Final Report

P6 – Future systems – Dairy Da.T.A

This project was led by Professor Cameron Clark
and Dr. Anna Chlingaran from the University of Sydney Dairy Research Foundation

Dairy UP (Phase 1) was a $16 million, five-year industry driven project with a portfolio of 10 research, development and adoption projects collectively aiming to realise three primary objectives:

- Increase Productivity and Profitability by unlocking the potential of milk, the cow and water,
- De-risking the industry and
- Developing new markets.

A key part of Dairy UP was a coordinated network of partner farms across New South Wales (and beyond) providing valuable insights into real world application of new practices, including the challenges and benefits of new innovative technologies.

Dairy UP made a big contribution to dairy research and development rejuvenation, (attracting new researchers, PhD students and Industry investment).

Dairy UP was funded through the Australian and NSW Government's Bushfire Industry Package – Sector Development Grant (BIP-SDG) program, with cash co-contributions from Dairy Australia, The University of Sydney's Dairy Research Foundation, Local Land Services, Norco, Leppington Pastoral Co Ltd and Dairy NSW; and in kind contributions by all the above organisations plus NSW DPI (Biosecurity and Food Safety; Agriculture), Scibus, Australia Fresh Milk Holding Ltd, Dairy Connect and NSW Farmers.

This project was delivered jointly by University of Sydney's Dairy Research Foundation, Scibus, Department of Primary Industries and Regional development.

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Charles Sturt University | DairyBio | DataGene | Eagle Direct | Entegra | Macquarie University | NSW EPA | smaXtec | UC Davis | University of Technology Sydney

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1. Executive Summary

The Australian dairy sector is rapidly shifting toward smarter, more resilient production systems. The P6: Future Systems – Dairy Da.T.A project funded under the Dairy UP program integrates animal science and data science to address three critical knowledge gaps affecting productivity, welfare, and resource efficiency on Australian farms. The project aims to utilise data, advanced technologies and automation to integrate information from multiple sources to enable the creation of tools that support on-farm decisions.

P6a – Resilient cattle (heat tolerance): optimising on-farm energy use and cooling systems

Heat stress (HS) imposes major economic and welfare costs on the Australian dairy industry each year, reducing milk yield, reproductive performance and overall cow comfort. Building herds with stronger heat-tolerance traits is a key strategy for reducing the impacts of HS. This subproject focused on developing new phenotypic indicators by examining how individual cows respond to heat events using continuous multi-sensor data, including core body temperature measurements and climate records. The work revealed substantial variation between animals, with rises in internal temperature occurring at around THI 67 - earlier than the 70-75 guidance commonly used on farms. Drinking behaviour also showed a clear relationship with heat load, and a model was developed to account for drinking events when interpreting temperature data. Seasonal and regional patterns were evident, with cows drinking more frequently in summer and in warmer climates. Advanced modelling approaches were applied to combine climate and production data, enabling more detailed patterns of heat response to be detected than with traditional methods alone. Through collaboration with DairyBio, these sensor-derived indicators provide a foundation for developing new heat-tolerance phenotypes that complement genomic information, and ongoing integration of phenotypic and genotypic data aims to further improve the reliability of the Heat Tolerance ABV.

P6b – Resilient cattle (health): early intervention enabled by advanced sensing

Advanced sensing technologies are reshaping herd-health management by enabling earlier detection of emerging issues than is possible through visual observation alone. Wearable and in-body systems such as CowManager and smaXtec boluses continuously capture data on activity, temperature, rumination and feeding behaviour, with algorithms identifying deviations from normal patterns that signal potential health events. Through collaboration with Moxey Farms, this subproject has successfully assembled and validated a substantial dataset linking sensor outputs with farm health and production records from DataGene, providing a strong foundation for developing early-warning indicators. Progress to date has focused on data collation, harmonising health-event definitions and securing access to external datasets. Further analytical work has been delayed due to health-related interruptions that required the PhD candidate to suspend their studies multiple times, but the project remains well positioned to advance early-intervention tools that can reduce disease impact and improve herd resilience.

P6c – Digital feeding: data-driven feeding to optimise grain allocation in pasture-based herds

Feed costs remain one of the largest expenses in Australian dairy systems, making efficient use of supplementary concentrate critical for profitability. This subproject explored how artificial intelligence can support more precise, individualised feeding decisions in pasture-based herds. Using machine learning models to predict milk yield from routinely collected cow data, and optimisation algorithms to adjust daily concentrate levels, the work demonstrated that data-driven allocation can improve feed-use efficiency without increasing total daily grain input. Across two studies, AI-based optimisation consistently increased herd-level milk yield by around 8%, highlighting the value of accounting for cow-to-cow variability rather than relying on flat-rate feeding.

These findings show strong potential for integrating machine-learning tools and optimisation algorithms into digital feeding systems to support more profitable and sustainable concentrate-use strategies in pasture-based dairying.

The P6 project delivered strong research outcomes, including two completed PhD theses and six peer-reviewed publications in high-impact international journals, with another manuscript currently under review. The work reached more than 3,810 people through about fifteen conference presentations in Australia and internationally, and further engaged industry through farmer meetings, interviews and media articles. Project results were also presented to fourth-year Bachelor of Animal and Veterinary Bioscience students at the University of Sydney as real-world examples of data-driven research applied to industry challenges, contributing to future workforce capability.

2. Project Overview

Item	Description
Project Title	Future Systems – Dairy Da.T.A
Funding Body	Dairy UP
Dairy UP Project	P6
Project Duration	2021-2026
Lead Organisation	The University of Sydney
Project Lead	Prof Cameron Clark
Key Collaborators	Charles Sturt University (CSU), Dairy commercial farms, CowManager, smaXtec, DataGene, Scibus, DairyBio

3. Abbreviations

AI – Artificial Intelligence
AliA – Artificial Intelligence in Agriculture
BOM — Bureau of Meteorology
COMPAG — Computers and Electronics in Agriculture
CSU — Charles Sturt University
DIM — Days in Milk
HAIM — Hybrid AI-based Model
HS — Heat Stress
LLM — Linear Mixed Model
ML — Machine Learning
MY — Milk Yield
RRM — Random Regression Model
RRT — Reticulorumen Temperature
SAT — Smart Agricultural Technology
THI — Temperature–Humidity Index
USyd — The University of Sydney

4. Project Background and Rationale

The Australian dairy industry faces increasing pressure to improve productivity, sustainability, and resilience. Rising input costs, climate variability, tightening environmental regulation, and competitive global markets are pushing producers and processors to find new ways to extract more value from existing resources. Dairy UP was established to accelerate applied research that directly addresses some of these pressures.

Within this context, the P6 "Future Systems – Dairy Da.T.A" program was funded to explore sensor-enabled, large-scale datasets and develop advanced data-driven approaches to enhance the selection of heat-tolerant cattle and strengthen early-intervention tools for animal health, as well as maximise herd-level milk production through optimised grain allocation in pasture-based herds. These focus areas were selected because they address core constraints on herd resilience and productivity in Australian dairy systems, and because each represents a clear opportunity to translate emerging sensor technologies and large-scale data into practical, on-farm decision tools.

5. Project Objectives

The project aimed to deliver practical, data-driven solutions to help dairy farmers improve herd resilience, animal health and feed efficiency under increasingly variable climatic conditions. The specific objectives were to:

- **Improve understanding of HS** by clarifying key terms and concepts so farmers, advisors and researchers can communicate consistently and make better decisions about heat-abatement strategies.
- **Enhance the use of sensor data on farm** by developing reliable methods to interpret reticulorumen temperature and drinking-behaviour data, improving the accuracy of heat-stress monitoring tools.
- **Identify cows that cope better with heat** by analysing large-scale datasets to understand individual differences in heat response and determine practical indicators that can support future breeding and management decisions.
- **Evaluate simple, on-farm indicators of heat tolerance** such as milk-yield changes, drinking patterns and temperature responses, to help farmers identify animals that are more vulnerable during hot conditions.
- **Develop advanced AI-enabled approaches to support breeding for heat tolerance** by integrating machine learning with statistical modelling to improve the accuracy of identifying heat-tolerant cows without compromising milk production.
- **Maximise herd-level milk production through optimised feed allocation** by developing machine-learning and optimisation tools that allocate grain more efficiently across the herd, improving milk yield without increasing feed costs.
- **Build integrated datasets that support future digital tools** by linking climate, production, behaviour and physiological data to enable next-generation decision-support systems.
- **Share practical insights with industry** through publications, presentations, farmer meetings and teaching activities to support adoption and build capability across the sector.

6. Subproject P6a – Resilient cattle (heat tolerance)

Research team: Cameron Clark (CSU), Yani Garcia (The University of Sydney - USyd), Anna Chlingaryan (USyd), Peter Thompson (USyd), Alice Shirley (USyd)

6.1 Background

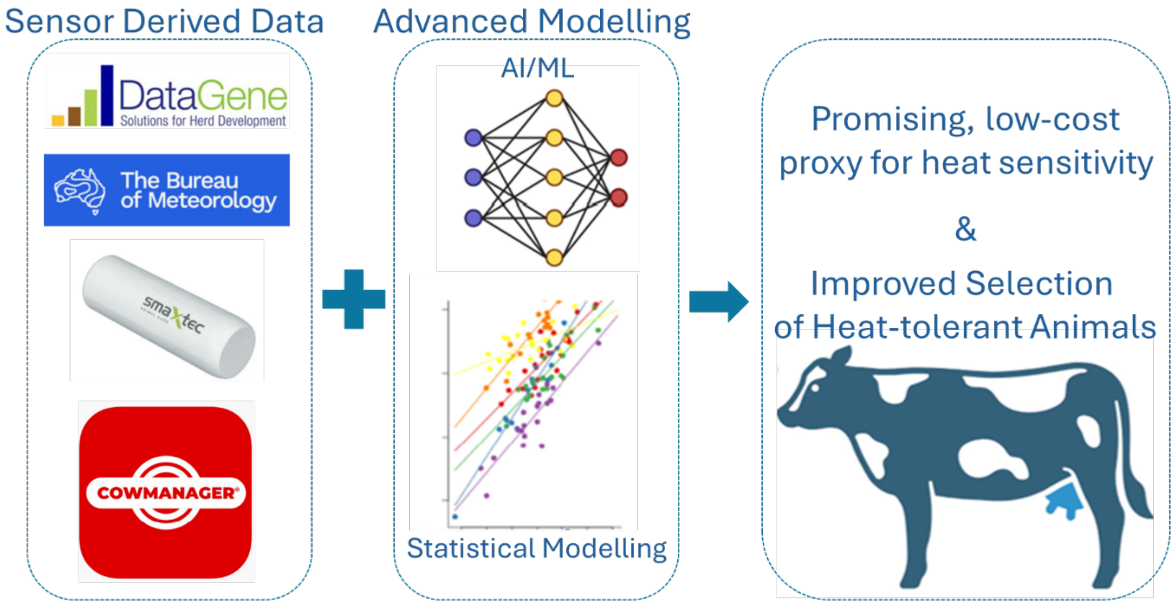
Dairy farming in Australia spans diverse production environments that are increasingly exposed to climate variability and rising HS risk. Heat stress reduces feed intake, milk yield, fertility and cow comfort, and can compromise animal welfare. Cattle respond to heat load through a range of behavioural and physiological mechanisms aimed at restoring thermal balance, but these responses vary widely among individuals. Understanding this diversity is essential for developing climate-smart dairy systems.

Recent advances in sensor technologies, particularly reticulorumen temperature (RRT) boluses, have created new opportunities to monitor physiological responses to heat in real time. However, interpreting these data is challenging. Drinking events cause rapid, pronounced drops in reticulorumen temperature, masking true core-temperature patterns and limiting the reliability of HS detection tools. Without robust methods to distinguish behavioural effects from physiological responses, sensor data cannot be confidently used for on-farm decision-making.

At the same time, the dairy industry lacks consistent terminology for describing HS responses. Terms such as tolerance, resistance, resilience and susceptibility are used inconsistently across research and advisory contexts, creating confusion and limiting the translation of scientific findings into practice.

There is also limited understanding of the extent to which cows differ in their sensitivity to heat load. Some animals show sharp increases in core temperature or declines in milk yield at relatively mild THI levels, while others maintain stable performance. Identifying this diversity is critical for both management and breeding.

Finally, while genetic selection for heat tolerance is recognised as a long-term strategy, current phenotyping approaches rely on established statistical models. Artificial intelligence (AI) and Machine Learning (ML) methods offer new opportunities to improve the accuracy and efficiency of heat-tolerance phenotyping (Fig. 1).



6.2 Objectives

1. Standardise HS terminology to improve communication and decision-making across the dairy sector.
2. Improve interpretation of sensor data by reliably separating drinking events from true core-temperature responses.
3. Identify variation in cow heat-stress responses using large-scale climate, temperature and production datasets.
4. Evaluate practical indicators of heat tolerance such as milk yield, drinking behaviour and temperature changes.
5. Develop AI-enabled heat-tolerance phenotypes to support future breeding and management decisions.

6.3 Materials & Methods

- Data sources:
    - For objectives 2, 3 and 4, the analysis used RRT data collected from 1,429 dairy cows across three pasture-based farms in Victoria, obtained via smaXtec boluses, together with matched climate data. Reticulorumen temperature was recorded every 10 minutes, producing approximately 75 million records. To develop and validate the drinking-event detection model, an additional 28 heifers from the USyd farm were monitored, contributing around 1,000 video-validated drinking events.
    - For objective 5, model development used ~3 million herd-test records (provided by DataGene) from 201,836 cows across 97 NSW herds (2003–2022). These records included daily milk yield, animal age, parity and DIM. The dataset was matched with 20 years of daily THI values (≈7,300 records) from the BOM to support AI-enabled heat-tolerance phenotyping.
- Statistical analysis: A range of statistical models were applied depending on the research aim.
    - Sensor-data processing: Time-series decomposition and threshold-based algorithms were developed to detect drinking events from characteristic temperature-drop patterns. Multiple detection settings were evaluated to ensure reliable separation of drinking events from true core-temperature responses.
    - Heat-response modelling: Mixed models were used to quantify associations between THI and RRT deviation, estimate individual sensitivity to heat load, and assess the influence of baseline THI conditions.
    - Phenotypic-indicator evaluation: Relationships among RRT, MY and drinking frequency were assessed using mixed models and slope-based analyses to identify potential proxy traits for heat tolerance.
    - AI-based phenotyping: A hybrid AI-statistical model was developed by integrating ML algorithms with LLMs to estimate heat-tolerance phenotype based on MY decline above THI threshold.

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6.4 Key Findings

- **Heat-stress terminology requires standardisation.** A critical review revealed major inconsistencies in the use of *tolerance*, *resistance*, *resilience* and *susceptibility*.
- **Drinking events can be accurately detected from sensor data.** A transparent, high-accuracy model (F-score = 0.99) was developed to identify drinking events (Fig. 1), improving interpretation of RRT and the accuracy of heat-stress monitoring tools.
- **Seasonal variation in drinking behaviour reflects underlying physiological diversity.** Drinking frequency, temperature-drop magnitude and recovery time differed between summer and winter.
- **Cows vary widely in their physiological response to heat.** Reticulorumen temperature increased with THI, but the magnitude of response differed substantially among individuals. Temperature deviations began at THI ≈ 65, suggesting current industry thresholds may underestimate heat load.
- **Drinking frequency influences cooling response.** Cows that drank more frequently showed a smaller temperature drop per drink, indicating reduced cooling efficiency at higher drinking rates (Fig. 2). Individual-animal differences in this relationship were substantial, highlighting variation in how cows regulate core temperature through drinking behaviour.
- **Multiple traits show heat-related variation.** Milk yield, drinking frequency and RRT all responded to thermal deviations, with strong individual differences. Inter-trait correlations confirmed that these measures are interconnected in how cows react to heat (Fig. 3). Drinking frequency emerged as a promising, low-cost proxy for heat sensitivity, offering farmers an early means to identify and support more vulnerable animals.
- **AI improves heat-tolerance phenotyping.** The hybrid AI-based model (HAIM) reduced residual error compared with RRM, improving milk-yield prediction accuracy by 3.56% (Table 1). The RRM and HAIM overlapped in identifying 84% of heat tolerant animals, but the HAIM replaced about 8% of the cows that weren't identified with the statistical method, while accounting for a greater proportion of the total observed variability (i.e. increasing accuracy).

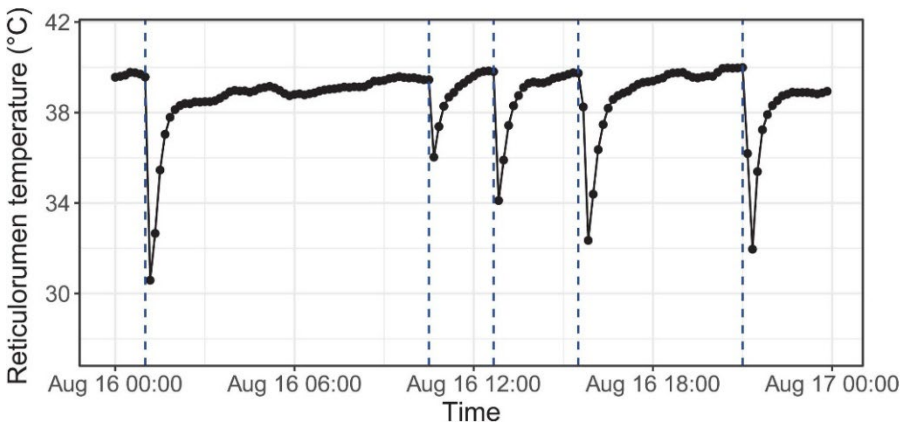

Figure 1 *Synchronisation of raw sensor data (black dots indicate 10-minute interval reticulorumen temperature readings) and manual video annotations (dashed blue lines indicate observed drinking events).*

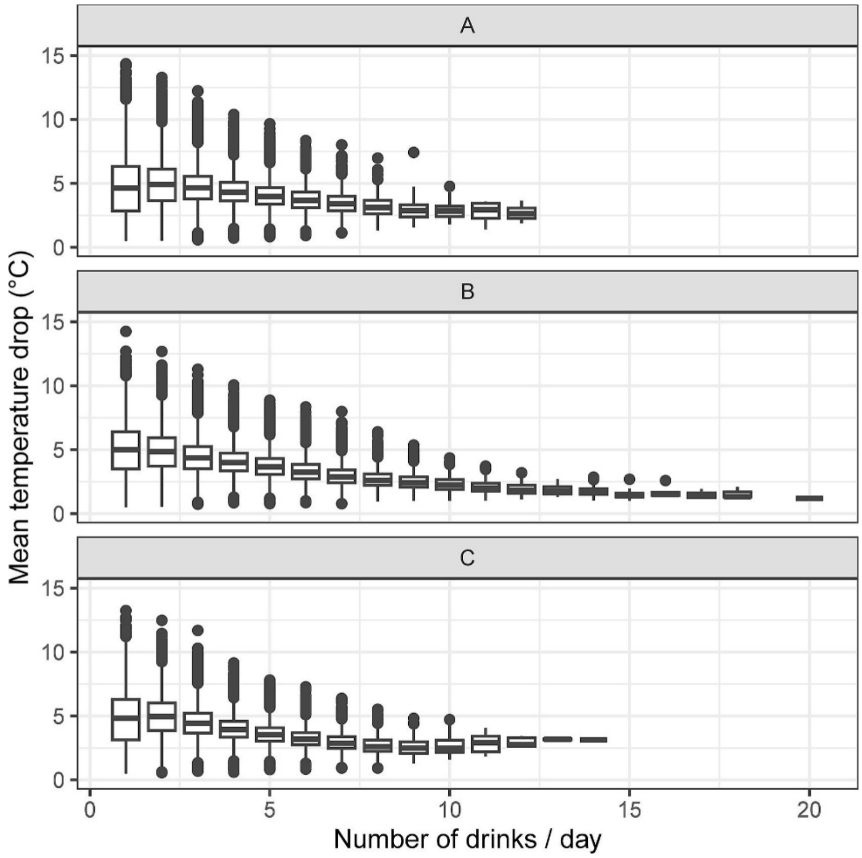

Figure 2 *Association between number of drinks per day and average drop in reticulorumen temperature (°C)*

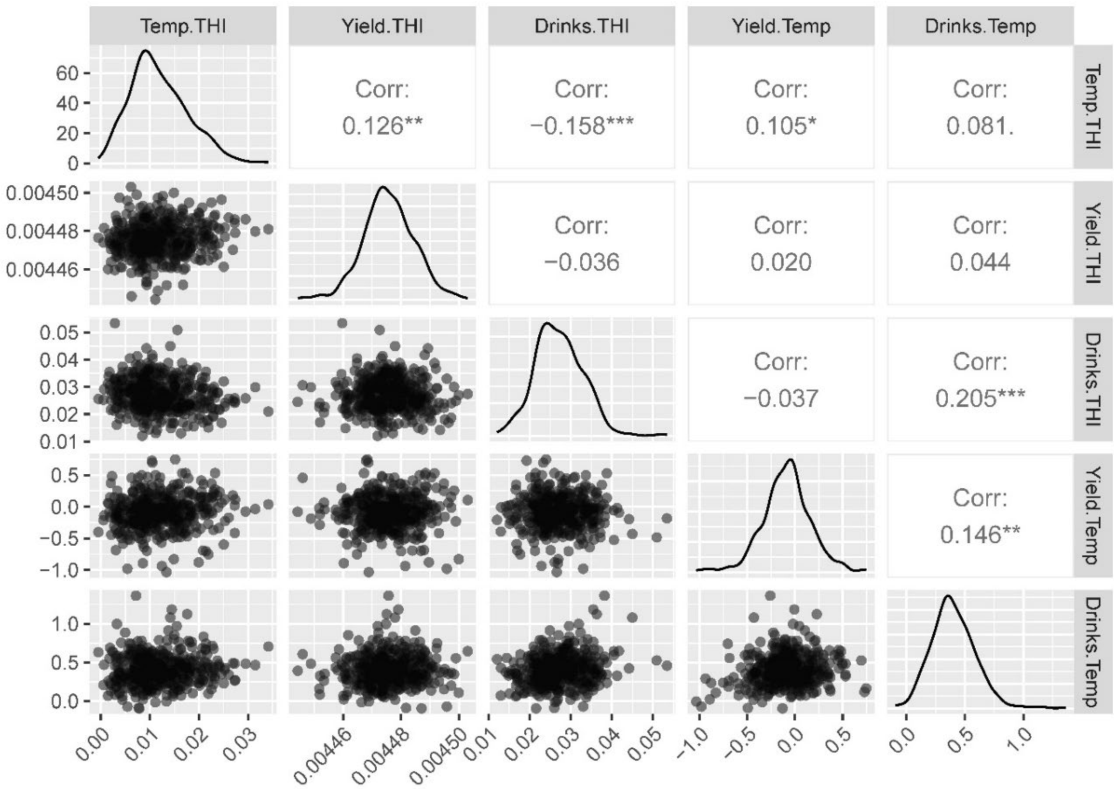

Figure 3 *Generalised pairs plot revealing the association between slopes of Tempdev per change in THImax_dev (Temp.THI), Yielddev per change in THImax_dev (Yield.THI), ndrinkdev per change in THImax_dev (Drinks.THI), Yielddev per change in Tempdev (Yield.Temp), and ndrinkdev per change in Tempdev (Drinks.Temp) for each individual.*

Table 1 Model performance comparison - key findings

	HAIM vs RRM
Predictive ability	
Statistical performance metric: SD of residuals (L/cow/test date)	3.25 for HAIM vs 3.37 for RRM, representing 3.56 % reduction of milk yield estimation error
Estimated random slopes / intercepts	High association between the random slopes (R^2 = 0.93) and intercepts (R^2 = 0.98) showing general agreement between the models with HAIM outperforming RRM (as evidenced by the HAIM's lower SD of residuals)
Practical relevance	
Heat-tolerant cattle classification	• Heat-tolerant: HAIM re-classified ~8 % of cattle in the sense of heat tolerance • High-producing and heat-tolerant: 18.1 % (of the total cow population) by HAIM and 18.24 % by RRM • Agreement RRM and HAIM: ~84 % out of the identified high-producing and heat-tolerant cattle
Importance of both traits: random slopes and intercepts	Negative association between random slopes and random intercepts estimated by both models

6.5 Applications & Impacts

The findings have direct relevance for improving heat-stress monitoring, management and long-term selection of heat-tolerant cattle.

- **Improved heat-stress monitoring**: Reliable detection of drinking events supports more accurate interpretation of temperature patterns by distinguishing true heat-stress responses from cold-water effects. This capability can already inform more targeted heat-abatement decisions within existing smaXtec systems. Although P6a incorporated climate data for research analysis, fully automated early-warning platforms that integrate climate, behaviour and predictive modelling will require further development before commercial release.
- **Better identification of vulnerable cows:** Understanding individual variation in heat responses can already help farmers recognise which cows are more vulnerable during hot conditions and prioritise shade, cooling and feeding strategies accordingly. While this provides immediate, practical value, developing automated vulnerability scores or decision-support tools that classify cows by heat-risk level will require further validation across farms and seasons before wider industry adoption.

- **Foundations for heat-tolerance breeding:** AI-enabled phenotyping and validated proxy traits provide a pathway for incorporating heat tolerance into breeding programs without compromising production.
- **Enhanced welfare and climate resilience:** By revealing meaningful diversity in physiological responses to heat, P6a provides insights that farmers can already use to support more welfare-focused management during hot conditions. These findings also contribute to longer-term progress toward climate-resilient dairy systems, where individual animal responses are incorporated into breeding, management and decision-support frameworks as they mature.
- **Improved decision-support tools:** Integrated datasets linking climate, physiology and production create a foundation for next-generation digital tools that support real-time management decisions.

6.6 Key Outputs

- A high-quality dataset integrating climate records, sensor measurements, drinking behaviour and milk production assembled across multiple farms. The structure enables seamless addition of new herds, supporting continuous expansion and long-term system learning.
- A high-accuracy method was developed and validated to identify drinking events from RRT data collected via smaXtec sensors, improving interpretation of physiological responses to heat.
- A methodology was developed that integrates AI with current statistical approaches, improving the selection of heat-tolerant cattle.
- Multiple phenotypic indicators were identified that respond consistently to thermal load, providing complementary insights into individual heat-tolerance profiles.
- The project contributed to ongoing DairyBio efforts to extend the Heat Tolerance ABV by incorporating sensor-based phenotypic indicators, supporting identification of animals that maintain production under hot and humid conditions.
- Five peer-reviewed publications in high-impact Q1 journals such as *Computers and Electronics in Agriculture, Smart Agricultural Technology, Scientific Reports*, and *Animal*
- Conference presentations, industry reports, and media interviews and articles disseminated findings to researchers, advisors and producers.

6.7 Future Research Opportunities

Building on the advances made in sensor interpretation, physiological characterisation and AI-enabled phenotyping, several opportunities remain to further strengthen heat-tolerance research and accelerate translation into breeding and management tools. These opportunities focus on deepening biological understanding, improving prediction accuracy and ensuring practical on-farm application.

- **Genomic marker discovery:** Identify genetic variants associated with heat-tolerance phenotypes derived from sensor and AI models.
- **Refinement of THI thresholds:** Develop region- and breed-specific thresholds based on physiological data rather than historical assumptions.
- **Integration into commercial decision-support tools:** Embed drinking-event detection and heat-response modelling into farm-management platforms.
- **Validation of proxy traits:** Confirm the utility of drinking frequency and MY slopes as practical indicators of heat sensitivity.
- **Development of amelioration strategies:** Use sensor-derived insights to design targeted cooling, feeding and management interventions.
- **Long-term selection strategies:** Evaluate the economic and production impacts of selecting for heat tolerance across different herd structures and environments.

7. Subproject P6b – Resilient cattle (health)

7.1 Background

Improving the resilience and health of dairy cattle requires earlier identification of emerging disorders than is possible through visual observation alone. Subproject P6b focuses on establishing the foundations for early-intervention health sensing by integrating advanced sensor technologies with detailed farm health and production records.

Health disorders both in the periparturient period and throughout lactation are an important factor impacting animal welfare and production in both the immediate and long term and are rarely observed in isolation within the dairy industry. The incidence of health disorders, including metabolic and reproductive illness, predominantly occur within the first month post calving. Production illnesses, including mastitis and lameness, generally occur throughout lactation and after drying off. Understanding the interconnected relationship between health disorders in conjunction with relevant risk factors is an essential aspect of developing prediction of potential illness with high sensitivity and specificity. This in turn enables earlier detection of disease and more timely interventions put in place to reduce both the incidence and severity of impact of the health disorders.

7.2 Objectives

- **Establish a strategic data partnership** with Moxey Farms to secure access to their large, year-round calving herd and associated health, production and management records, enabling high-resolution analysis of disease patterns in a commercial setting.
- **Integrate multi-source sensor and farm data** by linking outputs from wearable and in-body sensing systems with harmonised health-event and production datasets to create a reliable, research-ready database for modelling early-intervention indicators.
- **Quantify health-event patterns** by characterising the incidence, timing and production impacts of major metabolic, reproductive and production-related disorders across the periparturient period and throughout lactation, using harmonised herd-management and production records.
- **Develop predictive risk models** that identify animals at elevated likelihood of developing key health disorders, and map the relationships between these conditions, enabling earlier detection and more targeted intervention strategies.

7.3 Materials & Methods

- **A retrospective analysis using herd-level production and management records from a large year-round calving dairy herd.** Data were collected for 3,154 primiparous and multiparous cows over a six-month period (1 August 2022 – 31 January 2023). Health events were categorised into metabolic disorders (milk fever, displaced abomasum, ketosis, gut illness), reproductive disorders (retained foetal membranes, metritis), mastitis, and other production-related conditions such as respiratory disease, lameness and foot-rot. These events were harmonised into consistent categories to support comparative analysis. A descriptive epidemiological assessment was conducted to quantify event frequency and timing relative to calving, followed by a Kruskal–Wallis test to evaluate differences in temporal patterns between disorder groups.

- **Extension to a larger dataset:** Incorporate cows from multiple farms over an 18-month period (1 August 2022 – 31 January 2024), enabling assessment of cross-herd variation, seasonal influences and broader disease patterns. The expanded dataset also includes disorders occurring in late pregnancy to provide a more complete representation of the periparturient interval. Planned analyses include descriptive comparisons of incidence across herds and evaluation of differences in post-calving timing between disorder categories, forming the basis for subsequent predictive-model development.

7.4 Key Findings

- **Robust data partnership established** with Moxey Farms, enabling access to their large-scale herd health, production and management records for comprehensive analysis of disease patterns under commercial conditions.
- **Validated multi-source dataset** created by linking CowManager sensor outputs with harmonised farm health events and DataGene production records, providing a reliable, research-ready foundation for developing early-warning indicators.
- **Early postpartum identified as highest-risk period:** Analysis of 3,154 cows recorded 142 post-calving health events, with 40% (57/142) occurring within the first seven days after calving (Fig. 5). Event timing differed significantly between disorder categories ($P = 4.5 \times 10^{-7}$), confirming that metabolic, reproductive and production-related illnesses follow distinct temporal patterns and warrant further investigation using the larger multi-farm dataset

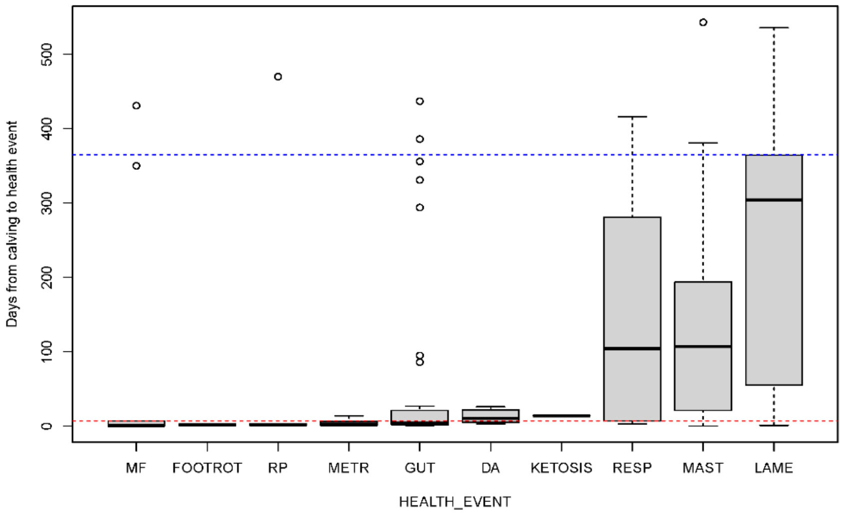

Figure 4 *Number of health events by category relative to number of days post-calving. The red dotted line indicates 7 days post calving, and the blue dotted line indicates 365 days post-calving. MF represents milk fever (hypocalcaemia), FOOTROT represents foot-rot, RP represents retained placenta/foetal membranes, METR represents metritis, GUT represents gut illness, DA represents displaced abomasum, KETOSIS represents clinical ketosis, RESP represents respiratory illness, MAST represents clinical mastitis, and LAME represents lameness requiring treatment.*

The subproject generated a peer-reviewed abstract presented at the ADSS 2024. Subproject activities were delayed due to health-related suspension of the PhD candidature.

8. Subproject P6c — Digital feeding

Research team: Yani Garcia (USyd), Anna Chlingaryan (USyd), Cameron Clark (CSU), Blessing Azubuike (USyd), Dr Martin Correa-Luna (USyd)

8.1 Background

Feed costs account for 40–60% of milk production expenses in Australian dairy systems, making efficient use of supplementary concentrate a major driver of farm profitability. Despite this, most pasture-based herds still rely on flat-rate feeding, where all cows receive similar concentrate levels regardless of their individual production potential, stage of lactation, or response to heat and pasture variability. This approach overlooks substantial cow-to-cow differences in feed efficiency and milk yield response.

Advances in ML and optimisation algorithms now offer the opportunity to move beyond flat-rate feeding toward individualised, data-driven concentrate allocation. By predicting each cow's expected milk yield from routinely collected data, and then optimising grain distribution across the herd, digital feeding systems can increase total milk production without increasing total daily concentrate use.

Subproject P6c evaluated this opportunity through two complementary studies. Both demonstrated that integrating ML prediction models with optimisation algorithms can increase herd-level milk yield by approximately 8%, highlighting the value of accounting for individual variability in pasture-based systems. These results provide a strong foundation for future digital feeding tools that support more profitable and sustainable concentrate use strategies.

8.2 Objectives

- Identify opportunities to improve concentrate use efficiency in pasture-based dairy herds.
- Develop data-driven methods to adjust grain allocation based on individual cow needs.
- Demonstrate how digital feeding strategies can increase herd-level milk production without increasing feed costs.
- Evaluate different digital optimisation approaches to determine which are most effective and practical for on-farm use.
- Provide a foundation for future digital feeding tools that support more profitable and sustainable concentrate use.

8.3 Materials & Methods

- **Data sources:** As the project included two complementary studies, it analysed large datasets from two commercial pasture-based dairy herds. The first pre-processed dataset contained 456,078 daily records from 1053 cows, including MY, concentrate intake, DIM, parity, breed and stage of lactation, matched with local climate information (temperature, humidity and vapour pressure). The second dataset included 32,504 records from 130 Holstein-Friesians for model development, with an additional 7,371 records from 81 cows used to test digital feeding strategies.
- **Data analysis to understand herd feeding patterns:** Milk yield, concentrate intake and animal characteristics were analysed to identify how cows differ in their response to grain. This included grouping cows with similar production levels and highlighting where flat-rate feeding may under- or over-supply concentrate.

- **Machine Learning for MY prediction:** Routine farm data (MY, DIM, parity, concentrate intake and weather) were used to build and evaluate sixteen ML models that estimate how much milk each cow is likely to produce under different feeding levels. These prediction models provided the foundation for testing alternative feeding strategies.
- **Optimisation tools for testing digital feeding strategies:** Optimisation tools, such as evolutionary algorithms and Dirichlet-Rescale algorithm with Monte Carlo simulation, were used to explore how concentrate could be redistributed across the herd without increasing total grain use. Feeding limits reflected normal farm practice, including minimum and maximum concentrate levels and limits on daily changes.
- **Comparing feeding approaches:** The performance of digital feeding strategies was compared with the farm's existing rule-based or flat-rate feeding system. This allowed the project to quantify potential improvements in milk production and feed efficiency under real-world conditions.

8.4 Key Findings

- **Digital feeding predicted an increase in herd-level milk production of 6.6–8.8% without increasing grain use.** The best-performing optimisation method (NSGA-II) consistently delivered around 8.6% more milk, demonstrating clear potential for improving feed efficiency on pasture-based farms (Fig. 7).
- **Cows differ widely in feed efficiency.** Milk produced per kg of concentrate ranged from 0.17 to 15.8 L/kg, showing that some cows convert grain into milk far more effectively than others. This variation highlights the limitations of flat-rate feeding and the opportunity to target grain to cows that respond best.
- **Machine learning-based milk yield prediction models performed reliably using routine farm data:** Machine learning models built from MY, DIM, parity, concentrate intake and weather explained around 61% of the variation in daily MY on *unseen* data. Days in milk and concentrate intake were the strongest predictors, confirming that accurate predictions can be made without liveweight data, which is often unavailable in pasture-based systems.
- **Individualised feeding outperformed the farm's existing feeding rules:** Digital feeding strategies shifted grain from low-responding cows to high-responding cows while respecting practical limits (e.g., minimum/maximum concentrate levels and daily change limits). This resulted in higher total milk production without extra feed costs.
- **Environmental conditions had only a small direct effect on milk yield:** Weather variables such as temperature and humidity added only minor improvements to prediction accuracy. Cow-level factors remained the main drivers of milk response, meaning farms can adopt digital feeding without needing additional sensors or climate monitoring equipment.
- **Digital feeding systems are practical for commercial pasture-based herds:** The approach worked with existing in-parlour feeding systems and used data already collected on most farms. Optimisation respected real-world feeding constraints and ran consistently across multiple days and seasons, demonstrating strong potential for on-farm adoption.

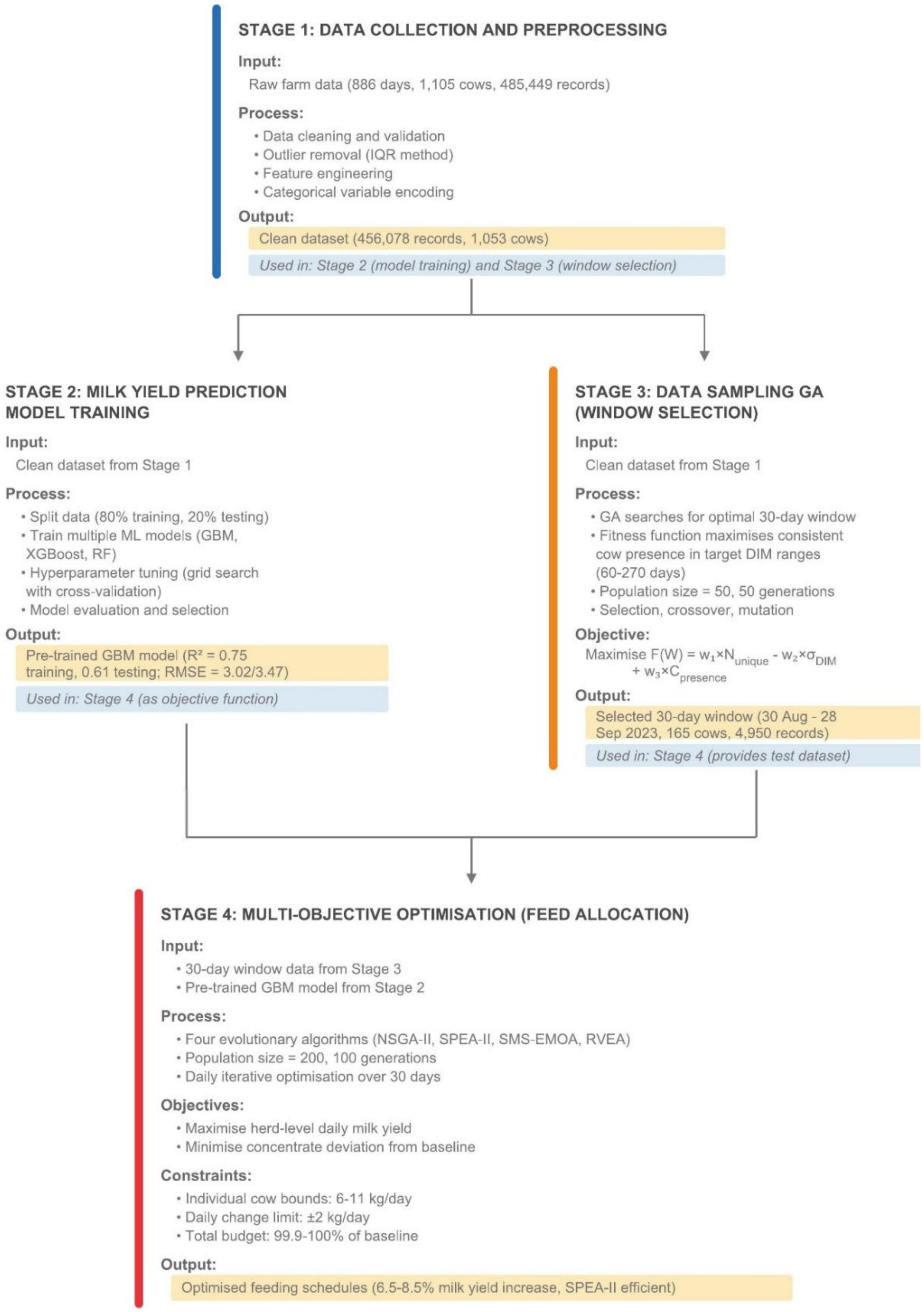

Figure 5 *Methodological framework showing the four-stage workflow. Stage 1: Data preprocessing; Stage 2: Machine learning model training (GBM selected as best model); Stage 3: Data Sampling GA for optimal 30-day window selection (165 cows); Stage 4: Multi-objective optimisation using evolutionary algorithms integrated with the pre-trained model. Arrows indicate data flow between stages, demonstrating how the Data Sampling GA (Stage 3) serves as a data selection tool for testing the optimisation algorithms (Stage 4).*

8.5 Applications & Impacts

- **Farm-level benefits:** Data-driven concentrate allocation provides a potential practical way for farmers to increase milk production by 6.6–8.8% without increasing total grain use. By shifting concentrate toward cows that respond best, farms can improve feed conversion efficiency, reduce waste, and lift overall herd performance. This approach supports more profitable and resilient feeding decisions in pasture-based systems.
- **Environmental and sustainability impacts:** Improving concentrate use efficiency reduces the amount of grain that is fed without contributing to milk output, lowering the environmental footprint of production. More efficient feeding supports reduced emissions intensity per litre of milk and aligns with sustainability expectations from processors, retailers and consumers.
- **Operational and management impacts:** The digital feeding approach works with existing in-parlour feeding systems and relies on data already collected on most farms. This means farmers can adopt precision feeding without major infrastructure changes. The system respects practical feeding limits, making it suitable for day-to-day use in commercial herds.
- **Technical and innovation impacts:** The successful development of ML models capable of predicting milk yield from routine farm data (without requiring liveweight) removes a major barrier to adoption in pasture-based systems. The integration of optimisation tools demonstrates that individualised feeding can be automated and scaled, providing a foundation for future digital decision-support tools.
- **Industry-wide opportunities:** The project provides clear evidence base for moving beyond flat-rate feeding. As digital feeding becomes more common, processors and advisory services can support farmers to improve feed efficiency, reduce production variability, and enhance the profitability of grain use across the sector.

8.6 Outputs

- **High-quality datasets linking production, feeding and climate data:** Compilation and preprocessing of two large commercial herd datasets, including over 456,000 cow-day records in Study 1 and 32,504 records in Study 2, providing robust evidence base for understanding concentrate use efficiency in pasture-based systems. The data-processing framework developed in this project is directly transferable to other commercial farms, meaning additional herds can be incorporated into the database to expand model accuracy, support benchmarking, and enable broader industry adoption.
- **Characterisation of cow-level variability in concentrate response:** Identification and quantification of substantial differences in feed efficiency between cows, providing a foundation for targeted concentrate allocation and future precision-feeding tools.
- **Predictive and optimisation tools for precision feeding:** Development and evaluation of sixteen MY prediction models using routine farm data, together with implementation of optimisation approaches demonstrating proof-of-concept for individualised concentrate allocation in pasture-based herds.
- **Peer-reviewed scientific contributions:** Publication of two peer-reviewed papers in high-impact journals (*Artificial Intelligence in Agriculture* (AIiA) and *Smart Agricultural Technology* (SAT)), along with conference presentations detailing the modelling framework, optimisation methods and implications for precision feeding in pasture-based dairy systems.

8.7 Future Research Opportunities

This subproject established proof-of-concept for a data-driven precision-feeding tool using commercial farm datasets, creating a strong foundation for further scientific development and industry adoption. Its key limitation is the absence of individual health indicators, forage intake and high-resolution pasture nutritional value data, which constrains the precision of cow-level response modelling. Building on this foundation, several opportunities exist to enhance the scientific robustness, practical utility and industry uptake of the approach.

- **Expansion of datasets and refinement of response modelling:** Incorporating additional commercial herds from diverse regions and production systems and extending the modelling framework to capture dynamic changes in feed efficiency across lactation, seasons and management conditions. Addressing current data gaps (individual health, forage intake and pasture nutritive value) would substantially enhance model accuracy and biological interpretability.
- **Testing the effectiveness of digital feeding on commercial farms:** this would require a well-designed experiment to address factors such as system type, region, pastures and concentrate types, etc.
- **Future industry engagement and knowledge transfer:** Further collaboration with farmers, advisors and technology providers to demonstrate the tool in real-time commercial settings, support adoption pathways, and facilitate integration into existing farm decision-support systems.
- **Economic modelling of return on investment:** Quantifying the financial benefits of precision-feeding strategies under varying milk prices, feed costs and pasture conditions to demonstrate the economic value proposition for commercial dairy farms.
- **Development of farmer-friendly decision-support interfaces:** Designing intuitive, user-centred interfaces that present model outputs in clear, actionable formats, enabling farmers to apply precision-feeding recommendations in daily management.

9. Project-wide Disseminations

The project has produced two PhD theses and six peer-reviewed publications in high-impact international journals, including *Artificial Intelligence in Agriculture* (Impact Factor (IF): 12.4), *Computers and Electronics in Agriculture* (IF: 8.9), *Smart Agricultural Technology* (IF: 5.7), *Animal* (IF: 4.2), and *Scientific Reports* (IF: 3.9), accumulating 12 citations to date (Table 2). These are leading Q1 journals in digital agriculture, sensor technologies and animal science, reflecting the scientific quality and international reach of the project's outputs.

Findings were also disseminated through multiple international and national conference presentations and industry-facing events, ensuring engagement across research, advisory and producer communities. This included presentations at the American Dairy Science Association (ADSA) Annual Meeting in the USA, as well as range of Australian and New Zealand forms, collectively reaching an estimated audience of more than 3,810 people (Table 3). A list of these outputs is provided in Tables 3 and 4 (Annexes).

In addition, the P6 outcomes were also presented to fourth-year Bachelor of Animal and Veterinary Bioscience students at the University of Sydney as real-world examples of data-driven research applied to industry challenges, contributing to future workforce capability.

Table 2. *Peer-reviewed publications in international journals.*

Author	Title	Journal	Year Published	Citations (to May 26)
Azubuike et al. (2026)	Leveraging artificial intelligence and evolutionary algorithms for optimising cow supplementation and milk production	AliA	2026	-
Shirley et al. (2026)	Probing the diversity in dairy cattle reticulorumen temperature for adaptation selection	SR	2026	-
Chlingaryan et al. (2025)	An AI-based hybrid model for dairy cattle heat tolerance phenotype	SAT	2025	1
Azubuike et al. (2025)	A data-driven approach for optimising supplement allocation to individual lactating dairy cows in pasture-based systems	SAT	2025	1
Shirley et al. (2025)	The diversity in dairy cattle reticulorumen temperature: Identifying water intake events	COMPAG	2025	6
Shirley et al. (2024)	Review: Ruminant heat-stress terminology	Animal	2024	4

10. Conclusions and Recommendations

The P6 Future Systems – Dairy DaTA project has delivered important progress across two interconnected areas of dairy research, generating evidence-based findings with clear, pathways to industry application.

P6a demonstrated that advances in sensor interpretation, physiological characterisation and AI-enabled phenotyping improve the reliability of heat-stress monitoring and support the development of more effective management and breeding approaches. Successful identification of drinking events from raw sensor data enabled large-scale analyses showing substantial individual variation in heat responses, with drinking frequency emerging as a practical, low-cost indicator of heat sensitivity. The AI-based phenotyping model further improved the accuracy of identifying heat-tolerant animals compared with traditional statistical approaches. The outcomes of P6a provide a strong foundation for data-driven accurate heat-stress detection, better identification of vulnerable cows, and future breeding strategies aimed at improving herd resilience under increasing climate variability. A key next step is to extend this work through ongoing collaboration with DairyBio to integrate sensor-derived and AI-enabled phenotypes into genomic selection pipelines.

P6c demonstrated that digital precision feeding can substantially improve concentrate use efficiency in pasture-based dairy herds. By replacing flat-rate feeding with ML-based milk yield predictions and optimisation algorithms, the project showed that herd-level milk production can increase by 6.6–8.8% without raising total concentrate use. The work highlighted large cow-to-cow variation in feed efficiency and confirmed that routine farm data are sufficient to support reliable prediction models. While the approach proved technically feasible and compatible with existing in-parlour feeding systems, further refinement of prediction accuracy and on-farm real-time validation will be required before commercial deployment.

Across the two subprojects, the project has produced several peer-reviewed publications, engaged audiences across Australia and internationally, and built productive industry partnerships, laying a solid foundation for the next phase of research.

Recommendations for future investment should prioritise:

- Development of a national herd-level heat-tolerance phenotype tailored to pasture-based systems, in collaboration with DairyBio, to enable genomic selection that reflects real-world grazing environments.
- Validation of sensor-derived and behavioural indicators across diverse production environments to ensure they are robust enough for incorporation into national heat-tolerance selection and herd-management frameworks.
- Large-scale on-farm trials to evaluate the real-time performance of digital precision feeding systems and quantify their economic benefits under commercial pasture-based conditions.

11. Annexes

Table 3. *Conference presentations, abstracts and other meetings*

uthors	Title	Presentation Type	Conference /Event	Location	Year	Audience
Shirley, A.K.	Revealing and exploiting the diversity in dairy cattle reticulorumen temperature data for heat stress amelioration	Final PhD Presentation (oral)	SOLES HDR Showcase (USYD)	Sydney	**2025**	40
Chlingaryan A.	Artificial intelligence and heat stress	Oral presentation	DRF Symposium	Wollongong	**2025**	150
Shirley A.K.	Association between three phenotypic indicators of heat stress in dairy cattle	Oral presentation	PDF	Christchurch, New Zealand	**2025**	300
Chlingaryan A.	AI for cattle tracking and behaviour identification from video footage	Oral presentation	PDF	Christchurch, New Zealand	**2025**	300
Chlingaryan A.	AI for dairy cattle heat tolerance phenotype	Oral presentation	ADSA, Annual Meeting	Kentucky, USA	**2025**	1000
Azubuike et al	Leveraging artificial intelligence and evolutionary algorithms for optimising cow supplementation and milk production	Abstract/Oral presentation	ADSS	Christchurch, New Zealand	**2024**	150
Shirley A.K.	The diversity in dairy cattle reticulorumen temperature: Correlation with drinking event activity.	Oral presentation	ADSS	Christchurch, New Zealand	**2024**	150
Pearce M.F.	Dairy disease associations: predicting and preventing illness incidence and impact	Oral presentation	ADSS	Christchurch, New Zealand	**2024**	150
Azubuike B.N.	A Data-Driven Approach for Optimising Supplement Allocation to Individual Lactating Dairy Cows in Pasture-Based Systems	Poster presentation (Intermediate PhD)	SOLES HDR Showcase (USYD)	Sydney	**2024**	40
Shirley et al.	The diversity in dairy cattle reticulorumen temperature: Identifying water intake events	Abstract/Oral presentation	ECPLF	Bologna, Italy	**2024**	200

Chlingaryan et al.	An AI-based phenotype for dairy cattle heat tolerance	Abstract/Oral presentation	ECPLF	Bologna, Italy	**2024**	200
Shirley et al.	The diversity in dairy cattle reticulorumen temperature: Exploring the influence of temperature humidity index.	Abstract/Oral presentation	EAAP Annual Meeting	Florence, Italy	**2024**	300
Shirley et al.	The diversity in dairy cattle reticulorumen temperature: Identifying variability in drinking behaviour	Abstract/Oral presentation	WAAFL	Florence, Italy	**2024**	200
Shirley A.K.	Heat stress – findings and considerations for design.	Oral presentation	Raising the Roof	Sydney	**2024**	50
Shirley A.K.	Hot Cows, Cool Solutions	Oral presentation	Thesis competition (USYD)	Sydney	**2023**	60
Cameron C.E.F.	P6 – Resilient Cattle	Farmer meeting presentation	Dairy UP Roadshow	Bega and Cobargo	**2023**	30
Shirley A.K.	Development of a threshold model to isolate and investigate water intake in dairy cattle fitted with a reticuloruminal sensor.	Oral presentation	DRF Symposium	Camden	**2023**	150
Shirley et al.	An exploratory analysis of rumen temperature for three dairy herds in Australia: a potential path for GHG emission reduction	Abstract/Oral presentation	International Symposium on the Nutrition of Herbivores	Florianopolis, Brazil	**2023**	200
Shirley A.K.	Revealing and exploiting the diversity in dairy cattle core body temperature data for heat amelioration	Oral presentation (Introductory PhD)	SOLES HDR Showcase (USYD)	Sydney	**2023**	40
Cameron C.E.F.	Better milk and dairy beef markets	Oral presentation	DRF Symposium	Sydney	**2022**	100

Table 4. *Technical reports, pamphlets, published material and other media engagements*

Authors	Title	Place Published	Year
Cameron C.E.F. & Chlingaryan A.	P6a Resilient cattle (heat tolerance)	Dairy UP Website	2026
Cameron C.E.F.	P6: Future Systems – Dairy DaTA	Dairy UP Website	2023