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Animal-specific estrus detection in grazing beef cattle using baseline-normalized ear-tag data

S. White*[1] , and G. Campbell[2]

[1]*CERES TAG INC., Overland Park, USA;* [2]*CERES TAG LTD, Brisbane, Australia;*
**Corresponding author: shane.white@cerestag.com*

Introduction

Reproductive efficiency is a critical driver of productivity, profitability, and sustainability in beef production systems. In extensive grazing environments, timely detection of estrus remains difficult due to large paddock sizes, labor constraints, and reduced expression of overt estrus behaviors. Missed or delayed estrus detection lowers artificial insemination (AI) submission rates, extends calving intervals, and increases the proportion of non-productive females within the herd.

Wearable sensor technologies have increasingly been adopted to support automated estrus detection, particularly in dairy systems. Most commercially available approaches rely on absolute or relative increases in activity derived from pedometers or collars; however, such methods often perform inconsistently in extensive beef systems, where baseline activity varies substantially between animals and changes over time in response to pasture availability, environmental conditions, physiological state, and management practices. Fixed thresholds or herd-level normalization can therefore result in both false alerts and missed estrus events.

CERES TAG develops infrastructure-free, ear-tag–based sensing platforms designed for long-term deployment in grazing cattle. To support the development of a robust estrus detection capability suitable for extensive beef systems, CERES TAG commissioned the Commonwealth Science and Industry Research Organisation (CSIRO) to undertake foundational research into behavior inference and physiological event detection using ear-tag inertial data. The technical details of the behavior classification pipeline developed through that commissioned work are reported separately in a companion manuscript currently under review (Arablouei *et al*., under review).

Building on that foundational research, the objective of the present study is to present the applied estrus detection algorithm derived from the commissioned work, with a specific focus on animal-specific baseline normalization and performance in grazing beef cattle. This paper emphasizes the estrus detection methodology and results as deployed in an industry context, rather than the underlying behavior classification architecture.

Materials & Methods

The study was conducted at the CSIRO Chiswick Research Station, New South Wales, Australia, using 33 Angus beef cows managed under a pasture-based grazing system. Animals were monitored continuously over approximately four months. All experimental procedures were approved by the relevant animal ethics committee and conducted in accordance with national animal welfare guidelines.

Each animal was fitted with a CERES TAG smart ear-tag incorporating a triaxial accelerometer designed for continuous, long-duration deployment in extensive grazing environments and an eGrazor collar which paired with the smart ear-tag over Bluetooth Low Energy (BLE) and enabled the streaming and storage of both smart ear-tag and collar accelerometer data.

Accelerometer data processing. Raw triaxial accelerometer data collected by the CERES TAG devices were processed to infer core behaviors, including grazing, ruminating, resting, and walking. Behavior inference was performed using a classification model developed by CSIRO as part of the commissioned research program, which is described in detail elsewhere (Arablouei et al., under review). In the present paper, behavior classification outputs are treated as upstream inputs to the estrus detection algorithm rather than as a primary contribution. Classified behaviors were then aggregated to daily durations (minutes per day) for each animal.

Estrus reference definition. Estrus events were confirmed using serum progesterone measurements in combination with visual mounting indicators. Estrus was classified when progesterone concentrations were ≤ 1 ng/mL. Non-estrus days were confirmed using mid-luteal (mid-cycle) progesterone concentrations. Both naturally occurring estrus events and hormonally synchronized estrus events were included to reflect practical commercial breeding conditions.

Baseline-normalised feature construction. To account for inter-animal variability and gradual temporal changes in behavior, animal-specific behavioral baselines were calculated for each cow and each behavior using a 14-day causal sliding window. Baselines were defined as trimmed means of the preceding 14 valid days, with the minimum and maximum values removed to improve robustness to outliers. Baselines were only considered when at least three valid historical days were available. For each cow-day, estrus detection features were defined as deviations between observed daily behavior durations and the corresponding animal-specific baselines. Four baseline-normalised features were derived: grazing deviation, ruminating deviation, resting deviation, and walking deviation (minutes per day).

Estrus classification model. Estrus detection was formulated as a binary classification problem (estrus vs non-estrus). A regularized logistic regression model was used to estimate the probability of estrus from the four baseline-normalised features. Logistic regression was selected due to its interpretability, robustness with limited sample sizes, and suitability for integration into low-power edge deployments consistent with CERES TAG smart ear-tag system architecture.

Model training and evaluation were performed using repeated stratified five-fold cross-validation. To avoid potential within-animal data leakage given our relatively small sample size (33 cows), cross-validation was strictly partitioned at the cow level rather than the cow-day level. This ensures that all data from any individual cow was kept entirely within either the training or the testing fold during any single run. Feature standardization was performed within each training fold to prevent information leakage.

Results

After quality control and baseline availability checks, the final dataset comprised 55 estrus cow-days and 927 non-estrus cow-days, corresponding to an estrus prevalence of approximately 5.6%. This prevalence is consistent with expectations for commercial beef herds under mixed natural and synchronized breeding programs.

Estrus days were consistently associated with deviations from individual behavioral baselines. On average, cows exhibited reduced grazing and rumination durations and increased walking and resting durations during estrus compared with non-estrus days. These relative changes were observed across animals despite substantial differences in absolute activity levels and baseline behavior profiles. Baseline normalization substantially reduced between-animal variability and allowed estrus-related behavioral changes to be expressed on a common, comparable scale across the herd.

The logistic regression classifier demonstrated strong discriminative performance across repeated cross-validation runs. At a default probability threshold of 0.5, the model achieved a precision of 0.92, a recall of 0.85, and a specificity of 0.99. To better illustrate performance under this low-prevalence class (5.6%), lowering the classification threshold to 0.3 increased recall to 0.94 while maintaining a precision of 0.81. Conversely, a high-stringency threshold of 0.7 yielded a precision of 0.98 at the cost of dropping recall to 0.71. The Matthews Correlation Coefficient (MCC) exceeded 0.93 at optimal thresholds. Adjusting the decision threshold to optimize MCC further reduced false positives with minimal impact on sensitivity, supporting flexible deployment depending on management objectives and tolerance for false alerts.

Discussion

This industry-led study demonstrates that animal-specific, baseline-normalized behavioral features derived from smart ear-tag inertial data can accurately detect estrus in grazing beef cattle. By explicitly accounting for inter-animal variability and gradual behavioral drift, the proposed approach addresses key limitations of absolute, or herd relative, activity systems commonly used in extensive production environments.

The observed reductions in grazing and rumination and increases in walking are consistent with established physiological responses associated cattle during estrus. Importantly, these changes were detectable even in animals with low absolute activity levels, highlighting the value of within-animal normalization rather than reliance on herd-level comparisons.

A primary strength of this study was the inclusion of both natural and hormonally synchronized estrus events. Post-hoc analysis of the model's predictions revealed no statistically significant differences in detection performance between the two groups. This suggests that the behavioral deviations mapped by our baseline-normalized features are robustly expressed in both biological contexts, cementing the algorithm's viability for standard commercial artificial insemination programs.

Conclusions

Baseline-normalized behavior data generated by ear-tag accelerometers can provide a highly accurate means of detecting estrus in commercial grazing beef operations. Individualized baselines eliminate the baseline noise associated with shifting environmental variables, allowing both natural and synchronized cycles to be tracked without the need for additional farm-based scanning infrastructure.

Acknowledgements

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