

Comparison of UAV, Reticuloruminal Temperature, and Tail Chalk Scoring for Estrus Detection and Pregnancy Association in Bos indicus Cows

Nathália Albaneze Anache

UFMS: Universidade Federal de Mato Grosso do Sul

Igor Matheus Amaral Gauna Zenteno

UFMS: Universidade Federal de Mato Grosso do Sul

Fernando Rech

UFMS: Universidade Federal de Mato Grosso do Sul

Karine Casanova da Silva

UFMS: Universidade Federal de Mato Grosso do Sul

Walvonvitis Baes Rodrigues

UFMS: Universidade Federal de Mato Grosso do Sul

Luiz Ernandes Kozicki

PUC Parana: Pontificia Universidade Catolica do Parana

Eduardo Rigon

PUC Parana: Pontificia Universidade Catolica do Parana

Fabricio de Lima Weber

UEMS: Universidade Estadual do Mato Grosso do Sul

Pedro Paulo Pires

EMBRAPA Centro Nacional de Pesquisas de Gado de Corte

Eriklis Nogueira

eriklis.nogueira@embrapa.br

Embrapa: Empresa Brasileira de Pesquisa Agropecuaria <https://orcid.org/0000-0002-7931-455X>

Research Article

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Abstract

Although Fixed-Time Artificial Insemination (FTAI) protocols allow beef cows to be inseminated without estrus detection, yet estrus expression remains a key determinant of fertility, as cows displaying estrus achieve higher pregnancy rates. Precision Livestock Farming (PLF) offers novel automated solutions to monitor estrus, reducing labor requirements. This study compared the efficacy of three estrus detection techniques—reticuloruminal temperature (Trr) boluses, unmanned aerial vehicle (UAV/drone) visual monitoring, and tail chalk scoring (HEATSC) and evaluated their association with subsequent pregnancy in *Bos indicus* (Nelore) cows. Multiparous Nelore cows ($n = 44$) grazing extensively were subjected to a progesterone-estradiol FTAI protocol. From D8 (progesterone device removal) to D10 (insemination), animals were evaluated for estrus using: (1) a Trr bolus; (2) a drone flying twice daily for 60 min to detect standing estrus; and (3) tail chalk scoring (HEATSC 1–3) at insemination. The overall pregnancy rate (P/AI) was 56%. The proportion of cows identified in estrus did not differ significantly: 75% for HEATSC (2 and 3), 61% for Trr, and 57% for drone ($P = 0.1794$). However, only the behavior-based methods significantly predicted pregnancy probability; both HEATSC ($P = 0.006$) and drone ($P = 0.016$) had significant effects, whereas Trr did not ($P = 0.3586$). Body condition score (BCS) significantly influenced pregnancy ($P = 0.04$), with cows of BCS 3.0–3.5 showing higher fertility. In conclusion, while all three techniques show similar technical capability to identify estrus, only behavioral-based methods (UAV and tail chalk) are strongly correlated with pregnancy outcomes. Internal physiological sensors like Trr boluses may be limited by confounding digestive or environmental factors that mask periovulatory temperature peaks.

1. Introduction

The demand for animal protein has increased significantly in the past years because of population growth, making the integration of Precision Livestock Farming (PLF) and intelligent technologies essential to improve production efficiency and sustainability in beef cattle (Neethirajan and Kemp 2021). In Brazil, which possesses one of the largest commercial cattle herds in the world, the adoption of reproductive biotechnologies such as Fixed-Time Artificial Insemination (FTAI) is fundamental. FTAI facilitates genetic improvement and allows the insemination of many cows at a predetermined time without the requirement for active estrus detection (Baruselli et al. 2017; Baruselli et al. 2019; Rodrigues et al. 2019a).

By design, FTAI protocols involve the insemination of all cows regardless of whether they actively show estrus at the time of insemination. However, numerous studies have confirmed that the active expression of estrus near FTAI is strongly associated with higher fertility and conception rates (Nogueira et al. 2019; Rodrigues et al. 2019b; Moraes et al. 2022). Cows that fail to exhibit estrus show lower ovulation rates, smaller pre-ovulatory follicle diameters, and sub-optimal uterine environments, which significantly increase the risk of late embryonic and gestational losses (Cerri et al. 2004; Galvão et al. 2004; Morotti et al. 2025). Consequently, the failure to identify and optimize estrus expression represents a major economic and biological bottleneck in modern cattle production systems.

To address this challenge, researchers have explored various PLF technologies to automate and refine estrus detection. Tail chalking combined with visual estrus expression scoring (HEATSC) has proven to be a low-cost, highly effective tool to monitor the cumulative mounting behavior of cows, showing a strong correlation with subsequent pregnancy rates (Rodrigues et al. 2019b; Morotti et al. 2025). Concurrently, the use of Unmanned Aerial Vehicles (UAVs or drones) has transitioned from simple mapping tools to active components of herd management, allowing real-time, non-invasive visual monitoring of animal behavior from a wide field of view (Jung et al. 2021; Arıkan et al. 2023). On the physiological front, reticuloruminal temperature (Trr) boluses offer a continuous stream of core body temperature data, which can theoretically detect the transient temperature rise (typically $\sim 0.4^{\circ}\text{C}$ to 1.0°C) associated with the pre-ovulatory LH surge and increased physical activity during estrus (Cooper-Prado et al. 2011; Kim et al. 2023).

While these technologies show high potential in intensive dairy herds, their comparative efficacy in extensive beef cattle systems—specifically for *Bos indicus* (Nelore) cows, which exhibit shorter and predominantly nocturnal estrus periods (Bó et al. 2003; Figueiredo et al. 1997)—remains poorly characterized. Therefore, the objective of this study was to compare the efficacy of three distinct estrus detection methodologies (reticuloruminal temperature bolus, visual drone observation, and tail chalk scoring) in *Bos indicus* cows subjected to a progesterone-estradiol FTAI protocol and to evaluate their correlation with subsequent pregnancy rates.

2. Materials and Methods

The experimental protocol was approved by the Ethics Committee on Animal Use (CEUA) of Embrapa Beef Cattle (Protocol No. 010/2014; Campo Grande, MS, Brazil). The study was conducted at the experimental farm of Embrapa Beef Cattle, located in Campo Grande, MS, Brazil ($20^{\circ}26'44''$ S, $54^{\circ}43'03''$ W).

2.1 Animals and Housing

Forty-four multiparous Nelore (*Bos indicus*) cows were used in this study, with a mean body weight of 372 ± 41 kg and an average Body Condition Score (BCS) of 3.0 ± 0.60 on a 1–5 scale (Nicholson and Butterworth 1986). The animals were kept under an extensive grazing system on *Brachiaria brizantha* pasture (50 ha) with ad libitum access to water and mineral supplement.

2.2 FTAI Protocol and Marker Application

All cows were synchronized using a standard progesterone-estradiol protocol. On Day 0 (D0), cows received an intravaginal progesterone-releasing device (1.9 g P4, CIDR®, Zoetis, São Paulo, Brazil) and an intramuscular (IM) injection of 2 mg of estradiol benzoate (EB; Ric-BE®, Agener União, São Paulo, Brazil). On Day 8 (D8), the CIDR devices were removed, and cows received IM injections of 500 μg of d-cloprostenol (PGF2 α -analogue; Prolise®, Arsa, Buenos Aires, Argentina), 300 IU of equine chorionic gonadotropin (eCG; Folligon®, MSD, São Paulo, Brazil), and 1 mg of estradiol cypionate (ECP®, Zoetis,

São Paulo, Brazil). At the time of CIDR removal on D8, tail head regions were marked with tail chalk (Raidl-maxi, Raidex GmbH, Germany) and numbered on their backs (1 to 44) to facilitate visual identification.

2.3 Estrus Detection Technologies

All 44 cows were simultaneously and independently evaluated using three different estrus detection techniques:

2.3.1 Reticuloruminal Temperature (Trr)

An intraruminal temperature-sensing bolus (DVM Systems®, Colorado, USA) was orally administered to each cow prior to the start of the protocol. The bolus recorded temperature hourly, storing up to 12 hours of readings. Data were automatically downloaded when cows passed within a 30-meter range of radio-frequency antennas positioned next to the pasture drinking trough, and processed via Temp Track® software (Melbourne, Australia). Estrus was identified by an abrupt, sharp increase in Trr ($\geq 0.5^{\circ}\text{C}$ and up to 1.0°C on average) within a 1–2 hour interval, persisting for several hours, in contrast to normal, slow circadian rhythms.

2.3.2 UAV (Drone) Observation

Visual monitoring of mounting behavior was conducted from D8 to D10 using a DJI Phantom 3 UAV (DJI, Shenzhen, China). Flights were performed twice daily (morning and afternoon) for 60 minutes per session. Cows were designated in estrus if they exhibited standing estrus (standing to be mounted by another animal).

2.3.3 Tail Chalk Scoring (HEATSC)

At the time of FTAI (D10, 48 hours after CIDR removal), the tail chalk was evaluated and scored: HEATSC 1 (no or little chalk removal, indicating no estrus), HEATSC 2 (partial chalk removal, low estrus expression), and HEATSC 3 (complete or near-complete chalk removal, high estrus expression).

2.4 Statistical Analysis

Estrus detection rates among the three methods were compared using the Chi-Square test ($p < 0.05$). Pregnancy diagnosis was performed 30 days after FTAI via transrectal ultrasonography. Logistic regression (PROC LOGISTIC, SAS Inst., Inc., Cary, NC) was used to analyze the effect of each detection method and body condition score (BCS) on the pregnancy per artificial insemination (P/AI) probability. Pearson correlation coefficients (r) were calculated to evaluate the relationships between estrus detection variables and P/AI. Significance was defined at $P \leq 0.05$.

3. Results

The overall pregnancy rate (P/AI) of the herd was 56% (25/44). Successful reticuloruminal temperature recordings were obtained for 95% of the animals. Figure 1 demonstrates the contrast between an animal

with active estrus expression, which showed a sharp, abrupt temperature rise of over 1.0°C during D9 (Panel A), and a non-estrus animal exhibiting typical, slow, and gradual circadian oscillations within the normal range of 38.2°C to 39.5°C (Panel B).

The absolute number of cows identified in estrus was 33/44 (75.0%) for HEATSC (combining scores 2 and 3), 27/44 (61.4%) for the Trr bolus, and 25/44 (56.8%) for UAV drone observation. These overall detection rates did not differ statistically ($P = 0.1794$; Table 1). For the tail chalk method, 17/33 (51.5%) of detected cows were classified as HEATSC 2 (low expression) and 16/33 (48.5%) as HEATSC 3 (high expression). The comparative estrus detection rates across all three methodologies are illustrated in Fig. 2.

Table 1
Estrus detection rates in multiparous Nelore cows (n = 44) subjected to FTAI using three different methodologies.

Parameter	HEATSC (Tail Chalk)	Trr (Bolus)	UAV (Drone)	P-value
Cows in Estrus (%)	75.0% (33/44)	61.36% (27/44)	56.81% (25/44)	0.1794
No Estrus (%)	25.0% (11/44)	38.64% (17/44)	43.19% (19/44)	

Although overall estrus detection rates were statistically similar, their correlation with fertility outcomes differed drastically. Body condition score (BCS) significantly influenced pregnancy probability ($P = 0.04$), with cows in higher BCS classes (3.0 to 3.5) exhibiting higher fertility and estrus expression. Furthermore, logistic regression analysis revealed that behavior-based estrus detection significantly influenced pregnancy probability (Fig. 3): tail chalk removal score (HEATSC) showed a highly significant effect ($P = 0.006$) on subsequent pregnancy, as did visual standing estrus observation with the UAV ($P = 0.016$). In contrast, the occurrence of reticuloruminal temperature peaks (Trr) did not exhibit any significant association with pregnancy ($P = 0.3586$; Table 2).

Table 2
Effect of body condition score (BCS) and estrus designation by Trr, UAV, and HEATSC on pregnancy per artificial insemination (P/AI).

Variable	Trr 0	Trr 1	P-Trr	UAV 0	UAV1	P-AV	SC 1	SC 2	SC 3	P-SC
BCS	3.00	3.00	0.522	2.50	3.00	0.151	2.50	3.00	3.50	0.379
P/AI (%)	41.17	51.85	0.3586	26.31	64.00	0.016	18.18	35.29	81.25	0.006
Note: Trr (0 = no peak, 1 = peak); UAV (0 = no standing estrus, 1 = standing estrus); SC (Tail Chalk: 1 = no, 2 = low, 3 = high expression).										

Pearson correlation coefficients (r) confirmed these findings. UAV drone visual observation and tail chalk removal (HEATSC) exhibited a strong, highly significant positive correlation ($r = 0.54$, $P = 0.001$),

demonstrating that both behavioral-based methods identify the same physical estrus activity (Fig. 4). Pregnancy was significantly correlated with HEATSC ($r = 0.50$, $P = 0.0005$) and UAV ($r = 0.33$, $P = 0.02$). Conversely, the reticuloruminal temperature bolus (Trr) was not significantly correlated with pregnancy ($r = -0.20$, $P = 0.18$), and was negatively correlated with tail chalk scoring ($r = -0.30$, $P = 0.04$).

4. Discussion

Although one of the principal advantages of fixed-time artificial insemination (FTAI) protocols is that they do not require visual estrus detection as a prerequisite for insemination, our results demonstrate that the intensity of estrus expression around the time of FTAI remains a strong determinant of subsequent pregnancy per AI (P/AI). This finding reinforces the clinical relevance of estrus-monitoring technologies even within FTAI-based reproductive programs and suggests that the framework validated here may serve as a model applicable to other production systems and reproductive management realities.

In fact, our study demonstrates that while reticuloruminal temperature boluses, visual drone observations, and tail chalking show comparable overall technical capability in detecting estrus-related events in extensive *Bos indicus* herds, but only behavior-based methods (UAV and tail chalk) are reliable predictors of fertility. Tail chalking (HEATSC) achieved the highest absolute detection rate (75%), followed by Trr (61.4%) and UAV (56.8%). This higher absolute rate is attributed to the temporal nature of the techniques; HEATSC acts as a cumulative indicator, capturing all mounting activity occurring throughout the entire 48-hour window from CIDR removal to FTAI. In contrast, UAV drone flights (60 minutes twice daily) provide discrete snapshots of standing behavior, and Trr boluses rely on real-time temperature tracking, which requires animals to actively visit antennas to discharge data.

The strong positive association between behavior-based estrus expression and fertility matches the findings of recent literature in dairy systems. In crossbred dairy cows (Holstein $\times$ Gir) monitored with automated activity-sensing collars (COWMED®), Martins (2026) demonstrated a highly significant positive trend between estrus intensity and subsequent conception rates using sexed semen: cows exhibiting strong estrus intensity achieved a 52.8% conception rate, compared to only 30.8% and 35.7% for weak and moderate estrus, respectively. He further noted that cows with longer days in milk (DEL > 120 days) exhibited a higher incidence of strong estrus and superior conception rates, owing to reduced metabolic and negative energy balance (NEB) challenges post-partum. This biological parallel is critical: whether in extensive beef systems (Nelore) or intensive dairy systems (Holstein $\times$ Gir), the physical intensity of estrus behavior directly reflects high pre-ovulatory estradiol concentrations (Gimenes et al., 2023). High estradiol coordinates critical physiological events, including the LH surge, optimal sperm transport, uterine pH regulation, and follicular maturation, which are vital to establish and maintain pregnancy (Cooke et al., 2019; Nogueira et al., 2019).

In contrast, the lack of significant association between reticuloruminal temperature (Trr) peaks and pregnancy ($P = 0.3586$), or actual behavioral estrus, highlights a major limitation of internal physiological

sensors in extensive grazing systems. While the bolus is highly capable of recording core thermal fluctuations, reticuloruminal temperature is highly sensitive to confounding physiological events occurring within a 24-hour cycle. In pasture-raised beef cattle, Trr is influenced by altered digestion, heat stress, diurnal ambient temperature spikes, and ruminal fermentation fluctuations (Bernabucci et al., 2010; Aungier et al., 2012). These non-estrus-related thermal variations generate significant noise, resulting in false-positive estrus alerts that decouple temperature peaks from actual periovulatory events, as supported by Rocha et al. (2025), who reported that automated activity/temperature sensors did not accurately predict pregnancy in grazing beef cows.

A similar phenomenon regarding device-induced stress and physiological confounding was documented by Henningsen et al. (2017) during their evaluation of the vagina-inserted iVET® birth monitoring system in primiparous dairy heifers. While the iVET® system successfully signaled the onset of Stage 2 labor earlier than visual observation, the physical presence of the device caused severe vaginal irritation, discomfort, and significant neuro-hormonal alterations in the birth process, with monitored heifers exhibiting frequent tenesmus, tail elevation, arched backs, and stagnation of labor, leading to a significantly higher incidence of severe dystocia (58.3%) compared to the control group (40.9%). These findings suggest that invasive or semi-invasive physical devices can trigger local irritation, pain, and systemic cortisol release, which can directly alter or mask natural physiological and behavioral processes. In our study, although the reticuloruminal bolus is non-invasive to the external vaginal tract, its continuous presence in the reticulorumen, coupled with grazing conditions, could interact with environmental heat stress and altered ruminal digestion, creating a stress-response or thermal noise that interferes with the clean mapping of periovulatory estrus. This highlights the crucial PLF principle that a monitoring system must be entirely innocuous and free of confounding environmental interactions to remain biologically reliable.

UAV (drone) monitoring demonstrated outstanding visual accuracy and represents a powerful, non-invasive alternative to traditional pasture visual monitoring. Drone observation eliminates the need for close-up human observers, reducing herd stress and visual blockages, and allows operators to record, save, and review videos to eliminate observer error. However, its operation remains limited by battery life (typically ~ 30 minutes per flight) and the high labor requirement of a dedicated pilot. Future advances combining UAV-mounted thermal/RGB cameras with automated computer vision and machine learning algorithms (Li et al., 2024; Ding et al., 2025) offer a promising avenue to automate drone-based estrus and health monitoring, minimizing these logistical constraints.

On the other hand, tail chalking remains an incredibly robust, high-accuracy, and cost-effective management strategy for beef breeders. Because tail chalking is a cumulative measure, it requires no extra handling or specialized piloting labor, allowing the cow to remain undisturbed in her extensive environment. Producers can strategically use HEATSC at the moment of FTAI to select high-expressing females (HEATSC 3) for high-value or sexed semen (since conception rates are highest at 81.25%), or administer exogenous GnRH to low-expressing females (HEATSC 1 and 2) to induce ovulation and

rescue pregnancy rates, thereby significantly enhancing overall herd reproductive efficiency (Rodrigues et al., 2019b; Morotti et al., 2025).

4.1 Practical implications and PLF perspectives

The integration of Precision Livestock Farming (PLF) tools in tropical extensive beef systems must balance technical accuracy with biological relevance and operational feasibility. Our findings demonstrate that while continuous physiological monitoring (Trr) and non-invasive behavioral observations (UAV/drones and HEATSC) yield statistically comparable overall estrus detection rates (61.36%, 56.81%, and 75.00%, respectively; $P = 0.1794$), their capacity to predict subsequent fertility (P/AI) diverges significantly. This biological and statistical divergence highlights key practical implications for reproductive management in *Bos indicus* herds.

Firstly, the strategic use of simple, low-cost cumulative behavioral indicators such as HEATSC remains highly effective for real-time decision-making at the time of FTAI. Nelore cows demonstrating high estrus intensity (HEATSC 3) achieved an outstanding P/AI of 81.25%, compared to only 18.18% for those with no expression (HEATSC 1). This large variation in fertility allows practitioners to optimize semen allocation: high-value or sex-sorted semen can be selectively directed toward high-expression females to maximize genetic progress and economic return, while low-expression females (HEATSC 1 and 2) can be targeted with exogenous GnRH analogues to rescue ovulation and improve pregnancy outcomes. This pattern mirrors the dairy findings of Martins (2026) discussed above, reinforcing that, across both beef and dairy sectors, the physical and behavioral intensity of estrus — driven by preovulatory estradiol secretion — is a robust bio-indicator of uterine readiness and subsequent luteal adequacy. Consistent with Martins' (2026) observation that metabolic status (days in milk) shapes estrus expression, our results also confirm that *Bos indicus* cows with a favorable body condition score (BCS 3.0–3.5) exhibit greater estrus expression and fertility ($P = 0.04$), reinforcing that nutritional management before AI programs is paramount.

Secondly, the use of UAVs represented a highly successful non-invasive technological approach, significantly predicting P/AI ($P = 0.016$). In extensive tropical grazing systems, where labor scarcity is an increasing challenge, UAVs eliminate the physical stress of traditional visual checking, allow simultaneous monitoring of multiple mounting interactions, and provide a permanent video archive for retrospective analysis. Their practical application, however, is currently constrained by operational limitations, particularly the short battery flight-time of approximately 30 minutes, which necessitates strategic, targeted observation windows (such as one hour in the morning and afternoon).

Thirdly, the telemetric reticuloruminal bolus, while highly capable of logging physiological parameters and detecting the characteristic sudden periovulatory thermal spike of $\sim 1^{\circ}\text{C}$, failed to predict pregnancy ($P = 0.3586$). This indicates that internal biosensors are highly susceptible to physiological and microclimatic confounding factors in extensive pasture-raised cattle: altered grazing digestion, ruminal fermentation shifts, diurnal heat stress, and episodic cold-water intake can generate significant thermal

"noise" that decouples the logged temperature spike from true ovulatory estrus behavior. The technical infrastructure required for telemetric boluses adds further practical challenges, including a limited antenna signal range (30 m), vulnerability of radiofrequency signals to local vegetation or topography, a fixed 2-year battery lifespan, and the inability to reuse the bolus post-slaughter — limitations that contrast with dairy operations, where cows pass through automated antenna gates in the milking parlor twice daily, minimizing signal loss.

4.1.1 Architectural challenges and multi-modal sensor fusion in grazing systems

The divergence observed between internal physiological sensors (Trr) and external behavioral manifestations (UAV, HEATSC) underscores the intrinsic limitations of single-sensor architectures in extensive beef cattle environments. In tropical rangelands, individual data streams are susceptible to isolated environmental and digestive artifacts: intraruminal boluses suffer from ruminal fermentation noise and line-of-sight RF transmission constraints (such as the 30-meter receiver radius at watering stations), while UAV systems are restricted by flight autonomy and the logistical burden of manual piloting.

Overcoming these bottlenecks requires moving from isolated metrics to multi-modal sensor fusion. At the perception level, current manual drone-video annotation could be replaced by real-time deep learning pipelines, incorporating YOLO-based convolutional detectors for individual animal detection coupled with spatial-temporal action-recognition architectures (e.g., SlowFast networks or Vision Transformers) to classify mounting behavior automatically. At the decision level, a late-fusion framework integrating temporal features from intraruminal boluses (Trr rate-of-change and variance) with aerial behavioral probabilities could suppress false-positive thermal peaks caused by ambient heat stress or feed intake. By cross-validating thermal spikes against automated aerial or paddock-gate vision tracking, such hybrid computational frameworks could deliver fully automated, high-confidence estrus alerts tailored to the scale of extensive grazing operations — pointing toward a future in which PLF in tropical beef systems relies not on a single standalone sensor, but on multiparametric, sensor-fusion approaches that filter out confounding physiological noise while remaining non-invasive and operationally feasible.

5. Conclusions

Behavior-based estrus detection methods, including visual drone observation and tail chalk scoring, are highly efficient and serve as strong predictors of pregnancy outcomes (P/AI) in extensive *Bos indicus* beef cattle. In contrast, while reticuloruminal temperature (Trr) boluses successfully record temperature changes, they are heavily confounded by digestive, ruminal, and heat-stress factors, making them unreliable as standalone predictors of pregnancy in extensive tropical pastures. Nutrition and pre-FTAI management remain vital, as higher body condition score (BCS) significantly increases estrus expression and subsequent pregnancy rates. Future PLF developments should focus on integrating multi-sensor data streams (UAV computer vision, accelerometers, and physiological boluses) through

machine learning algorithms to overcome the biological and environmental limitations of individual sensors.

Declarations

Conflict of Interest:

The authors declare that they have no competing interests.

Ethics Approval:

The study was reviewed and approved by the Committee on Animal Use and Experimentation (CEUA) of Embrapa Beef Cattle (Protocol No. 010/2014).

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Claude to support manuscript organization, language refinement, and formatting according to journal guidelines. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the article.

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Author Contributions:

Nathália Albaneze Anache: Conceptualization, Investigation, Data curation, Writing – original draft. Igor Matheus Amaral Gauna Zenteno: Visualization, Writing – review & editing. Victória Marques: Writing – review & editing. Fernando Rech: Formal analysis, Statistical modeling, Writing – review & editing. Karine Casanova da Silva: Formal analysis, Writing – review & editing. Walvonvitis Baes Rodrigues: Writing – review & editing. Luiz Kozick: Writing – review & editing, Validation. Pedro Paulo Pires: Writing – review & editing, Validation. Ériklis Nogueira: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

Data availability:

The data that support the findings of this study are available from the corresponding author upon reasonable request, subject to confidentiality restrictions related to commercial farm records.

Data Availability:

The datasets generated and analyzed during the current study are the property of Embrapa Beef Cattle and are available from the corresponding author on reasonable request.

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Figures

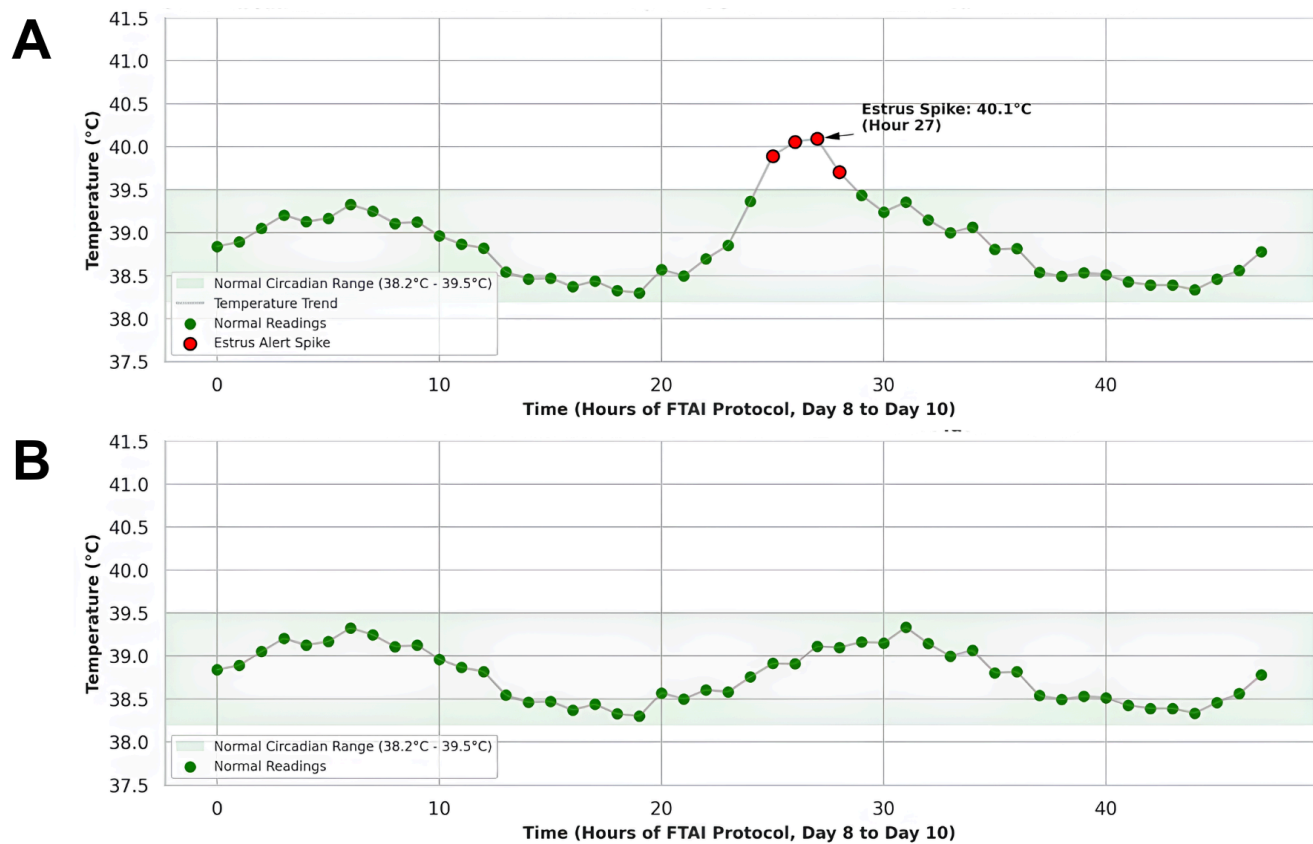


Figure 1

Intraruminal temperature profiles in *Bos indicus* cows. A: animal exhibiting estrus with a characteristic temperature spike (40.1°C at hour 27, $\geq 0.5^{\circ}\text{C}$ increase within < 2 h). B: animal without estrus expression showing normal circadian fluctuations (38.2–39.5°C). Green lines represent normal readings; red lines indicate estrus alert spikes. Shaded zone denotes the normal circadian temperature range

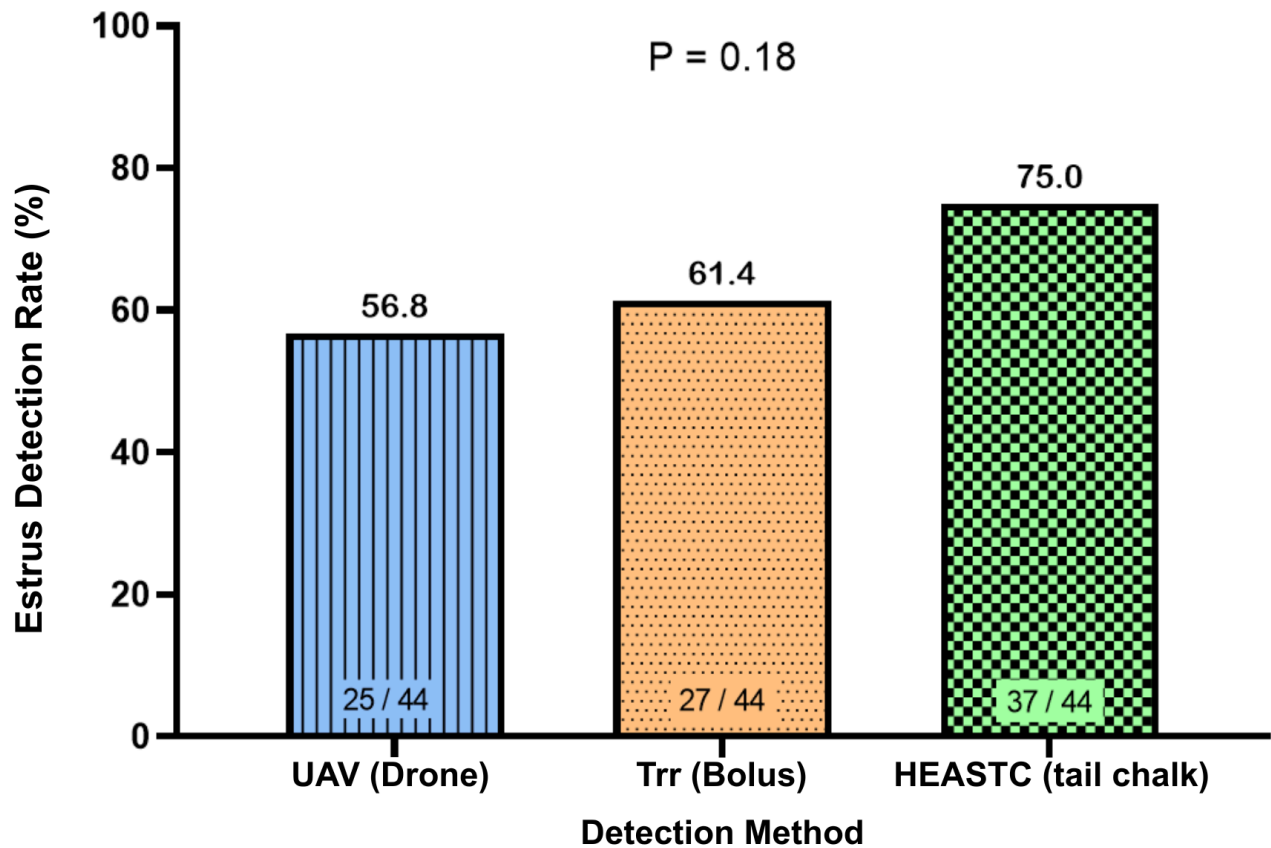


Figure 2

Estrus detection rates (%) across three methodologies in *Bos indicus* cows subjected to timed artificial insemination. UAV (drone-based visual observation, 56.8%), intraruminal bolus temperature (Trr (Bolus) 61.4%), and tail chalk scoring (HEATSC, 75.0%). No significant difference between methods ($P = 0.1794$). Numbers above bars indicate percentage and raw counts (n/N)

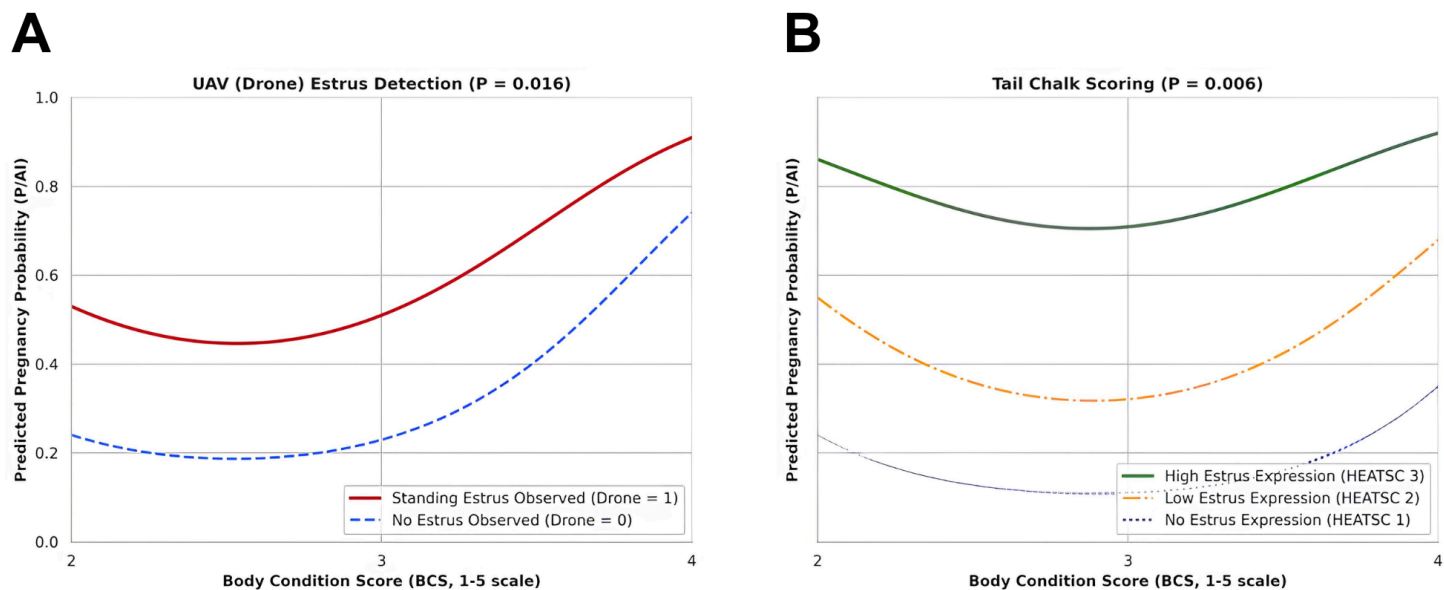


Figure 3

Graph of logistic regression curves estimating the probability of pregnancy (P/AI) according to Body Condition Score (BCS) and estrus expression measured by UAV (P= 0.016) and HEATSC (P= 0.006)

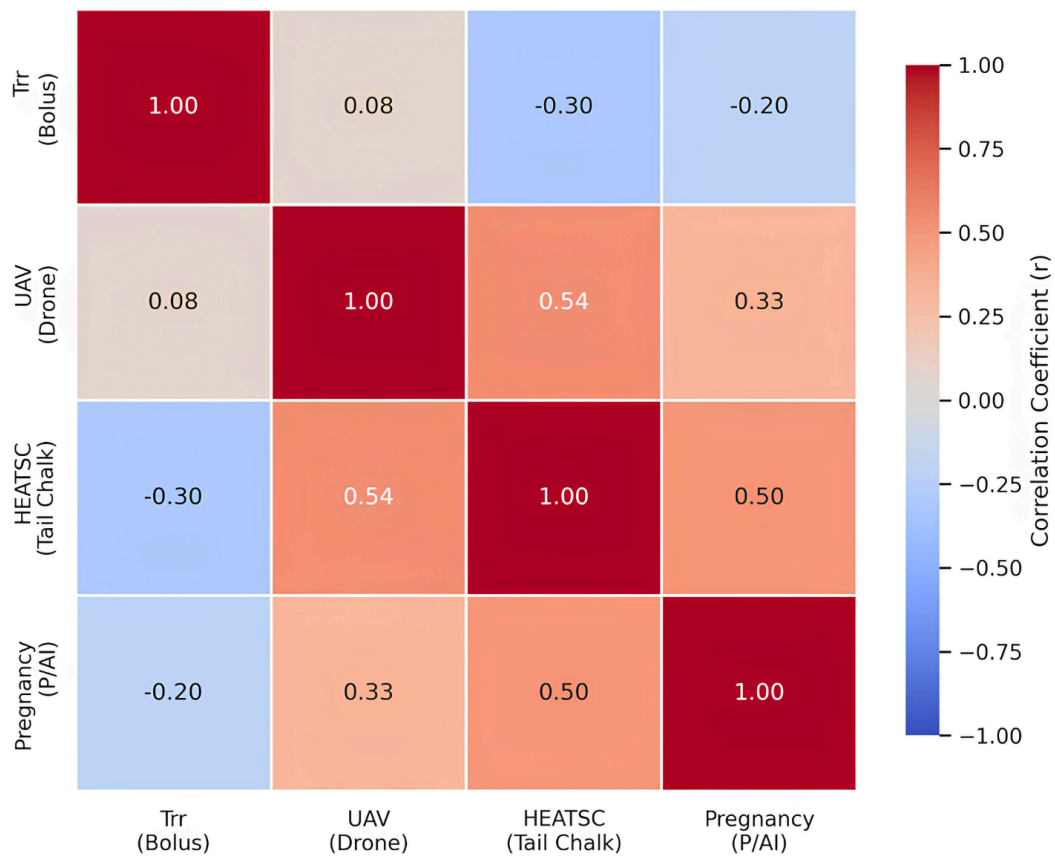


Figure 4

Pearson correlation matrix in heatmap format, highlighting the behavioral methods that are strongly correlated with pregnancy rate. Red indicates positive correlation; blue indicates negative correlation. Trr: intraruminal bolus temperature; UAV: drone-based visual observation; HEATSC: tail chalk scoring; P/AI: pregnancy per artificial insemination. Correlation coefficients (r) are shown within each cell