

Measuring Methane Emissions from the Tasmanian Institute of Agriculture Dairy HIGH2 Farmlets

Final Report

*Producer Demonstration Site Host
Agreement between the Tasmanian
Institute of Agriculture (TIA) and Zero
Net Emissions Agriculture Cooperative
Research Centre (ZNE-Ag CRC)*



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1. Executive Summary

1.1 Overview

This report summaries the outcomes of the Producer Demonstration Site Host Agreement between the Tasmanian Institute of Agriculture (TIA) and the Zero Net Emissions from Agriculture Cooperative Research Centre (ZNE-Ag CRC), delivered at the TIA Dairy Research Facility (TDRF) between October 2025 and March 2026. Enteric methane emissions from cows enrolled in the Dairy HIGH2 (short for 'high integrity grass-fed herds') farmlet trial were quantified using GreenFeed Units and compared with estimates derived from National Greenhouse Gas Inventory (NGGI) methodology. The report also details attendance and feedback from the TDRF Open Day and includes a fact sheet summarising key findings for producers as an appendix.

1.2 Background and Purpose

TIA, in partnership with Dairy Australia, leads the Dairy HIGH2 program, which compares four high-quality pasture-based farmlet systems (F1-F4) varying in pasture mixes and amounts of synthetic nitrogen fertiliser. This ZNE-Ag CRC-funded study extended Dairy HIGH2 by measuring methane production, yield, and intensity from these farmlets, with the purpose of improving our understanding of emissions and validating emissions outcomes in pasture-based dairy systems. GreenFeed units were deployed across two measurement rounds (Deployment 1: F1, F4; Deployment 2: F2, F3) and methane data were linked to individual milk production and composition data, alongside body weight and condition score records and dry matter intake back-calculations.

1.3 Key Findings

On average, cows measured in first deployment period produced more methane than cows in the second, which may reflect a seasonal or diet-related effect. Within deployment periods, no effect of farmlet on methane emissions was observed. Methane emissions exhibited a distinct diurnal pattern, consistent with daily fluctuations in feeding behaviour and rumen fermentation. Methane measurements were also consistent within individual cows, with higher-producing cows generally producing more methane. Emissions were lower than NGGI estimates during early summer but consistent with estimates during late summer/early autumn, coinciding with reducing pasture quality and silage supplementation.

Key take-home messages:

- 1. Higher-producing cows produce more methane.***
- 2. Methane emissions vary with season and time-of-day.***
- 3. Methane yields were generally consistent with values reported in the National Greenhouse Gas Inventory, although they tended to be slightly lower for animals grazing high-quality pastures.***
- 4. Farmlets achieved lower emission intensities than industry benchmarks.***
- 5. Producers are interested in emissions monitoring and emerging methane measurement technologies.***

1.4 Limitations and Conclusions

GreenFeed deployment periods were confounded with farmlet (F1/F4 measured only in Deployment 1; F2/F3 only in Deployment 2). As such, farmlet-specific methane differences cannot be statistically separated from deployment period or seasonal effects and are reported descriptively rather than as validated treatment comparisons. Nevertheless, the study successfully generated a dataset that can inform future emissions validation work on improved pasture systems. Differences between observed and estimated methane production suggests current NGGI methodology may overestimate emissions in pasture-based cows fed a high-quality diet. Overall, these findings highlight the importance of cow- and diet-related influences on methane production, and their relevance to refining emissions accounting frameworks in modern pasture-based dairy systems.

2. Main Report

2.1 Abstract

Enteric methane (CH_4) emissions from dairy cattle represent a major component of agricultural greenhouse gas (GHG) emissions, yet uncertainties remain regarding their magnitude under high-quality pasture-based systems. This study quantified enteric CH_4 emissions from lactating dairy cows across four irrigated farmlets (F1– F4) in Tasmania and compared measured values with estimates derived from the Australian National Greenhouse Gas Inventory (NGGI). The farmlets differed in pasture composition, nitrogen fertiliser inputs, and stocking rate, but all were based on high-quality perennial ryegrass–white clover systems. Methane emissions were measured using GreenFeed systems over two deployment periods. Mean daily CH_4 production ranged from 387 to 481 g CH_4 /cow/day across farmlets, with higher emissions observed during the later summer deployment (Deployment 2 vs Deployment 1: $\Delta = 57$ g CH_4 /day; Welch's $t(31.3) = -2.96$, $p = 0.006$). Methane yield varied from 17.4 to 22.2 g CH_4 /kg dry matter intake (DMI), while methane intensity ranged from 11.0 to 15.3 g CH_4 /kg energy-corrected milk (ECM). Emissions were consistently lower than NGGI predictions during the early summer measurement period (by ~13%) but aligned more closely with inventory estimates later in the season when pasture quality declined and silage supplementation was introduced. After accounting for deployment period, methane production was positively associated with ECM ($\beta = 8.04$, $\text{SE} = 2.11$, $p < 0.001$). A clear diurnal pattern was observed, with peak enteric methane emissions occurring following milking and feeding events. Accounting for diurnal variation had minimal impact on farmlet comparisons. At the whole-farm scale where all farm GHG emissions were accounted for using the Australian Dairy Carbon Calculators, emissions intensity ranged from 0.61 to 0.66 kg $\text{CO}_2\text{-e}$ /kg fat and protein corrected milk, with enteric CH_4 as the dominant source. These findings demonstrate that enteric CH_4 emissions in high-quality grazing systems can be lower than inventory estimates, particularly under highly digestible pasture conditions, and highlight the importance of diet quality and whole-farm management in determining emissions intensity.

2.2 Introduction

Globally, there is increasing pressure to reduce greenhouse gas (GHG) emissions to mitigate the impacts of climate change. Agriculture contributes approximately 14% of global emissions (Lee et al., 2023), with ruminant livestock representing the largest source within the sector in Australia (Cottle et al., 2011), primarily through the production of enteric methane (CH_4). Enteric methane is produced during the microbial fermentation of carbohydrates in the rumen and is released mainly via eructation and, to a lesser extent, respiration (Johnson and Johnson, 1995). Given its relatively short atmospheric lifetime and high global warming potential, CH_4 mitigation is widely recognised as one of the most effective short-term strategies for slowing global temperature rise and supporting pathways towards limiting warming to 1.5°C above pre-industrial levels (Beauchemin et al., 2022).

A wide range of mitigation strategies has been proposed to reduce enteric methane emissions. These include methane inhibitors and rumen modifiers, vaccines, early-life interventions, genetic selection, improvements in pasture and forage quality, and alternative production systems such as extended lactation (Garnett and Eckard, 2024). Many of these approaches act by improving animal productivity and feed efficiency, thereby reducing methane emissions intensity (g CH_4 per unit of product) through the dilution of maintenance energy requirements (Beauchemin et al., 2022). However, the extent to which such strategies are represented within national emissions accounting frameworks remains limited.

In Australia, the National Greenhouse Gas Inventory (NGGI) applies a Tier 2 approach in which methane emissions from forage-fed cattle are estimated using a fixed methane yield factor of 20.7 g CH_4 /kg dry matter intake (DMI) (Charmley et al., 2016). Within this framework, DMI is modelled as a function of liveweight, liveweight change, and milk production (Munidasa et al., 2024), and methane production is subsequently derived from estimated intake and the assumed emission factor. While this approach provides consistency and scalability, it does not explicitly account for variability in diet quality or the effects of specific management interventions that may alter methane yield.

Emerging evidence suggests that methane yield is sensitive to pasture nutritive characteristics. Cows grazing high-quality pastures with elevated metabolisable energy (ME) and organic matter digestibility (OMD), and moderate neutral detergent fibre (NDF) content, can produce less methane per unit of feed intake than assumed under default inventory values (Kay et al., 2026). For example, in Ireland, Lahart et al. (2024) reported a methane conversion factor (CH_4 as a proportion of gross energy intake) of 0.046 for cows grazing highly digestible spring pasture, compared with the IPCC default value of 0.063 (Baasansuren et al., 2019). These findings highlight that current default factors may not fully capture dietary effects on methane production in intensive, high-quality grazing systems.

Accurate quantification of methane emissions under improved pasture systems is therefore critical for refining national greenhouse gas inventories and for evaluating mitigation strategies at farm scale. This is particularly relevant in regions such as Tasmania, where irrigation has enabled the expansion and intensification of dairy systems by supporting the year-round production of high-quality pasture. Irrigated perennial ryegrass and white clover systems have been shown to maintain consistently high nutritive value across the lactation

season (Pembleton et al., 2017); however, there remains limited empirical data on the associated enteric methane emissions under these production conditions.

The aim of this study was therefore to quantify enteric methane emissions using two GreenFeed (GF) units across four irrigated dairy farmlets based on high-quality perennial ryegrass–white clover pastures, and to compare observed emissions with estimates derived using the NGGI methodology. This comparison provides an opportunity to evaluate the suitability of current inventory assumptions under intensive, high-nutritive pasture-based dairy systems and to improve understanding of methane emissions in irrigated grazing environments.

2.3 Materials and Methods

2.3.1 Ethical Statement

All animal procedures were conducted with prior institutional animal ethics approval (University of Tasmania Animal Ethics Committee, #27608 under the requirement of the Tasmanian Animal Welfare Act (1993) in accordance with the National Health and Medical Research Council/Commonwealth Scientific and Industrial Research Organisation/Australian Animal Commission Australian Code of Practice for the Care and Use of Animals for Scientific Purposes.

2.3.2 Physical Site Details

The study was conducted at the Tasmanian Institute of Agriculture Dairy Research Facility (TDRF), Elliott, Tasmania (41°08'S, 145°77'E), on a clay loam Ferrosol under a cool temperate climate with winter-dominant rainfall (long-term mean 1,180 mm). Four farmlets were established across a 29.44 ha irrigated site using a randomised complete block design. The site comprised eight blocks (3.68 ha), each containing four 0.92 ha paddocks, with farmlet treatments randomly allocated within each block and maintained for the duration of the study. Each farmlet therefore consisted of eight paddocks (7.36 ha total), with blocking used to account for spatial variation in topography and soil properties (Figure 2.1).



Figure 2.1 Spatial layout of the four experimental farmlets (F1-F4) at the Tasmanian Institute of Agriculture Dairy Research Facility.

The site was prepared over 12 months prior to sowing through cultivation, soil nutrient amendment and successive herbicide applications, with an interim Italian ryegrass (*Lolium multiflorum* Lam.) crop used for ground cover before final termination. Farmlets were then established with treatment-specific pasture mixtures. Farmlets 1 and 2 (F1, F2) targeted 80% perennial ryegrass (*Lolium perenne* L.) and 20% white clover (*Trifolium repens* L.). Farmlet 3 (F3) targeted 40% ryegrass, 30% white clover and 30% plantain (*Plantago lanceolata* L.). Farmlet 4 (F4) was sown as a diverse mixture of grasses (tall fescue (*Festuca arundinacea* Schreb.), perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata* L.) and brome (*Bromus* spp.), legumes (white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.) and strawberry clover (*Trifolium fragiferum* L.)) and herbs (plantain (*Plantago lanceolata* L.) and chicory (*Cichorium intybus* L.)). Each of the four farming systems were fully irrigated and stocked at 3.9 cows ha⁻¹ except F4, which was stocked at 3.0 cows ha⁻¹. F1 received 300 kg N ha⁻¹ yr⁻¹; F2 and F3 received 150 kg N ha⁻¹ yr⁻¹; and F4 received 0 kg N ha⁻¹ yr⁻¹.

2.3.3 Cow Selection and Animal Measurements

All cows were selected from a 350-cow commercial herd at the TDRF, comprising predominantly Holstein–Friesian and Friesian × Jersey genetics. Cows were allocated to farmlets to ensure balance for parity, calving date, previous lactation performance, performance at start of the current lactation, body weight (BW) and body condition score (BCS). Cows entered the farmlets at approximately 21 days in milk (DIM), with the first cohort (approximately 70% of the herd) allocated on 21 August. The remaining cohort

(approximately 30% of the herd) entered the farmlets at a similar stage of lactation on 24 September.

Milk yield was recorded twice daily for all cows using DeLaval MM27BC2 milk meters, an International Committee for Animal Recording (ICAR)-accredited system calibrated to measure milk volume (L). An aliquot of milk was collected fortnightly during routine herd testing from consecutive morning and evening milkings. Milk samples were analysed for fat and protein concentrations (g/kg), milk urea nitrogen (mg/dL), and somatic cell count (SCC) using a Bentley Instruments Inc. B2000 Infrared Milk Analyser. Analyses were conducted by TasHerd Pty Ltd (Hadspen, Tasmania, Australia). On milking days without a scheduled herd test, fat and protein concentrations were estimated by linear interpolation. Milk yield and milk composition were subsequently used to calculate energy-corrected milk (ECM), standardised to 4.0% fat and 3.3% protein, using the equation described by Tyrrell and Reid (1965):

$$\text{ECM (L/cow per day)} = [\text{milk yield (L)} \times (376 \times \text{fat\%} + 209 \times \text{protein\%} + 948)] / 3138$$

As the cows exited the dairy, their body condition score was assessed using the in-race DeLaval three-dimensional body condition camera. The body condition score was recorded in the data system using a scale from 0 to 10. In addition, body weight data were collected twice daily using walk-over scales (DeLaval AWS100 automatic weighing system). Each cow was fitted with a Halter collar (Halter HQ, 66 Sale Street, Auckland City, Central 1010, NZ) and individual cow behaviours (grazing and ruminating) were logged continuously and reported as total minutes per behaviour per 15 min.

2.3.4 Enteric Methane Assessment

Two deployments of two GreenFeed units were conducted to assess daily enteric methane emissions (g CH₄/cow.day) across the four dairy farmlets. During the first deployment, one GreenFeed unit was deployed in each of F1 and F4. During the second deployment, one GreenFeed unit was deployed in each of F2 and F3. Both deployments included an initial training phase of between one and two weeks. Deployment 1 had a 33-day measurement period between 20/12/2025 and 22/01/2026 while Deployment 2 had 26-day measurement period between 14/02/2026 and 12/03/2026. The mean visits per day throughout the study period was 2.48 with a mean airflow of 38.3 L/s.

The Greenfeed units were positioned within the paddock of the grazing herd and followed the grazing rotation allowing continual access for the cows (Figure 2.2). The minimum visit interval was set a 4-hours and concentrate pellet were dispensed at a rate of between 36 and 42g in 30 s interval and the amount of concentrate consumed per day was recorded. The amount of concentrate that individual cows were consuming in the GreenFeed unit was deducted from the amount fed to these cows in the dairy during milking, to achieve a consistent concentrate intake and diet. The concentrate pellet consisted of a 50:50 mix of barley and wheat with 1.5% Molafos Gold.



Figure 2.2 Greenfeed unit 794 among farmlet cows during deployment.

2.3.5 Pasture Measurement and Intake Assessment

Pasture mass (kg DM/ga) was measured using a calibrated rising plate meter (Jenquip EC20, Fielding, New Zealand). Paddock-level pasture intake was estimated as the difference between pre- and post-grazing pasture mass. Pre-grazing measurements were typically collected within 24 h prior to grazing, except on weekends when assessments occurred 48–72 h beforehand. Post-grazing measurements were generally taken within 24 h of grazing, or within 48–72 h on weekends where required. Individual cow DMI was estimated by back-calculation from animal performance, including milk yield and composition, BW, and stage of lactation and gestation, using the Primary Industries Standing Committee (PISC, 2007) method.

2.3.6 Data Analysis

Methane emission data were screened for outliers within each cow using the $1.5 \times$ interquartile range (IQR) method. Observations with CH_4 values below the first quartile minus $1.5 \times$ IQR or above the third quartile plus $1.5 \times$ IQR were removed separately for each Cow. This filtering process removed 56 of 4,766 observations, representing 1.17% of the total dataset.

Animals with 40 or fewer observations were excluded prior to analysis. For Deployment 1, this filtering removed 160 of 2,117 observations (7.6% of the dataset) and excluded 7 of 30 cows (23.3%). The final dataset retained 23 cows, comprising 14 cows from F1 and 9 cows from F4. For Deployment 2, the same filtering approach removed 262 of 1,252 observations (20.9%) and excluded 14 of 31 cows (45.2%). The final dataset retained 17 cows, consisting of 8 cows from F2 and 9 cows from F3.

Methane production (g CH_4 /day) was averaged for each cow across its eligible GreenFeed measurements, then averaged across cows for each farmlet. Methane intensity (g CH_4 /kg DMI) was also determined for each cow and farmlet using a back-calculation method for feed intake. Methane intensity (g CH_4 /L ECM) was calculated as the ratio of average daily

methane production to estimated average daily energy-corrected milk (ECM) production over the measurement period.

Within-farmlet variation was characterised by the mean, standard deviation, and range of individual cow means. Between-deployment differences in mean methane production were assessed using a Welch's two-sample t-test, with deployment period (1 vs 2) as the grouping variable. Within each deployment, farmlet pairs (F1 vs F4 in Deployment 1; F2 vs F3 in Deployment 2) were compared on six methane-related metrics (daily methane production, carbon dioxide production, methane intensity per kg milk solids, methane intensity per litre ECM, methane per kg BW, and methane yield per kg DMI) using Welch's two-sample t-test (unequal variances assumed). P-values were Holm-corrected within each deployment.

To examine the relationship between methane production and milk yield, a linear regression model was fitted with average daily methane production ($\text{g CH}_4/\text{cow}/\text{day}$) as the response variable and average daily ECM ($\text{L}/\text{cow}/\text{day}$) as a continuous predictor. Deployment period was included as a categorical covariate to account for systematic differences between sampling periods.

Between-cow and within-cow variation in spot CH_4 measurements was quantified using a linear mixed model. Deployment was included as a fixed effect, and cow was included as a random intercept. The intraclass correlation coefficient (ICC) was extracted and interpreted as the proportion of total variance attributable to between-cow differences after accounting for deployment period. Normality and variance assumptions were checked for each model using Shapiro-Wilk test, Levene's test, and diagnostic plots. All analyses were conducted in R version 4.5.2.

To account for diurnal variation in CH_4 emissions, spot-measurement data were aggregated into discrete time-of-day bins and analysed at the cow level. Specifically, hourly observations were categorised into four 6-hour periods (0000–0600, 0600–1200, 1200–1800, and 1800–0000) to capture key phases of daily activity, including milking and feeding events. For each cow within each farmlet, mean CH_4 emissions were calculated within each time bin, thereby reducing the influence of short-term fluctuations and uneven sampling across hours. These bin-level means were then averaged to derive an overall diurnal-adjusted CH_4 estimate for each cow. This approach ensured that all periods of the day contributed equally to the final estimate, rather than being biased toward time periods with more frequent measurements or higher emission events. The diurnally adjusted cow-level estimates were merged with the raw spot-measurement CH_4 dataset to enable direct comparison between unadjusted and diurnally standardised values. Agreement between raw and diurnally adjusted per-cow estimates was assessed using Lin's Concordance Correlation Coefficient (CCC).

2.4 Results

Average daily methane production ($\text{g CH}_4/\text{day}$) varied both within and between farmlets. Farmlet 1, which had the highest number of cows with more than 40 measurements, showed a range of individual cow mean methane production, spanning 283 to 498 $\text{g CH}_4/\text{day}$, with a mean of 387 $\text{g CH}_4/\text{day}$. Farmlet 4, measured during the same deployment period, had a mean methane production of 406 $\text{g CH}_4/\text{day}$, with a range of 344 to 449 $\text{g CH}_4/\text{day}$ (Figure 2.3). Despite within-farmlet variability, a consistent pattern emerged, with Deployment 2 (F2 and F3) tending to exhibit higher methane outputs compared with Deployment 1. This difference between deployment periods was statistically significant (Welch's t-test: $t(31.3) = -2.96$, $p = 0.006$), with Deployment 2 cows producing on average 57 $\text{g CH}_4/\text{day}$ more than

Deployment 1 cows (95% CI: 18–96 g CH₄/day). Farmlet 2 had the highest overall mean methane production at 481 g CH₄/day, with values ranging from 417 to 521 g CH₄/day, while F3 had a mean of 425 g CH₄/day, with a range of 318 to 523 g CH₄/day (Figure 2.3).

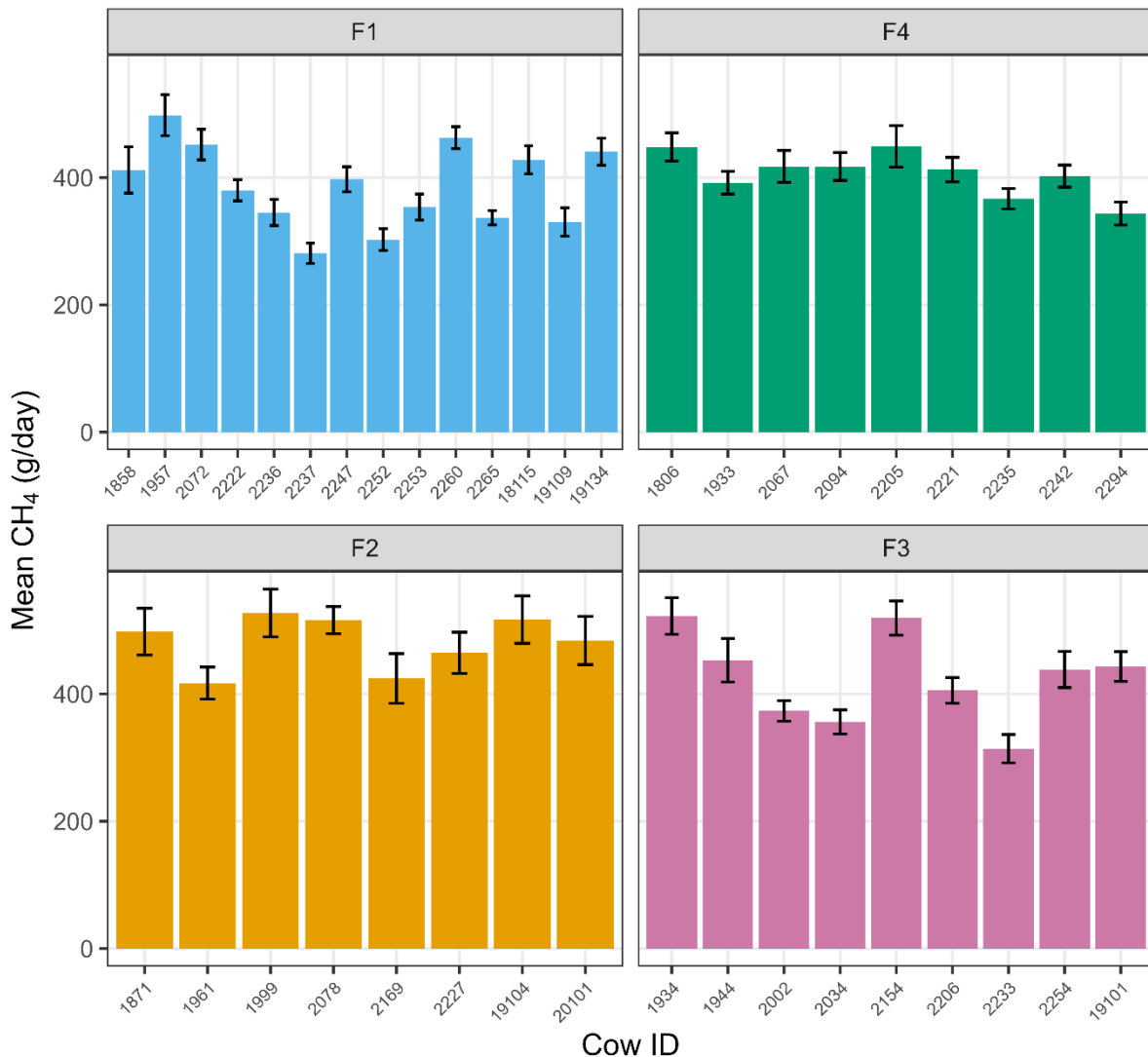


Figure 2.3. Mean daily methane production for individual cows in Farmlet 1 (F1; $n = 14$), Farmlet 2 (F2; $n = 8$), Farmlet 3 (F3; $n = 9$), and Farmlet 4 (F4; $n = 9$). Error bars represent the 95% confidence interval of the mean for each cow.

The estimated mean DMI for F1, F2, F3, and F4 was 22.3, 21.7, 21.0, and 23.2 kg DM/cow, respectively. This corresponded to mean methane yields of 17.4, 22.2, 20.2, and 17.5 g CH₄/kg DMI. Mean daily ECM for F1, F2, F3, and F4 was 35.2, 31.7, 30.7, and 36.4 kg/cow, respectively, resulting in methane intensities of 11.0, 15.3, 13.9, 11.3 g CH₄/kg ECM (Table 2.1).

Table 2.1 Mean $\pm$ standard error of the mean (SEM) by farmlet of cow mean daily milk yield (L/day), milk fat and protein concentration (%), milk solids production (kg/day), energy-corrected milk (ECM; kg/day), body weight (BW; kg), body condition score (1–10 scale), and estimated dry matter intake (DMI), including total intake, pasture intake, concentrate intake, and silage intake (kg DM/day).

	Deployment 1 (20/12/25 to 22/01/26)		Deployment 2 (14/02/26 to 12/03/26)	
	Farmlet 1	Farmlet 4	Farmlet 2	Farmlet 3
Milk yield (L/d)	31.91 $\pm$ 1.28	31.42 $\pm$ 2.05	28.44 $\pm$ 1.45	25.20 $\pm$ 0.93
Fat (%)	4.06 $\pm$ 0.16	4.43 $\pm$ 0.19	4.20 $\pm$ 0.27	4.65 $\pm$ 0.20
Protein (%)	3.61 $\pm$ 0.10	3.76 $\pm$ 0.10	3.49 $\pm$ 0.12	3.94 $\pm$ 0.08
Milk solids (kg/day)	2.42 $\pm$ 0.06	2.54 $\pm$ 0.12	2.16 $\pm$ 0.09	2.17 $\pm$ 0.11
ECM (L/day)	32.53 $\pm$ 0.88	33.70 $\pm$ 1.73	29.28 $\pm$ 1.18	28.31 $\pm$ 1.32
BW (kg)	535.64 $\pm$ 10.81	558.10 $\pm$ 15.84	591.17 $\pm$ 19.13	584.09 $\pm$ 24.07
BCS (1-10)	4.23 $\pm$ 0.06	4.31 $\pm$ 0.10	4.21 $\pm$ 0.14	4.50 $\pm$ 0.16
Estimated Total DMI (kg/day)	22.3	23.2	21.7	21.0
Estimated Pasture DMI (kg/day)	16.4	17.3	16.0	15.4
Estimated Concentrate DMI (kg/day)	5.94	5.94	4.95	4.95
Estimated Silage DMI (kg/day)	0	0	0.73	0.63
Feeding (min/day)	481.68 $\pm$ 8.20	473.34 $\pm$ 9.97	510.77 $\pm$ 12.34	486.61 $\pm$ 17.88
Ruminating (min/day)	515.76 $\pm$ 12.43	528.84 $\pm$ 16.99	453.66 $\pm$ 13.01	466.38 $\pm$ 13.01

No significant differences in methane production, intensity, or yield were found between farmlet pairs within either deployment after p-value correction for multiple comparisons (Table 2.2). While F2 showed higher methane intensity (g CH₄/cow/kg milk solids; $p = 0.022$) and methane yield (g CH₄/cow/kg DMI; $p = 0.032$) than F3, neither difference remained significant after Holm correction ($p = 0.129$ and $p = 0.158$, respectively).

Table 2.2 Farmlet-level mean $\pm$ standard error of the mean (SEM) of cow mean daily methane production (g CH₄/day), carbon dioxide emissions (kg CO₂/day), methane intensity (g CH₄/kg milk solids and g CH₄/l energy-corrected milk; ECM), methane production per kilogram of body weight (BW), and methane yield (g/kg dry matter intake; DMI). Farmlet pairs within each deployment were compared using Welch's *t*-test with Holm correction for multiple comparisons. Farmlet 1: *n* = 14; Farmlet 2: *n* = 8; Farmlet 3: *n* = 9; Farmlet 4: *n* = 9.

	Deployment 1 (20/12/25 to 22/01/26)			
	Farmlet 1	Farmlet 4	p	p (Holm)
Methane production (g/day)	387.19 $\pm$ 17.32	405.53 $\pm$ 11.54	0.388	1.000
Carbon dioxide (kg/day)	13.27 $\pm$ 0.29	13.37 $\pm$ 0.37	0.838	1.000
Methane/milk solids (g/kg MS)	160.72 $\pm$ 6.92	161.80 $\pm$ 6.55	0.911	1.000
Methane/ECM (g/L ECM)	11.94 $\pm$ 0.49	12.21 $\pm$ 0.51	0.698	1.000
Methane/BW (g/kg)	0.72 $\pm$ 0.02	0.73 $\pm$ 0.01	0.808	1.000
Methane/DMI (g/kg)	17.58 $\pm$ 0.73	17.50 $\pm$ 0.47	0.931	1.000

	Deployment 2 (14/02/26 to 12/03/26)			
	Farmlet 2	Farmlet 3	p	p (Holm)
Methane production (g/day)	481.12 $\pm$ 14.95	425.17 $\pm$ 23.52	0.065	0.233
Carbon dioxide (kg/day)	14.12 $\pm$ 0.21	13.05 $\pm$ 0.46	0.058	0.233
Methane/milk solids (g/kg MS)	223.23 $\pm$ 3.90	197.26 $\pm$ 8.87	0.022	0.129
Methane/ECM (g/L ECM)	16.49 $\pm$ 0.33	15.08 $\pm$ 0.65	0.077	0.233
Methane/BW (g/kg)	0.82 $\pm$ 0.04	0.73 $\pm$ 0.04	0.120	0.233
Methane/DMI (g/kg)	22.33 $\pm$ 0.52	20.20 $\pm$ 0.72	0.032	0.158

Methane production (g CH₄/cow/day) was not significantly associated with ECM (L/cow/day) when considered alone (β = 3.01, *p* = 0.21, *R*² = 0.04). Once deployment period was accounted for, a significant positive relationship emerged, with methane production increasing by approximately 8.1 g/day for each additional litre of ECM (*p* < 0.001; Table 2.3; Figure 2.4). Together, ECM and deployment period accounted for 43% of the variation in methane production (*R*² = 0.43, adjusted *R*² = 0.39), with deployment period alone explaining 20% of this variation (*R*² = 0.20).

Table 2.3 Coefficients and model fit statistics from the deployment-adjusted linear model of methane production ($\text{g CH}_4/\text{day}$) by energy-corrected milk (ECM; L/day), using cow means across the sampling period (Deployment 1: $n = 23$ cows; Deployment 2: $n = 17$ cows). Deployment 1 is the reference category. CI, confidence interval; SE, standard error.

Predictor	Estimate	95% CI	SE	p
Mean ECM ($\text{L}/\text{cow}/\text{day}$)	8.04	3.76, 12.32	2.11	<0.001
Deployment				
1	—	—	—	
2	91.07	53.65, 128.49	18.50	<0.001
R^2	0.422			
Adjusted R^2	0.390			
F statistic	13.48			
df	2			
df residual	37			
Model p	<0.001			

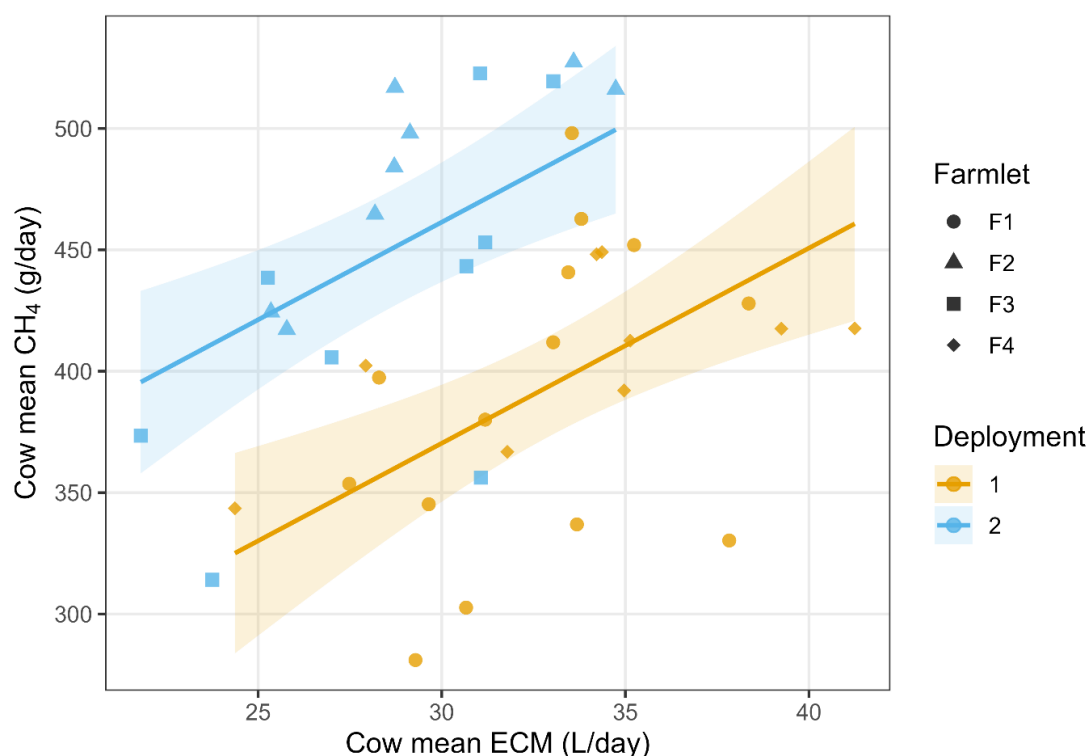


Figure 2.4 Relationship between methane production ($\text{g CH}_4/\text{day}$) and energy-corrected milk yield (ECM; L/day) by GreenFeed deployment (Deployment 1: $n = 23$ cows; Deployment 2: $n = 17$ cows). Points show individual cow means across the sampling period, with shape indicating farmlet. Lines and shaded ribbons show fitted values and 95% confidence intervals from the deployment-adjusted linear model.

Hourly variation in methane (CH_4) emissions exhibited a diurnal pattern, with both the magnitude and variability changing throughout the day (Figure 2.5). Median CH_4 emissions ranged from approximately 300 to 500 $\text{g CH}_4 \text{ day}^{-1}$, with substantial within-hour variability. Emissions were lowest during the early morning period (00:00–05:00), prior to morning milking, with median values generally between 300 and 350 $\text{g CH}_4 \text{ day}^{-1}$. Following the morning milking, CH_4 emissions increased steadily, reaching elevated levels between 07:00 and 10:00, where median values exceeded 400 $\text{g CH}_4 \text{ day}^{-1}$ and variability also increased. A moderate decline or plateau in emissions was observed during the midday to early afternoon period (11:00–15:00), prior to the afternoon milking, with median values returning to approximately 350–420 $\text{g CH}_4 \text{ day}^{-1}$. Emissions then increased again during the late afternoon and evening (17:00–20:00) period, following the afternoon milking, when some of the highest median values were recorded (approximately 450–500 $\text{g CH}_4 \text{ day}^{-1}$). Overall, the results demonstrate a consistent diurnal pattern, characterised by peak emissions following milking events and associated feeding periods, and comparatively lower emissions during overnight hours.

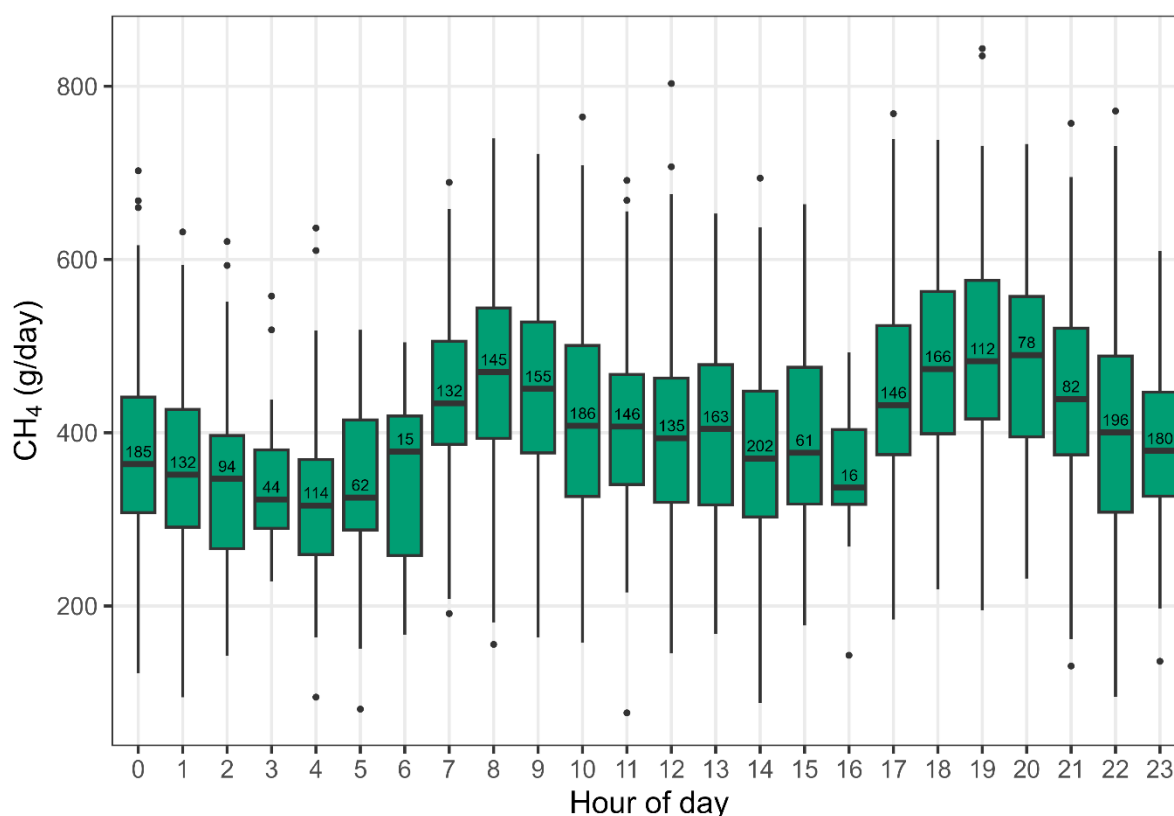


Figure 2.5 Diurnal distribution of methane (CH_4) emissions ($\text{g CH}_4 \text{ day}^{-1}$) by hour of day. Boxplots represent hourly medians, interquartile ranges, and overall variability, with outliers shown as individual points. Numbers within each box indicate the sample size (n) for that hour.

Adjustment for diurnal variation had a modest effect on estimated CH_4 emissions across farmlets, with overall patterns remaining largely consistent between raw and corrected data (Figure 2.6). Across all farmlets, the relative ranking of CH_4 emissions was unchanged following diurnal correction (Lin's CCC = 0.99, 95% CI 0.98–0.99). This indicates that diurnal

adjustment did not materially alter between-system comparisons. However, small shifts in central tendency were observed. In general, diurnally corrected values were slightly lower compared to raw estimates (notably F2), while in F1 and F4 the corrected medians were similar. These differences reflect the influence of uneven sampling across periods of high emissions, particularly around peak feeding times. Interquartile ranges were broadly similar between methods, although some tightening of spread was evident, suggesting reduced influence of extreme hourly values. Nevertheless, substantial within-farmlet variability remained, highlighting persistent between-cow differences in CH₄ production.

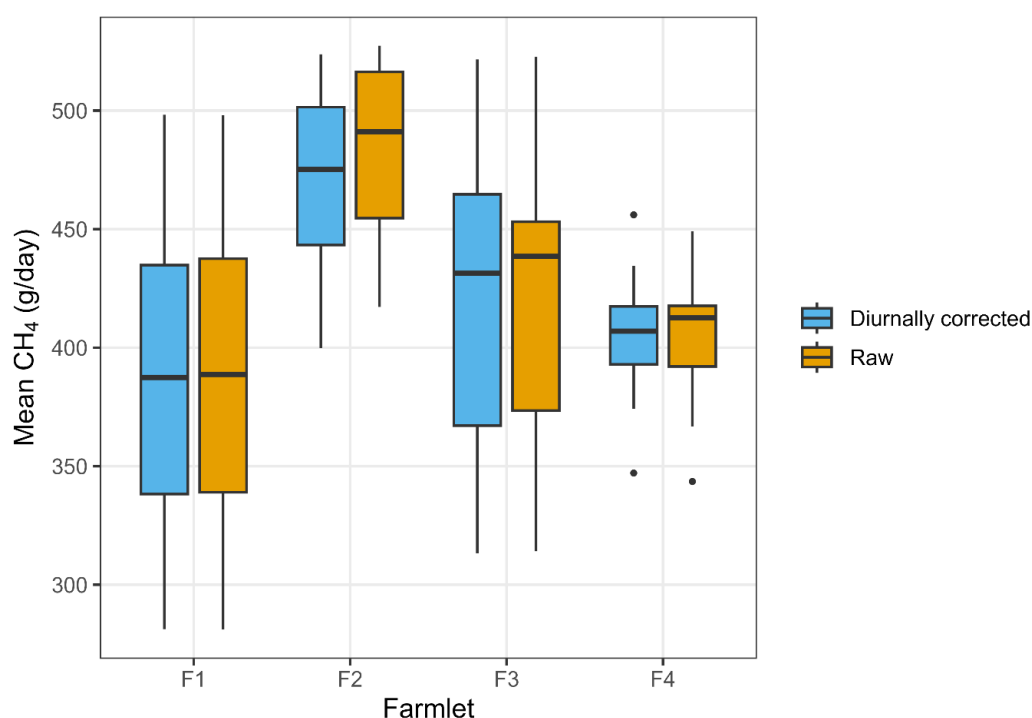


Figure 2.6 Comparison of raw and diurnally corrected methane (CH₄) emissions (g CH₄/day) across four farmlets (F1–F4). Boxplots display medians, interquartile ranges (boxes), and whiskers representing the range of values within 1.5 × the interquartile range, with outliers shown as individual points.

The 5-day rolling mean of daily CH₄ emissions highlighted persistent individual cow effects, alongside temporal differences among farmlets (Figure 2.7). Across all farmlets, cows that exhibited relatively high CH₄ emissions tended to remain consistently high, while those with lower emissions remained low throughout the measurement period. This pattern was stable over time, with very little crossover between individuals. The consistency of individual cow rankings was confirmed by a linear mixed model, with a deployment-adjusted ICC of approximately 0.25, indicating that approximately 25% of the total variance in daily CH₄ emissions was attributable to between-cow differences. In addition to these individual patterns, a temporal effect was evident across farmlets. The farmlets measured later in the season (F2 and F3) generally showed higher CH₄ emissions, with many cows consistently exceeding ~450–500 g CH₄/day. In contrast, farmlets measured earlier in the season (F1 and F4) exhibited lower overall CH₄ levels, with most cows falling below 450g CH₄/day. Overall, these results indicate that while absolute CH₄ production shifts over time (likely reflecting seasonal influences), relative differences among cows are consistent, with high- and low-emitting individuals maintaining their positions across the study period.

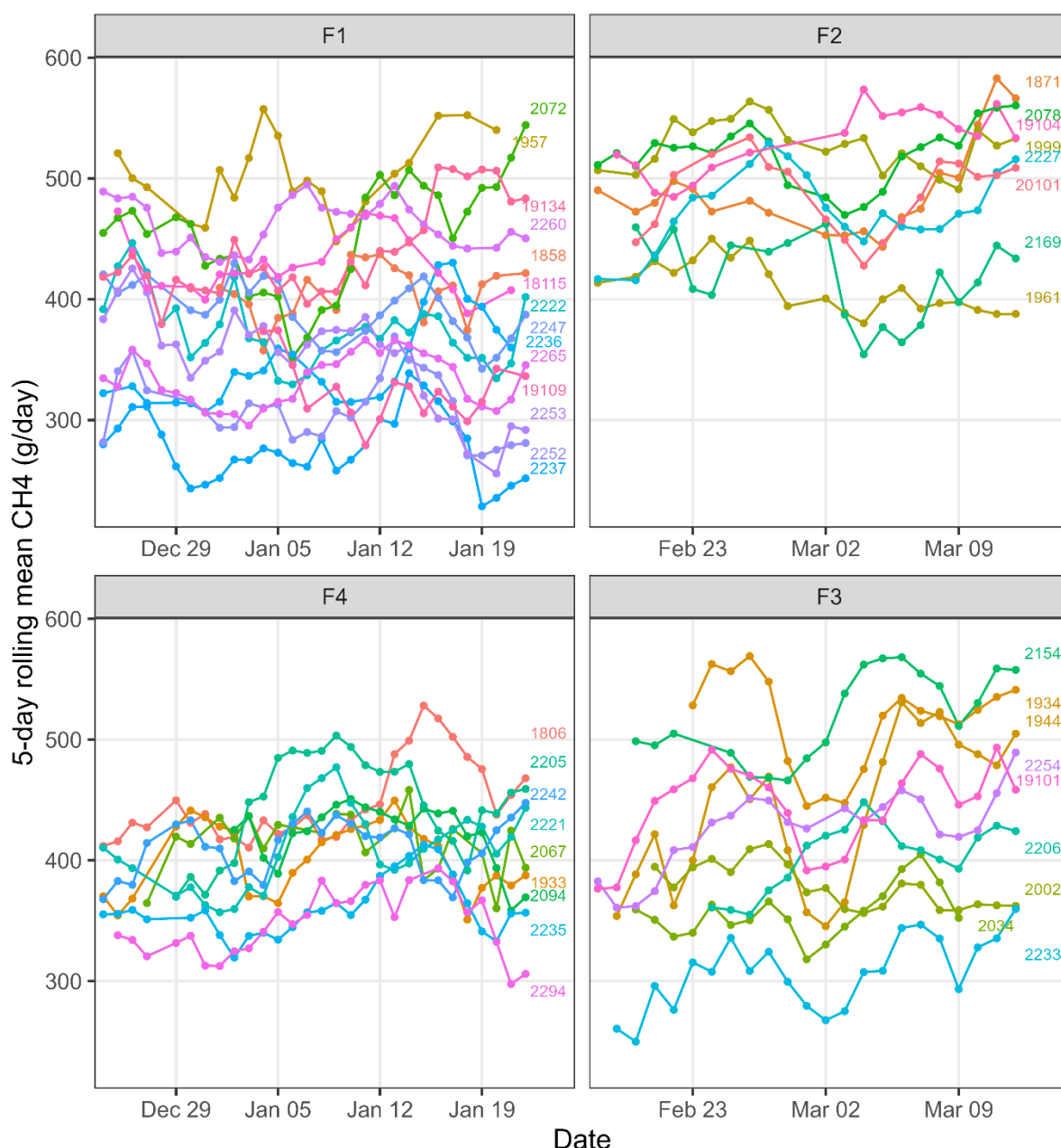


Figure 2.7 Five-day rolling mean of daily methane (CH₄) emissions for individual cows across four farmlets (F1–F4). Each coloured line represents a single cow tracked over time, labelled with its identification number. Panels are faceted by farmlet.

2.5 Discussion

Enteric methane production measured using GreenFeed systems was generally consistent with predictions derived from the National Greenhouse Gas Inventory (NGGI) equation, although notable seasonal differences were observed. In Australia, methane yield from forage-fed cattle is commonly estimated at 20.7 g CH₄/kg DMI (Charmley et al., 2016), which equates to approximately 455 g CH₄/day for a cow consuming 22 kg DM/day. During Deployment 1, methane production in F1 and F4 was approximately 15% and 11% lower than predicted, respectively, resulting in an overall methane production that was 13% below the estimated value. In contrast, methane production during Deployment 2 closely aligned

with predicted values, with F2 producing 6% more methane and F3 producing 6% less methane than expected. GreenFeed units have been shown to underestimate methane emissions in grazing dairy heifers (Hammond et al., 2015), which may partly explain why current inventory methodologies appeared to overestimate emissions in the present study. Overall, these findings suggest that current inventory methodologies provide reasonable estimates of methane production in pasture-based dairy systems.

The higher methane production observed during Deployment 2 may partly reflect changes in diet composition which include the addition of silage and 1kg DM less supplementary grain. This would have resulted in an increased dietary fibre concentration and a reduced ruminal passage rate, resulting in greater methane production per unit of feed consumed (Janssen, 2010). Consequently, the lower methane emissions observed during Deployment 1 were likely associated with the greater proportion of high-quality pasture in the diet. This interpretation is consistent with previous research showing that lactating cows grazing high-nutritive-value pastures characterised by high metabolisable energy (ME), high organic matter digestibility (OMD), and moderate neutral detergent fibre (NDF) concentrations can produce methane yields that are 15–20% lower than values predicted by inventory equations (Kay et al., 2026).

Direct measurement technologies such as GreenFeed systems provide valuable insights into methane production under practical grazing conditions and enable temporal variation in emissions to be quantified. GreenFeed units were deployed throughout the grazing season, allowing repeated measurements of methane production from individual cows under commercial grazing management. Robust estimates of methane production require adequate visit frequency and an averaging period appropriate to the study objectives (Kay et al., 2026). A minimum threshold of approximately 40 valid visits per animal has been recommended to provide reliable estimates of methane production (Beck et al., 2024), and this criterion was applied in the present study. As a result, 7.6% of observations from Deployment 1 and 20.9% from Deployment 2 were excluded from analysis. Despite these exclusions, sufficient animal numbers remained within each farmlet to provide robust estimates of methane production.

A clear seasonal pattern in methane production was observed, with emissions increasing as the grazing season progressed. Similar seasonal trends have been reported previously in pasture-based dairy systems and are generally attributed to changes in pasture quality and composition throughout the year (Kay et al., 2026). Lower methane emissions during spring are likely associated with the superior nutritive value of the pasture and total diet. Highly digestible forages typically reduce acetate and butyrate production while promoting propionate formation in the rumen, thereby reducing the availability of hydrogen for methanogenesis. In addition to dietary effects, animal physiology may contribute to seasonal variation in methane production. Changes in energy balance throughout lactation can influence methane emissions independently of diet, while alterations in rumen passage rate and microbial populations may further modify methane production.

Methane production was positively associated with animal productivity, consistent with previous studies demonstrating relationships between methane emissions, feed intake, metabolic liveweight, and ECM production (Starsmore et al., 2024). In the present study, regression analysis indicated a positive relationship between ECM and methane production.

However, this relationship only emerged after deployment period had been accounted for, with deployment period alone explaining approximately 20% of the variation in methane production. In a separate linear mixed model that included cow as a random effect, approximately 25% of the variation in methane production was attributable to differences between individual cows. These findings suggest that factors other than milk production, including diet composition, animal characteristics and grazing management, also contribute substantially to variation in methane production.

Despite the positive association between methane production and milk yield, methane intensity remained comparatively low across all farmlets. Methane intensity is commonly used as an indicator of production efficiency and environmental performance (Niu et al., 2018). The lower methane intensities observed in the present study compared with previous reports (Starsmore et al., 2024; Waghorn et al., 2016) were likely a consequence of the high milk production achieved by cows across all farmlets. Increased productivity dilutes maintenance-related methane emissions over a greater volume of milk production, thereby reducing methane intensity (Capper et al., 2009).

Daily methane production also exhibited a distinct diurnal pattern. Emissions were lowest during the early morning period prior to milking, increased following the morning milking event, declined during the middle of the day, and peaked again during the evening period after afternoon milking. This pattern is consistent with daily fluctuations in feeding behaviour and rumen fermentation activity and highlights the importance of collecting measurements across the full 24-hour period when estimating methane production. Failure to adequately capture diurnal variation may introduce bias into methane estimates derived from spot measurements.

Diversification of grazing systems through the inclusion of legumes such as white clover has attracted considerable interest as a strategy to improve environmental sustainability. Clover can reduce reliance on synthetic nitrogen fertiliser and lower greenhouse gas emissions associated with fertiliser manufacture and application. However, evidence for direct reductions in enteric methane emissions remains inconsistent. All farmlets in the present study contained more than 20% white clover in their botanical composition. Although clover-rich swards generally contain lower NDF concentrations and may favour rumen fermentation pathways associated with lower methane yield, these benefits are often offset by increased feed intake and milk production. Consequently, reductions in methane yield do not necessarily translate into reductions in total methane production, which may explain why previous studies have reported inconsistent responses.

These findings emphasise the complexity of methane mitigation in pasture-based dairy systems. Strategies that improve productivity or reduce one source of environmental impact do not necessarily reduce enteric methane emissions. Consequently, potential trade-offs between productivity, profitability and greenhouse gas emissions must be carefully considered when evaluating mitigation options.

Overall, the results demonstrate that methane production in pasture-based dairy systems is strongly influenced by seasonal changes in diet quality and animal productivity. While current inventory equations provide reasonable estimates of methane production, they may overestimate emissions when cows consume highly digestible spring pastures. Furthermore, improvements in whole-farm environmental performance appear to be driven not only by

reductions in methane emissions but also by optimising productivity and reducing emissions associated with fertiliser and supplementary feed inputs.

2.6 Collaboration with Green Cow Project

We have engaged in collaborating with the Green Cow project, led by Agriculture Victoria Research. The Green Cow project is aiming to develop an enteric methane breeding value for dairy cows and is planning to do a full genome analysis of cows involved in our project that have methane data. We will share the methane and additional cow related data, including MIR data from herd tests.

2.7 Conclusions

This study demonstrated that enteric methane production in high-performing pasture-based dairy systems can differ from values predicted using standard inventory equations and that inventory equations may overestimate emissions when cows consume highly digestible, low-fibre pasture diets. Seasonal changes in feed supply and the inclusion of pasture silage were associated with increased methane production later in the grazing season, highlighting the influence of diet quality on enteric methane emissions.

Methane production was positively associated with milk production, although the strength of this relationship varied among farmlets. Despite differences in management, methane intensity was lower than values reported in comparable pasture-based dairy systems, reflecting the high productivity achieved by the cows. At the whole-farm scale, emission intensity was lowest in the unfertilised clover-based system due to reduced nitrogen fertiliser and the reduced supplementary feed requirements. Overall, these findings emphasise the importance of integrating productivity, feed management and whole-farm emissions when evaluating methane mitigation opportunities in grazing dairy systems.

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3. Net Farm Greenhouse Gas Emissions

3.1 Calculating Net Farm Greenhouse Gas Emissions

Net farm greenhouse gas (GHG) emissions for each farmlet were estimated using the Australian Dairy Carbon Calculator (ADCC; v6.1), which applies Australia's National Greenhouse Gas Inventory methodology. From this, we determined milk emissions intensity [EI; kg carbon dioxide equivalents per kg fat and protein-corrected milk (kg CO₂e kg FPCM⁻¹)]. Milking cows entered the farmlets at approximately 21 days post-calving and exit the farmlet prior to 300 days in milk. To enable comparison with industry benchmarks, milk production and key farm inputs (i.e. grain, electricity and diesel) were scaled to a 300 day-lactation. In addition, calculated enteric methane production, yield, and intensity were compared with those measured using the GreenFeed units.

3.2 Key Findings

Total greenhouse gas emissions intensity varied modestly across the four farmlets, ranging from approximately 0.61 to 0.66 kg CO₂-e kg FPCM⁻¹ (Figure 3.1). Farmlet 1 exhibited the highest emissions intensity (0.66 kg CO₂-e kg FPCM⁻¹), followed by F2 and F3 (0.64–0.65 kg CO₂-e kg FPCM⁻¹). The lowest emission intensity was observed in F4, reflecting the absence of nitrogen fertiliser inputs and reduced requirements for purchased silage. Farmlet 4 received no nitrogen fertiliser, whereas F1 received approximately 300 kg N ha⁻¹ year⁻¹ and F2 and F3 each received approximately 150 kg N ha⁻¹ year⁻¹. In addition, F4 operated at a lower stocking rate (3.0 cows ha⁻¹) than the other farmlets (3.9 cows ha⁻¹), reducing supplementary feed demand.

Across all farmlets, enteric fermentation was the dominant source of emissions, contributing the majority of total emissions (approximately 0.45–0.47 kg CO₂-e kg FPCM⁻¹) and showing minimal variation between systems. Smaller contributions were observed from manure management, direct emissions from dung and urine deposited on pasture, indirect nitrogen losses, fertiliser-related emissions, and energy use (electricity and fuel), as well as feed inputs including concentrates and forages. Overall, the differences in total emissions intensity between farmlets were primarily driven by relatively small variations in non-enteric emission sources, particularly nitrogen fertiliser inputs and imported feed. In contrast, the contribution from enteric fermentation remained consistently high across all systems.

All farmlet systems achieved substantially lower emission intensities than those reported in the most recent Tasmanian Dairy Farm Monitor Project (DFMP), which averaged 0.86 kg CO₂e kg FPCM⁻¹ across 24 farms (Dairy Australia, 2025). A key distinction between the experimental farmlets and DFMP farms was milk solids production per cow, which averaged approximately 650 kg MS/cow compared with 460 kg MS/cow in the DFMP. This higher level of productivity likely contributed to greater dilution of maintenance-related greenhouse gas emissions, resulting in lower overall emission intensity.

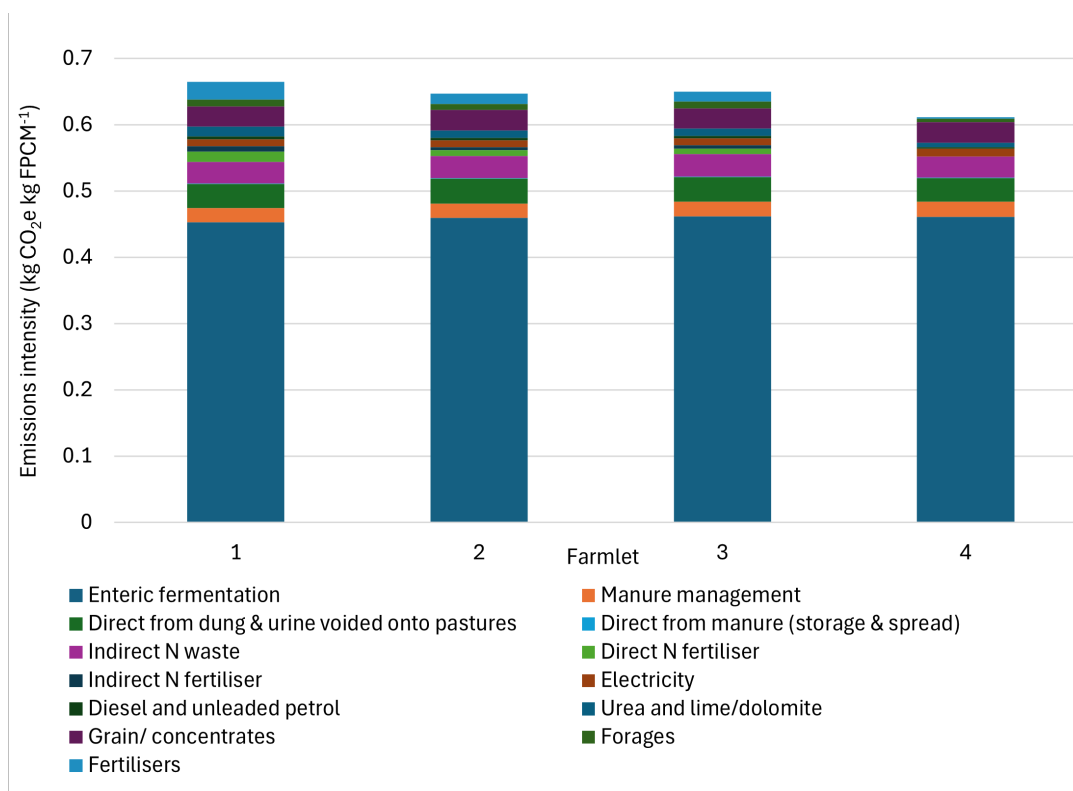


Figure 3.1 Calculated emission intensity ($\text{kg CO}_2\text{e kg FPCM}^{-1}$) at whole-farm level for each farmlet using the Australian Dairy Carbon Calculator.

4. Tasmanian Institute of Agriculture Dairy Research Facility Open Day Attendance and Feedback

On 17 February 2026, the TDRF Open Day attracted 120 visitors, including dairy producers, industry stakeholders, researchers, and members of the wider community. As part of the event, project staff delivered three separate 15-minute in-field presentations on the operation and application of the GreenFeed system. The presentations highlighted activities being undertaken through the ZNE-Ag CRC Demonstration Site project, including research investigating enteric methane emissions from dairy cows grazing the DairyHIGH2 farmlet systems. The sessions provided an overview of how GreenFeed technology measures methane emissions from grazing cattle and how these measurements contribute to improving understanding of greenhouse gas emissions from dairy production systems. Attendees showed strong interest in the technology, particularly its potential role in validating and improving current national greenhouse gas inventory methodologies and supporting

future emissions reporting and mitigation strategies for the dairy industry. Discussion and questions from participants reflected a high level of interest in methane measurement technologies and their practical application within commercial grazing systems, highlighting the value of the demonstration activity in increasing industry awareness and knowledge of emissions monitoring approaches. Feedback on the farm walk was positive, with 47.4% of attendants rating the presentation as *Excellent* and 31.6% rating it as *Good*. The remaining 21.1% chose not to evaluate the presentation.