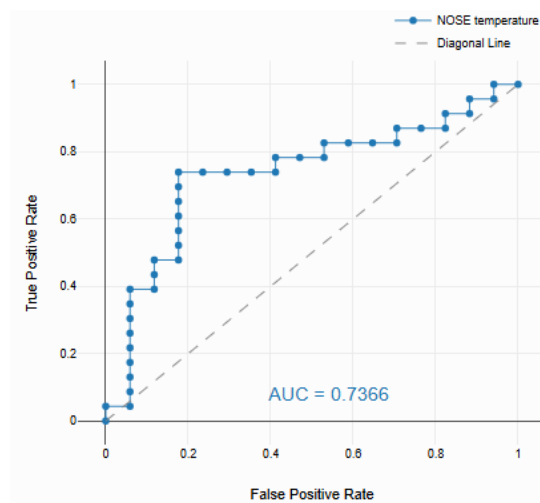
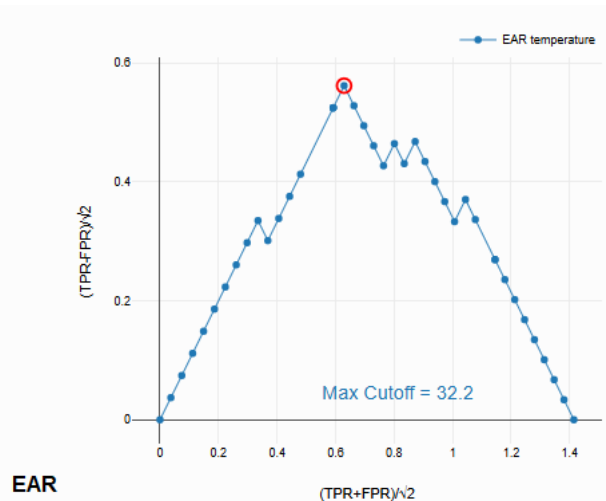
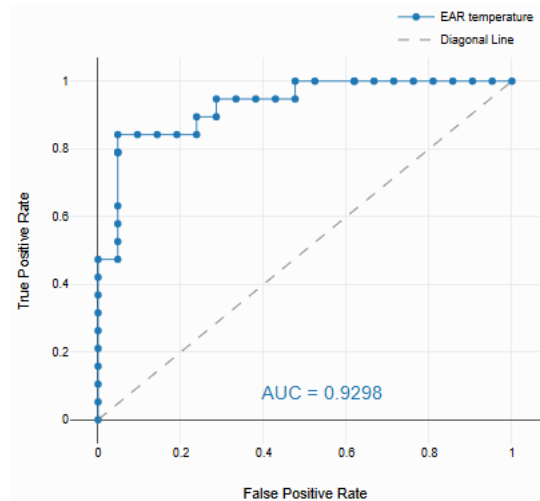
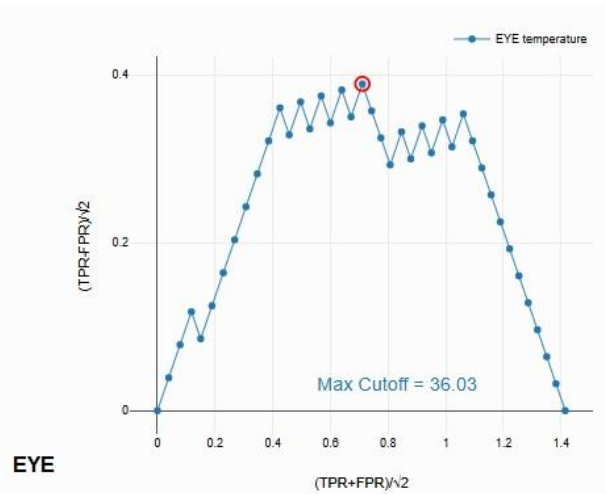
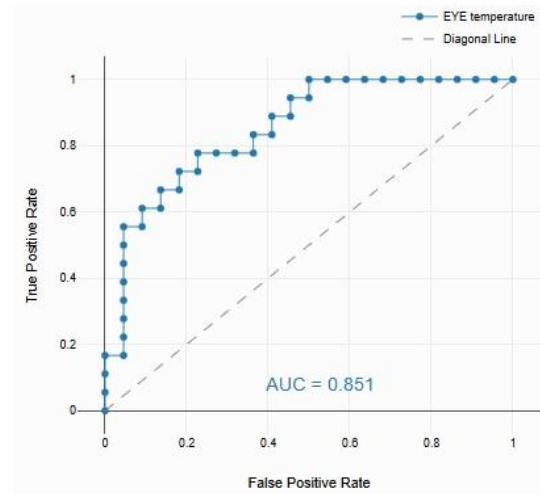
The cut-off values for body surface temperature above which cows may be classified as experiencing heat stress were 36.06 °C for the eye, 32.2 °C for the ear, 33.6 °C for the nose, 37.3 °C for the forehead, 35.8 °C for the whole head, 35.1 °C for the abdomen, 36.6 °C for the udder, 32.3 °C for the front limb, 33.5 °C for the hind limb, and 35.95 °C for the whole body. These data are shown in Figure 1.

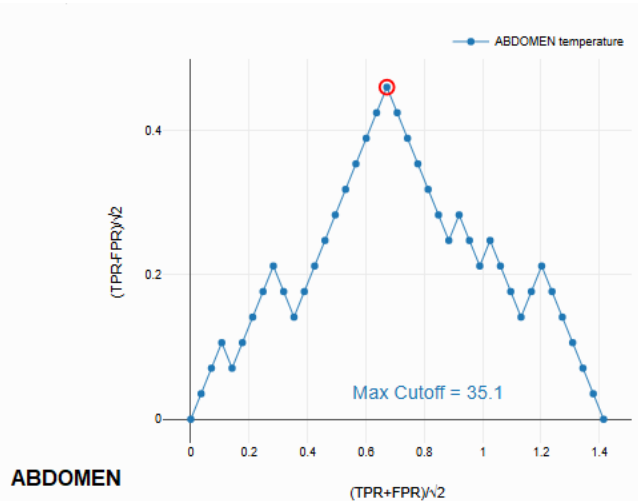
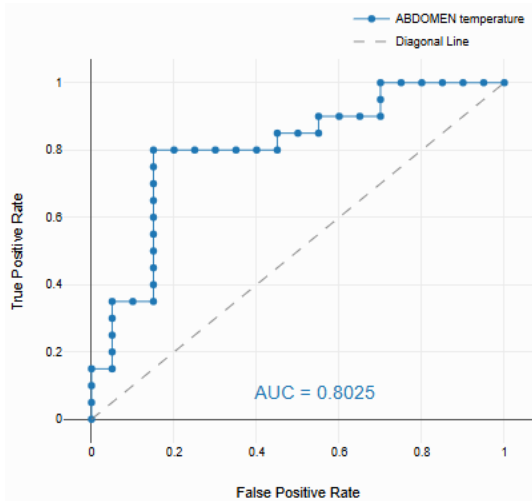
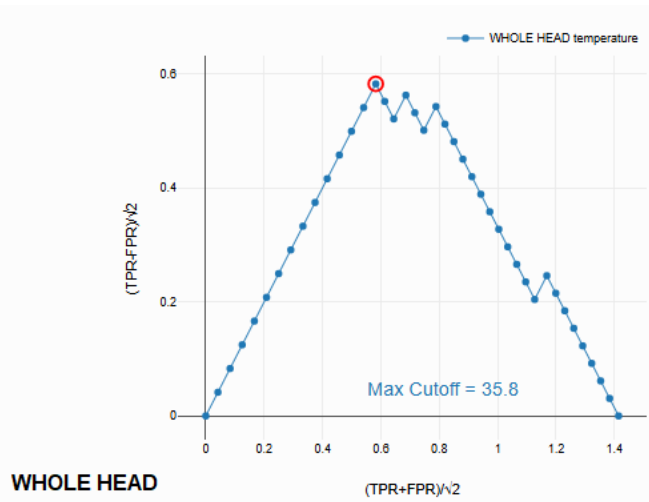
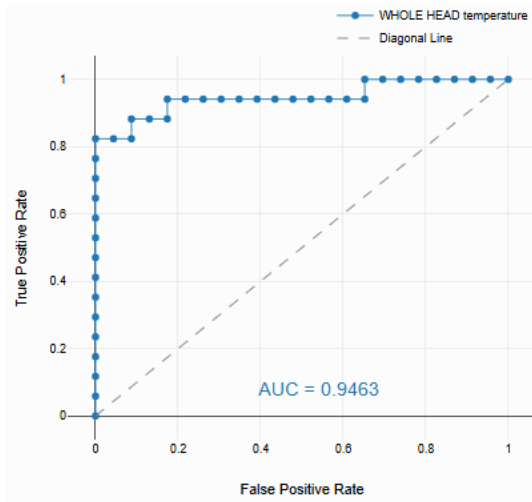
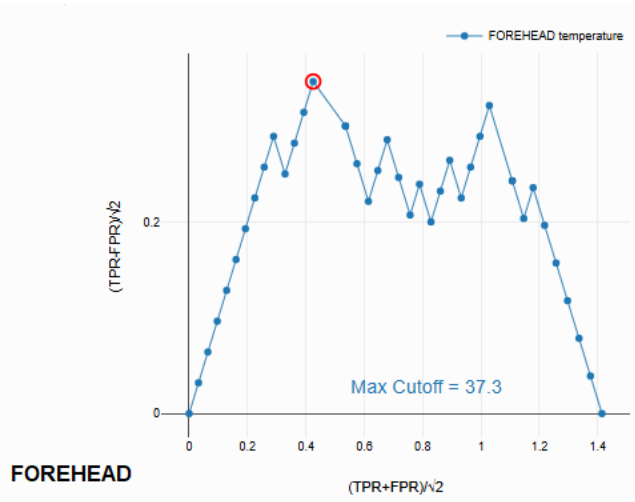
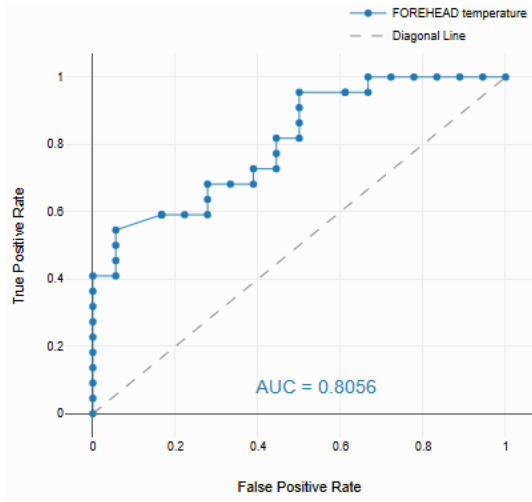
The corresponding THI values at which the surface temperature cut-off points were identified were 73 for the eye, 69 for the ear, 76 for the nose, 72 for the forehead, 70 for the whole head, 71 for the abdomen, 68 for the udder, 76 for the front limb, 76 for the hind limb, and 74 for the whole body.

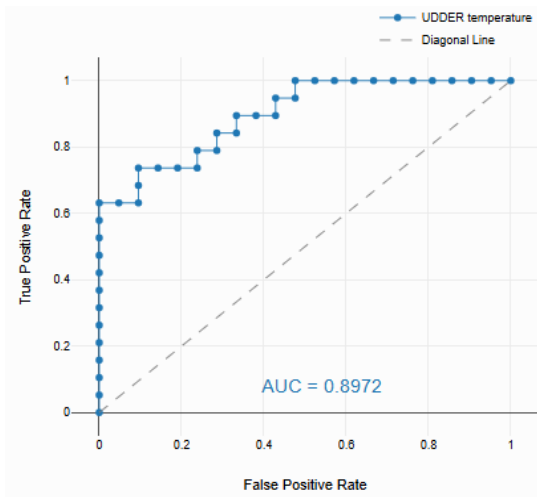
Temperature measured using infrared thermography represents a sensitive indicator in the assessment of heat stress load. Such measurements reflect diurnal fluctuations (Majkić et al., 2023a) as well as variations depending on the housing systems of the animals (Čukić et al., 2023). Furthermore, heat stress induces significant metabolic alterations (Majkić et al., 2017), and these metabolic changes have been shown to correlate with body surface temperature (Blond et al., 2024). The relationship between the Temperature-Humidity Index (THI) and body surface temperature in dairy cows, as measured by infrared thermography (IRT), has been confirmed by numerous studies demonstrating a strong and consistent positive correlation between these parameters. Previous studies have confirmed a correlation between body surface temperature and the values of the Temperature-Humidity Index (THI), regardless of the specific formula used to calculate the index (Spasojević et al., 2023). Correlation coefficients between THI and BST across various body regions frequently range from 0.6 to 0.9, clearly indicating that increases in THI are directly accompanied by rises in surface temperature.

For example, Peng et al. (2019) reported a correlation of 0.808 between THI and forehead temperature, while Salles et al. (2016) documented similarly high correlations for the forehead and flanks. These findings

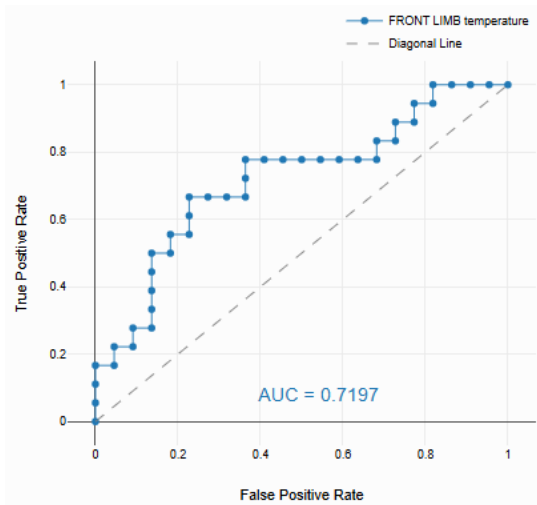
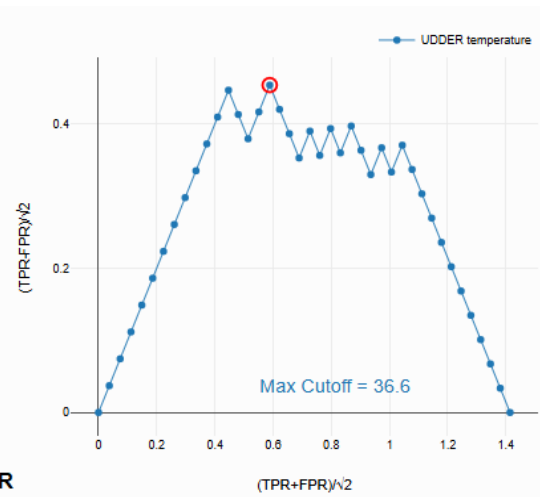
confirm that IRT is a reliable and non-invasive tool for the early detection of heat stress in dairy cows, allowing real-time monitoring of thermoregulatory changes.



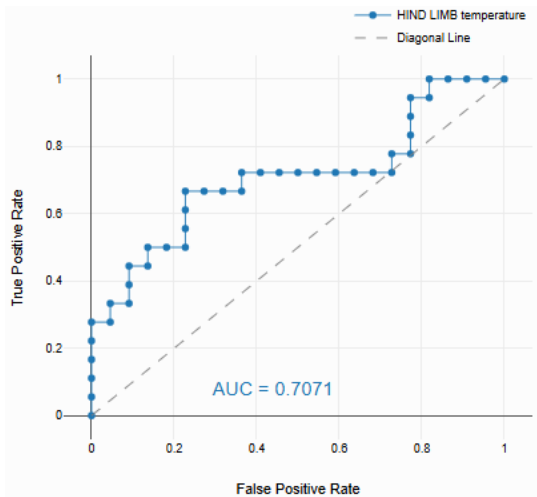
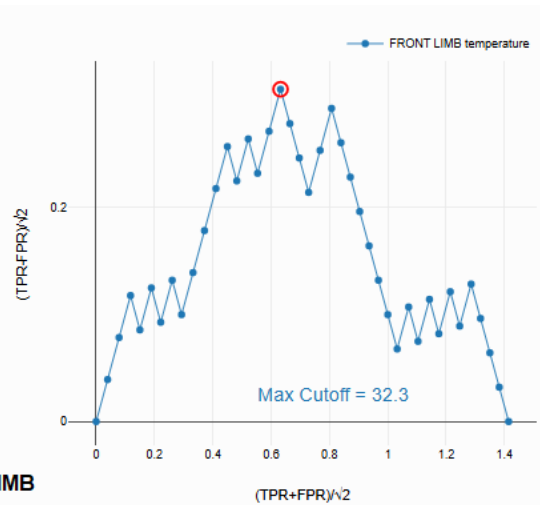




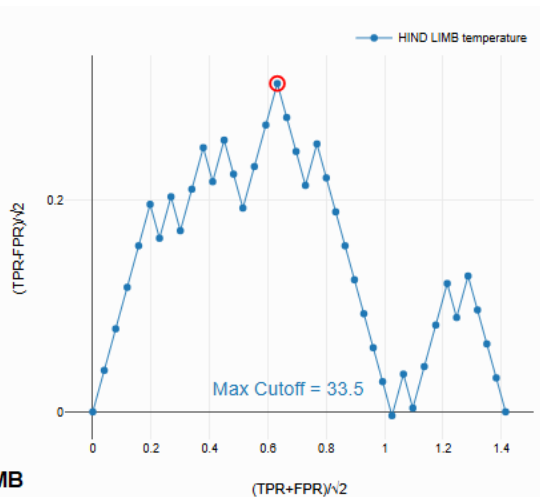
UDDER



FRONT LIMB



HIND LIMB



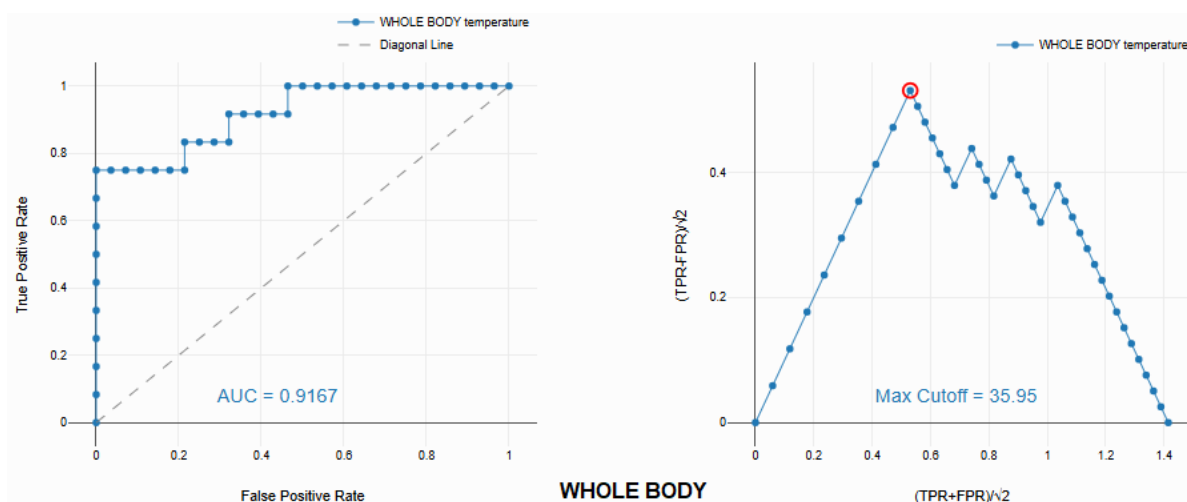


Figure 1. Area under ROC curve and cut-off value of surface body temperature measured by infrared thermography for assessment of heat stress in dairy cows

Cut-off values for body surface temperature used to identify the onset and intensity of heat stress vary depending on the anatomical region, although certain thresholds are consistently reported across studies. For instance, eye temperatures exceeding 37.5 °C are considered reliable indicators of heat stress (Salles et al., 2016; Kim et al., 2020), whereas thresholds for the frontal forehead region are slightly lower, typically ranging from 36.5 to 37.0 °C (Peng et al., 2019; Wang et al., 2023). The udder, a key region related to milk production, shows threshold values between 34.5 and 35.5 °C, with elevated temperatures indicating a negative impact of heat on productive performance (Martello et al., 2016; Ghezzi et al., 2024). Thresholds for other body parts, such as the flanks, sides, horns, and nose, generally fall between 35.0 and 36.0 °C, offering additional insights into the animal's overall thermal load. Although these thresholds provide important guidance, their application should be contextualized, as factors such as breed, age, and environmental conditions significantly influence both baseline and maximum surface body temperatures (Martello et al., 2016; Herbut et al., 2018). The correlation between ocular surface temperature and rectal temperature in cows under heat stress conditions represents a critical area of research aimed at developing non-invasive methods for early detection of thermal load. Infrared thermography, particularly the measurement of temperature in the eye region (e.g., the medial canthus), has demonstrated strong potential as an indicator of core body temperature and physiological stress response (Ghezzi et al., 2024; Peng et al., 2019; Wang et al., 2023).

A comparison of THI and body surface temperature cut-off values indicates that the critical thresholds for THI generally fall between 72 and 78, which coincides with an increase in surface temperature beyond established limits. Slightly lower thresholds observed for the udder and ear can be attributed to reduced hair coverage and insulation, as well as greater exposure to ambient environmental conditions. This synergy between THI and body surface temperature enables timely interventions such as cooling strategies or adjustments in feeding and work schedules that mitigate the detrimental effects of heat on cow health and productivity. However, numerous

challenges arise during infrared imaging, ranging from environmental to biological factors (Gálik et al., 2024). Methodological inconsistencies and data variability present significant barriers to the standardization and broader adoption of infrared thermography. Imaging conditions including camera angle, distance, hair coverage, and external influences such as wind and solar radiation can affect measurement accuracy (Stewart et al., 2017). Additionally, internal animal factors such as lactation stage, health status, and individual stress responses further modulate surface temperature (Mota-Rojas et al., 2021; Herbut et al., 2018). Therefore, future research must focus on establishing standardized protocols and integrating IRT with other indicators of thermal stress, including behavioral and physiological parameters, to enhance the accuracy and reliability of these methods. From a practical standpoint, implementing surface temperature cut-off values as tools for welfare monitoring and heat stress prevention allows farms to respond proactively to climatic challenges. The development of IRT-based approaches, combined with automated systems for continuous monitoring and alerting, represents a crucial step toward sustainable livestock production under changing climate conditions (Stewart et al., 2017). Several advanced models based on large-scale datasets and deep learning techniques have been developed to improve the prediction and recognition of heat stress in dairy cows (Becker et al., 2021; Chapman et al., 2023; Rodrigues et al., 2023).

When body surface temperature measured via infrared thermography (IRT) is used as the sole parameter in thermal stress analysis, the question arises whether a lower THI threshold for stress detection may be applicable. Surface temperature tends to respond more rapidly and locally to environmental changes compared to core body temperatures. Anatomical regions, such as the area around the eyes, forehead, or horns, which are richly vascularized and directly exposed to ambient conditions exhibit earlier increases in temperature under thermal load (Salles et al., 2016; Peng et al., 2019). This rapid responsiveness of superficial tissues may allow for the detection of early stages of heat stress even before visible or clinical symptoms appear, and before THI reaches conventionally defined thresholds. For instance, studies

indicate that ocular surface temperatures exceeding 37.5 °C may signal heat stress at lower THI values than typically recognized (Kim et al., 2020). Such early detection may be beneficial, as it enables more timely implementation of cooling interventions or environmental management adjustments, thereby mitigating the adverse effects of heat stress. However, body surface temperature is also more susceptible to transient fluctuations caused by ambient temperature, wind, humidity, and other environmental variables, which can lead to false-positive indications of thermal stress (Stewart et al., 2017). This suggests that THI thresholds derived solely from surface temperature data must be carefully calibrated to avoid overreaction to short-term environmental changes that do not reflect true physiological stress.

Compared to conventional THI thresholds, a lower THI cut-off derived from body surface temperature may be indicative of an earlier stage of heat stress, but it does not necessarily represent a direct equivalence with internal physiological parameters. For example, THI values in the range of 68–70, which are associated with increases in surface temperature, may reflect the onset of an adaptive physiological response, whereas thresholds above 75 are more closely linked to pronounced thermal stress and a higher risk to animal health and productivity (Martello et al., 2016; Herbut et al., 2018). Thus, using surface temperature to define stress thresholds provides an additional layer of sensitivity and early warning, but it requires integration with other indicators to ensure comprehensive and reliable assessment.

4. Conclusions

Surface temperatures of different body regions vary significantly between cows in thermoneutral conditions and those under heat stress, and show a positive correlation with the THI index. Measuring surface temperature enables the discrimination of cows experiencing heat stress from those within the thermoneutral zone. The defined cut-off values for surface temperatures of various anatomical regions provide practical guidelines for identifying cows under thermal load. The THI threshold for the onset of heat stress, when based solely on surface body temperature, may be lower and more sensitive than conventional thresholds, allowing for earlier detection and timely intervention. However, it is essential that such thresholds be used in combination with other indicators and contextualized according to environmental conditions and herd-specific factors to ensure optimal accuracy and effectiveness in heat stress detection. Further research and technological development will provide additional support for improving systems aimed at protecting cattle welfare in the face of climate change.

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Declaration of competing interests

The authors declare that they have no personal and/or financial relationships with other people or organizations that could inappropriately influence their work.

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