Final Report

P1d Carbon neutral Kikuyu pasture systems

THE UNIVERSITY OF SYDNEY

Dairy Research Foundation

This project was led by Luciano Gonzalez
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.

Proudly funded by

Delivery organisations

Additional program supporters, collaborations or partnerships

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

Contents

1. Executive Summary

Australian dairy systems play a vital role in national food security and rural economies but contribute significantly to greenhouse gas (GHG) emissions, particularly enteric methane (CH_4) and nitrous oxide (N_2O). Achieving carbon-neutral dairy production requires system-specific, evidence-based strategies that reduce emissions while supporting productivity and long-term farm viability. This Dairy UP project, supported by the NSW Environmental Protection Authority, generated integrated data on whole-farm emissions, feeding strategies, CH_4-monitoring technologies, soil carbon (C) and others nutrient stocks, digital soil product accuracy, and pasture-level GHG fluxes across Australian dairy systems.

Whole-farm assessments showed that emissions intensity was similar between confinement and pasture-based systems, averaging 1.02 ± 0.038 and 1.07 ± 0.069 kg CO_2-eq/kg fat- and protein-corrected milk (FPCM), respectively. Enteric CH_4 was the dominant emission source (54–58%) in both systems. Secondary emissions differed by production system: manure-related emissions were higher in confinement systems, while fertiliser-related N_2O and upstream feed emissions were higher in pasture-based systems. Tree sequestration offset up to 6% of emissions in pasture-based systems but only 1% in confinement systems. These findings underscore where priorities may lie to mitigate GHG emissions in each production system such as improved manure management in confinement systems, fertiliser optimisation in pasture systems, and enteric CH_4 reduction across both systems.

Analysis of 120 commercial pasture-based farms showed that 2–3 t DM/cow/year concentrate supplementation increased milk production and reduced emissions intensity by approximately 12%. Although farm profits varied, the overall trend shows that this level of concentrate feeding can improve emissions efficiency, with actual profitability depending on each farm's management and market conditions.

Low-cost CH_4 sensors demonstrated moderate agreement with GreenFeed but lower repeatability and sensitivity to environmental conditions. While not yet suitable as a replacement for established systems, the results indicate strong potential for future low-cost, scalable CH_4 monitoring to support benchmarking and mitigation verification.

Soil assessments across nine NSW dairy farms showed that pasture-based systems stored substantially more soil organic carbon (75% higher) and nitrogen (65% higher) than confinement systems, particularly under permanent pasture and tree cover. In contrast, confinement systems accumulated significantly higher phosphorus stocks (3.7-fold higher), underscoring the need for targeted nutrient management. These findings highlight how land use, climate, and farming system influence soil C and nutrient stocks.

Validation of the Soil and Landscape Grid of Australia (SLGA) showed moderate accuracy for C and nitrogen at whole-farm scales but poor performance for phosphorus and fine-scale variation, limiting its suitability for carbon crediting or paddock-level planning. While SLGA can assist with broad baseline assessments where direct sampling is not possible, its accuracy is not sufficient for C crediting or for sub-farm planning and nutrient management decisions.

Measurements of GHG fluxes from C3 (ryegrass) and C4 (kikuyu) pastures revealed that pasture type and management strongly influence short-term C dynamics. Ryegrass pastures acted as net CO_2 sinks during regrowth, whereas kikuyu pastures became net GHG sources when surplus biomass required slashing. Shorter chamber closure times improved flux accuracy, and non-linear models were necessary for reliable CO_2 estimation under longer closures. These findings highlight the importance of pasture species, grazing management, and measurement methodology in assessing pasture-level contributions to whole-farm C balances.

Overall, the project shows that achieving C neutrality in Australian dairy systems is possible only through integrated, system-specific pathways that combine enteric CH_4 reduction, productivity-enhancing nutrition, improved manure and fertiliser management, and long-term stewardship of soil and vegetation C. One-size-fits-all mitigation approaches are unlikely to deliver optimal outcomes.

2. Project Overview

Please complete the table below

Item	Description
Project Title	Carbon on NSW Dairy Farms
Funding Body	Dairy UP and NSW EPA
Dairy UP Project	PhD research component
Project Duration	2022–2026
Lead Organisation	The University of Sydney
Project Lead	Luciano Gonzalez
Key Collaborators	The University of Sydney and

Research team: Prof. Luciano González (University of Sydney), Mulisa Dida (University of Sydney), Prof. Sergio García (University of Sydney), Madison Luke (University of Sydney), Milad Bagheri Shirvan (University of Sydney), Budiman Minasny (University of Sydney), Ho Jun Janga (University of Sydney), Feike A. Dijkstra (University of Sydney) and Toshikazu Kawaguchi (Hokkaido University, Japan).

3. Abbreviations

List of all abbreviations, using the example formatting below

ADCC	**Australian Dairy Carbon Calculator**
ADSA	**American Dairy Science Association**
AARN	**Australian Association of Ruminant Nutrition**
C	**Carbon**
ASAS	**American Society of Animal Science**
CH_4	**Methane**
CO_{2eq}	**Carbon dioxide equivalent**
DM	**Dry matter**
DRF	**Dairy Research Foundation**
EBIT	**Earnings before interest and tax**
FPCM	**Fat protein corrected milk**
g	**Gram**
GHG	**Greenhouse gases**
HDR	**Higher Degree by Research**
Kg	**Kilogram**
LCA	**Life cycle assessment**
n	**Number of observations**
N_2O	**Nitrous oxide**
NSW	**New South Wales**
NZSSS	**New Zealand Society of Soil Science**
SLGA	**Soil and Landscape Grid Australia**
SOC	**Soil organic carbon**
SOLES	**School of Life and Environmental Science**
SSA	**Soil Science Australia**
t	**Tone**
USYD	**The University of Sydney**

4. Project Background and Rationale

The Australian dairy industry is a major contributor to national food security and rural economies, but it also generates substantial greenhouse gas (GHG) emissions, particularly enteric methane (CH_4), manure-derived CH_4, and fertiliser-related nitrous oxide (N_2O) (Christie, 2019; Garnett and Eckard, 2024). Nationally, dairy farming produces an estimated 9–10 Mt CO_2-eq annually, accounting for around 12–14% of agricultural emissions, with enteric CH_4 consistently representing more than half of total farm-level emissions (Australian Government DCCEEW, 2023; Christie, 2019). In response to climate change and obligations under the Paris Agreement, Australia has committed to net-zero emissions by 2050 and an interim 43% reduction below 2005 levels by 2030. Consistent with these national targets, Dairy Australia aims to reduce the emissions intensity of dairy production by 30% relative to 2015 levels by 2030 (Dairy Australia & Agriculture Victoria, 2021).

Australian dairy farms operate under diverse production systems, ranging from predominantly pasture-based operations to increasingly intensive confinement and hybrid systems (Christie, 2019; Joubran et al., 2021). These systems differ in feeding strategies, manure management, fertiliser use, land-use patterns, and reliance on external inputs, resulting in distinct emissions profiles and mitigation opportunities (Christie, 2019; Garnett and Eckard, 2024). Feeding strategies particularly concentrate supplementation play a central role in productivity and emissions intensity, yet their combined environmental and economic impacts under commercial Australian conditions remain insufficiently quantified (Arndt et al., 2022).

Progress toward emissions reduction is further constrained by limited access to affordable CH_4-monitoring technologies. Gold-standard systems such as GreenFeed provide accurate measurements but are costly and impractical for widespread adoption (Hammond et al., 2016; Hristov et al., 2018). Soils and vegetation also contribute significantly to whole-farm C balances, but reliable farm-scale information on soil C and nutrient stocks is scarce (Guo and Gifford, 2002; Eckard and Cullen, 2011). Digital soil products such as the Soil and Landscape Grid of Australia (SLGA) offer potential for scalable assessment, yet their accuracy for dairy systems has not been well validated. Pasture systems themselves influence C dynamics through CO_2 exchange (Liang et al., 2021, Bagheri Shirvan et al., 2025), but empirical data on GHG fluxes from C3 and C4 dairy pastures in Australia remain limited.

This Dairy UP project was established to address these knowledge gaps. By integrating whole-farm emissions assessment, feeding strategy analysis, CH_4-monitoring technology evaluation, soil and nutrient stock quantification, digital soil product validation, and pasture-level GHG flux measurement, the project provides practical, regionally relevant evidence to support climate-smart dairy production and inform pathways toward carbon-neutral dairy systems.

5. Project Objectives

The overall aim of this project was to generate practical, region-specific evidence to support reductions in GHG emissions while maintaining productivity and profitability in Australian dairy systems. The specific objectives were to:

- Quantify whole-farm GHG emissions from pasture-based and confinement dairy systems and identify the major emission sources.
- Assess how different levels of concentrate supplementation affect milk production, emissions intensity, and farm profitability in commercial farms.
- Evaluate the performance of low-cost CH_4 sensors against the GreenFeed system to determine their potential for scalable on-farm CH_4 monitoring.
- Quantify soil C and nutrient stocks across key land-use types in pasture-based and confinement systems.
- Test the reliability of the SLGA for farm- and sub-farm-scale assessment of soil C, nitrogen, and phosphorus.
- Quantify GHG fluxes from C3 and C4 pastures and evaluate how pasture type, grazing, and measurement methodology influence short-term carbon dynamics.

Together, these objectives were designed to inform practical, whole-farm mitigation strategies and support evidence-based decision-making for industry, policymakers, and producers working toward carbon-neutral dairy pathways.

6. Subproject 1: Whole-farm GHG emissions of confinement vs pasture-based dairy systems

Research team: Prof. Luciano González (University of Sydney), Mulisa Dida (University of Sydney), and Prof. Sergio García (University of Sydney),

6.1. Background & Rationale

Australian dairy farms operate under diverse production systems that differ in feeding, manure management, fertiliser use, and land-use patterns, leading to distinct emissions profiles. However, there is limited Australian-specific data comparing whole-farm GHG emissions across confinement and pasture-based systems using consistent boundaries. This subproject addressed this gap by quantifying system-level emissions and identifying mitigation priorities.

6.2. Objectives

- Quantify whole farm GHG emissions from pasture based and confinement dairy systems.
- Identify major emission sources and system specific mitigation priorities.
- Assess the contribution of tree-based C sequestration to whole farm emissions.
- Provide evidence to support system specific pathways toward C neutral dairy production.

6.3. Methods

Farm sample: Ten commercial NSW dairy farms were assessed (five pasture-based and five confinement).

Emissions modelling: Whole-farm GHG emissions were estimated using the Australian Dairy Carbon Calculator (ADCC), incorporating:

- Herd structure and productivity
- Feed used and purchased feed emissions
- Manure management systems
- Fertiliser inputs and N_2O emissions
- Energy use
- Tree cover and carbon sequestration

Emission sources included:

- Enteric CH_4
- Manure CH_4 and N_2O
- Fertiliser-related N_2O
- Upstream feed emissions
- Tree-based carbon offsets
- All results were expressed as kg CO_2-eq per kg fat- and protein-corrected milk (FPCM).

6.4. Key Findings

- Emission intensity was similar across systems
    - *Pasture-based: 1.07 ± 0.069 kg CO_2-eq/kg FPCM*
    - *Confinement: 1.02 ± 0.038 kg CO_2-eq/kg FPCM*
- Enteric CH_4 dominated emissions, confirming its central role in mitigation.
- Manure emissions were substantially higher in confinement systems *(31% of total vs 13% in pasture-based)* due to stored manure and anaerobic conditions.
- Fertiliser and pre-farm emissions were higher in pasture-based systems, reflecting greater reliance on N fertiliser.
- Tree-based carbon offsets were modest, contributing:
    - *~1% of total emissions in confinement systems*
    - *~6% in pasture-based systems*
- System-specific mitigation priorities emerged:
    - Confinement → manure management
    - Pasture-based → fertiliser optimisation
    - Both → enteric CH_4 reduction

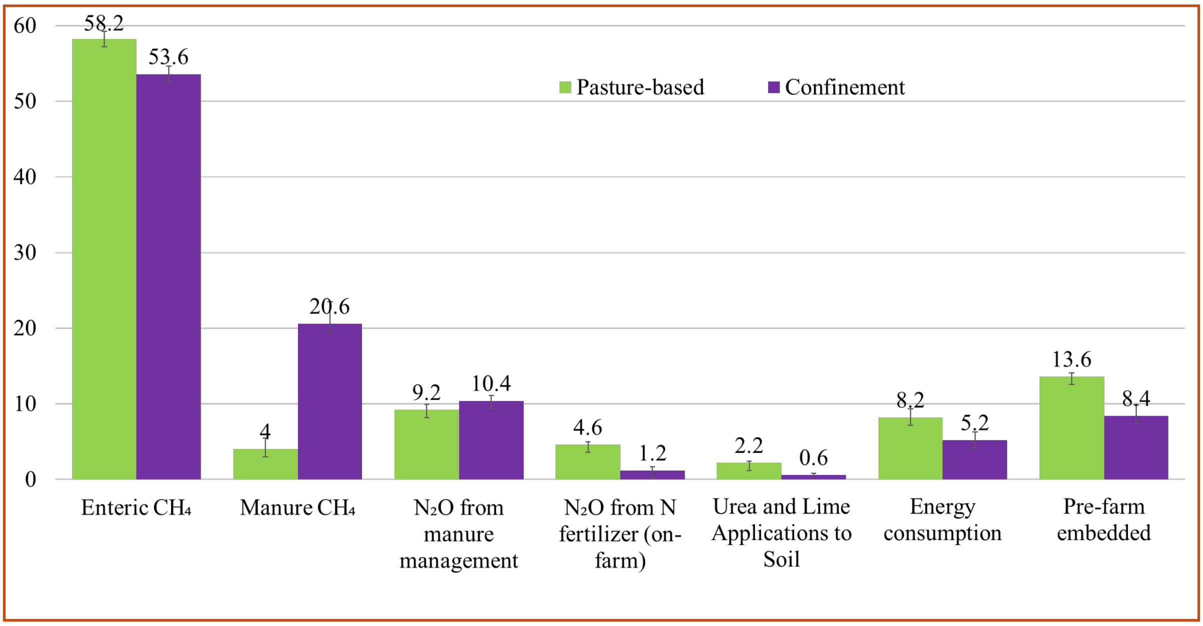

Figure 1. Breakdown by source, % of total farm CO_{2eq}

6.5 Applications & Impacts

Farm-level:

- Confinement farms can reduce emissions through improved manure storage and handling.
- Pasture-based farms can benefit from fertiliser efficiency strategies and optimised N use.
- Enteric CH_4 mitigation (e.g., feed additives, genetics, diet optimisation) is essential across all systems.

Industry-level:

- Results support improved national GHG inventories and C-accounting frameworks.
- Evidence informs Dairy Australia's sustainability reporting and net-zero planning.

Environmental:

- Tree cover provides modest offsets but cannot replace direct mitigation.
- System-specific strategies are required; one-size-fits-all approaches are ineffective.

6.6. Limitations of the study

- SOC sequestration was not included in whole-farm balances.
- Sample size (n=10 farms) limits national representativeness.
- Tree sequestration estimates rely on default factors.

6.7. Key Outputs

- Whole-farm emissions dataset for 10 NSW dairy farms.
- Peer-reviewed publication in Journal of Dairy Science (2025).
- Integrated modelling framework combining herd, feed, manure, fertiliser, and tree-cover data.
- Conference presentations at ADSA, AARN, and DRF Symposium.

6.8. Future Research Opportunities

- Expand whole-farm assessments across more regions and production systems.
- Integrate soil C sequestration into whole-farm C balances.
- Evaluate combined mitigation strategies (feeding, manure, fertiliser, genetics).
- Develop system-specific emission factors for Australian conditions.
- Support industry adoption through training and improved C-accounting tools.

7. Subproject 2: Concentrate supplementation, emissions intensity, and profitability

Research team: Prof. Luciano González (University of Sydney), Mulisa Dida (University of Sydney), and Prof. Sergio García (University of Sydney).

7.1. Background & Rationale

Concentrate supplementation is widely used to support milk production in pasture-based dairy systems, yet its combined effects on emissions intensity and profitability under commercial Australian conditions remain poorly quantified. Variation in supplementation practices across regions creates uncertainty about optimal feeding levels. This subproject examined how different supplementation rates influence productivity, emissions, and economic outcomes.

7.2. Objectives

- Quantify how different levels of concentrate supplementation affect milk yield.
- Assess the impact of supplementation on emissions intensity (CO_2-eq/kg FPCM).
- Evaluate economic outcomes (gross margin, EBIT) across supplementation levels.
- Identify supplementation ranges that optimise both productivity and emissions efficiency.

7.3. Methods

Dataset: A stratified sample of 120 pasture-based dairy farms across South Australia, New South Wales, Tasmania, and Victoria was analysed using Dairy Australia's Dairy Farm Monitoring Project dataset.

Farm classification: Farms were grouped by annual concentrate feeding level:

- Low: <1 t DM/cow/year
- Moderate: 1-2 t DM/cow/year
- High: 2–3 t DM/cow/year
- Very high: >3 t DM/cow/year

Emissions modelling: Emissions were estimated using the Australian Dairy Carbon Calculator (ADCC) following National Greenhouse Gas Inventory methodologies.

Economic analysis: Gross margin and EBIT were calculated using data extracted from the DFMP dataset and compared across supplementation groups.

7.4. Key Findings

- Supplementation of 2–3 t DM/cow/year increased milk yield and reduced emissions intensity by approximately 12% compared with supplementation of <1 t DM/cow/year
- Economic indicators (gross margin, EBIT) were generally highest in the 2–3 t DM/cow/year.
- Supplementation above 3 t DM/cow/year showed diminishing productivity returns and higher manure-related emissions.
- Productivity gains were the primary driver of improved emissions efficiency.

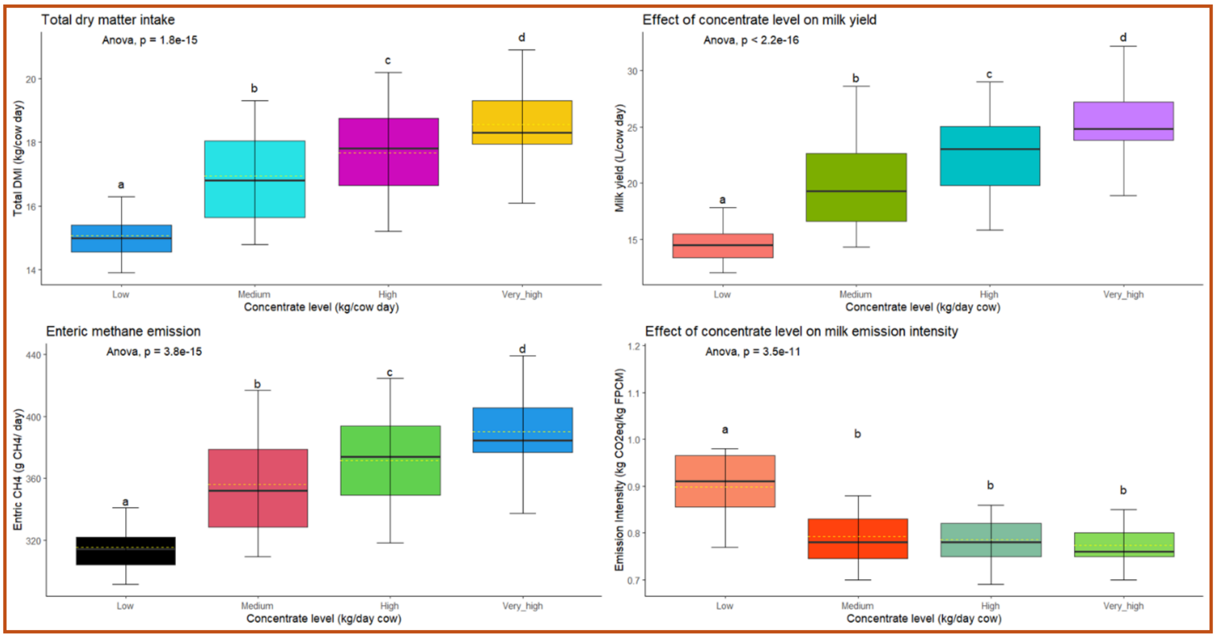

Figure 2. Effects of concentrate feeding on dry matter intake (DMI), Milk yield, enteric CH_4, FPCM emission intensity

7.5. Applications & Impacts

Farm-level:

- 2–3 t DM/cow/year supplementation is a practical, scalable strategy to reduce emissions intensity.
- Over-supplementation (>3 t) increases costs.
- Feeding strategies should be integrated with manure management to avoid shifting emissions between sources.

Industry-level:

- Results support refinement of feeding guidelines and benchmarking tools.
- Evidence informs Dairy Australia's sustainability reporting and extension programs.

Environmental:

- Improved emissions efficiency contributes to national net-zero targets.
- Strategic supplementation reduces emissions per litre of milk without compromising profitability.

7.6. Limitations of this study

- Feed quality and dry matter intake were not directly measured.
- Economic outcomes vary with milk price and feed cost fluctuations.

7.7 Key Outputs

- Integrated dataset linking supplementation, emissions, and profitability across 120 farms.
- Peer-reviewed publication in *Journal of Dairy Science* (2024).
- Conference presentations at ADSA, AARN, and DRF Symposium.
- Evidence-based recommendations for feeding strategies in pasture-based systems.

7.8 Future Research Opportunities

- Conduct controlled trials measuring dry matter intake, feed quality, and CH_4 emissions.
- Develop diet-specific emission factors for Australian pasture-based systems.
- Evaluate combined feeding and manure-management strategies.
- Model long-term economic and environmental impacts of supplementation strategies.
- Integrate supplementation data into digital decision-support tools.

8. Subproject 3: Low-cost Methane Sensor Validation

Research team: Prof. Luciano González (University of Sydney), Mulisa Dida (University of Sydney), Prof. Sergio García (University of Sydney), Milad Bagheri Shirvan (University of Sydney) and Toshikazu Kawaguchi (Hokkaido University, Japan).

8.1. Background

Accurate CH_4 measurement is essential for benchmarking emissions and verifying mitigation strategies, but existing systems such as GreenFeed are costly and impractical for widespread farm use. Low-cost sensors offer potential for scalable monitoring, yet their performance under real farm conditions is not well understood. This subproject evaluated the accuracy and suitability of a low-cost CH_4 sensor for dairy applications.

8.2. Objectives

- Test the performance of a low-cost CH_4 sensor against the GreenFeed system.
- Assess whether the sensor can detect meaningful differences in CH_4 output.
- Determine whether the technology is suitable for on-farm monitoring or requires further development.

8.3. Materials & Methods

A 45-day trial was conducted with 28 dairy heifers. Each animal was monitored using:

- A low-cost MQ-4 CH_4 sensor module
- A GreenFeed system was used as reference method

Sensor performance was evaluated using:

- Correlations between the two systems
- Repeatability (how consistent the sensor is over time)
- Daily and weekly CH_4 patterns

8.4. Key Findings

- Moderate agreement with GreenFeed: Weekly correlation was 0.62, meaning the sensor captured general CH_4 patterns but not precise values.
- Lower repeatability than GreenFeed: The sensor's repeatability was 0.13 compared with 0.31 for GreenFeed, indicating more variability.
- Environmental sensitivity: Temperature, humidity, and airflow affected sensor readings, reducing accuracy.
- Potential for future use: While not yet suitable as a replacement for GreenFeed, the sensor showed enough promise to justify further development.

8.5. Applications & Impacts

Farm-level:

- Low-cost sensors could eventually allow farmers to track CH_4 trends without expensive equipment.
- They could support decision-making around feed changes, additives, or herd management.

Industry-level:

- Affordable CH_4 monitoring is essential for verifying mitigation strategies and supporting carbon-neutrality programs.
- This work provides the first Australian evidence on the potential of low-cost sensors.

Environmental:

- Scalable CH_4 monitoring is a key enabler of national emissions-reduction goals.

8.6. Limitations

- Sensor performance was tested under a single season and production system, limiting broader applicability.
- Readings were sensitive to temperature, humidity, and airflow, which were not fully corrected for.
- Calibration relied on one reference method (GreenFeed) and one animal group.
- The study assessed short-term performance only; long-term sensor drift was not evaluated.
- The sensor measured relative CH_4 concentrations rather than absolute emissions.

8.7. Key Outputs

- First Australian field evaluation of a low-cost CH_4 sensor for dairy cattle.
- Peer-reviewed publication in *Smart Agricultural Technology* (2025).
- Dataset linking sensor readings with GreenFeed measurements.

8.8. Future Research Opportunities

- Improve sensor calibration and environmental correction algorithms.
- Test sensors across different feeding systems, climates, and herd types.
- Integrate sensors into digital farm platforms for real-time monitoring.
- Develop low-cost systems suitable for commercial adoption.

9. Subproject 4: Soil Carbon and Nutrient Stocks Across Dairy Land-Use Types

Research team: Prof. Luciano González (University of Sydney), Mulisa Dida (University of Sydney), Prof. Sergio García (University of Sydney), Madison Luke (University of Sydney), Milad Bagheri Shirvan (University of Sydney), and Budiman Minasny (University of Sydney),

9.1. Background

Soil C and nutrient stocks are critical components of whole-farm C balances and nutrient management, yet farm-scale data for Australian dairy systems are limited. Differences in land use, climate, and production system likely influence soil properties, but these patterns are not well quantified. This subproject assessed soil C, N, P and other soil physiochemical properties and stocks across major land-use types in NSW dairy farms.

9.2. Objectives

- Quantify soil C, and other soil physiochemical properties and stocks across major land-use types.
- Compare soil C and other soil physiochemical properties and stocks stocks between pasture-based and confinement dairy systems.
- Identify land-use drivers of soil C and nutrient variation.

9.3. Methods

Soil samples (n=810) were collected from nine NSW dairy farms across permanent pasture, mixed pasture-cropping, cropping, tree areas, and natural pasture. Laboratory analyses quantified SOC, total N, total P and other soil physiochemical properties. Stocks were calculated based on land-use proportions.

9.4. Key Findings

- Pasture-based farms stored more carbon and nitrogen:
  - *SOC: 75% higher than confinement farms*
  - *Total N: 65% higher*
- Tree areas and permanent pastures had the highest SOC and N stocks.
- Confinement farms had much higher phosphorus stocks (3.7-fold higher).
- Rainfall and land-use history were major drivers of SOC differences.

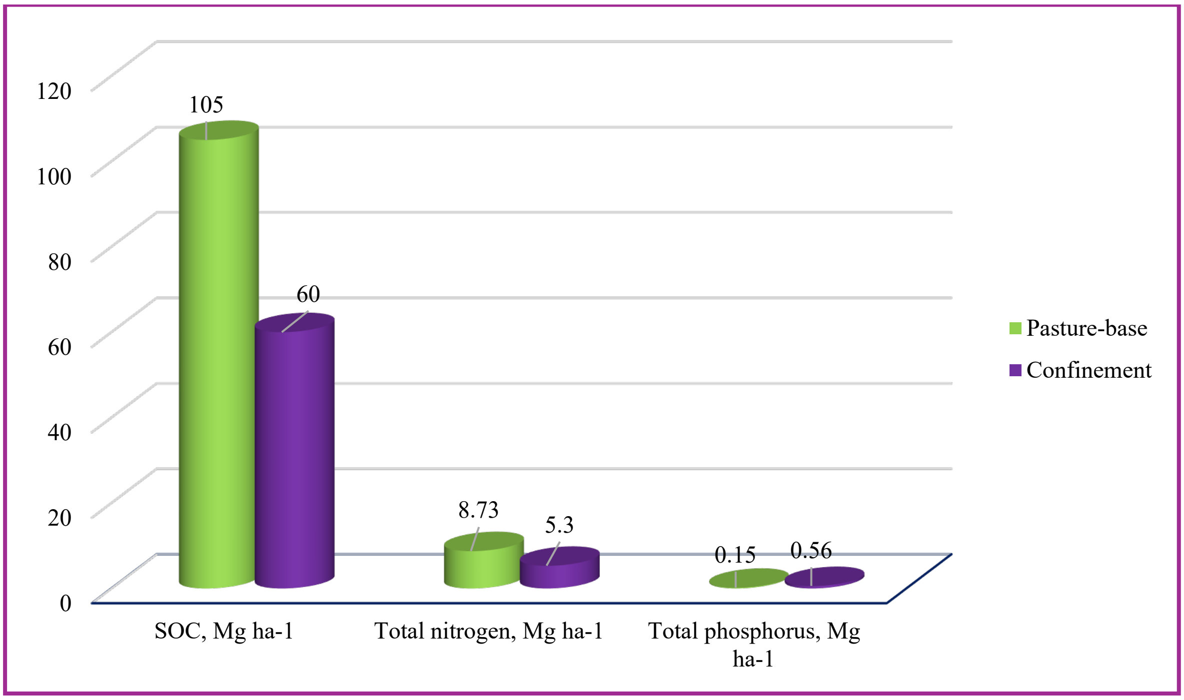

Figure 3. Effect of farming system on SOC stock and total nitrogen and phosphorus (Mg ha $^{-1}$) in dairy farms

9.5. Applications & Impacts

Farm-level:

- Maintaining permanent pastures and tree areas helps build soil C.
- Confinement farms need careful phosphorus management to avoid nutrient overload.
- Soil testing supports better fertiliser decisions and cost savings.

Industry-level:

- Results support improved C accounting and nutrient-management guidelines.
- Evidence helps refine national soil-C models for dairy systems.

Environmental:

- Healthy soils contribute to climate resilience and long-term sustainability.

9.6. Limitations

- The study assessed soil stocks at one point in time; changes in soil C sequestration rates were not measured.
- Sampling was limited to NSW dairy farms, reducing national representativeness.
- Sampling occurred across farms with different rainfall zones, soil types, and management histories, which may influence comparability

9.7. Key Outputs

- Comprehensive soil dataset across nine NSW dairy farms.

- Peer-reviewed publication in Environmental Impact Assessment Review (2026).
- Evidence supporting soil stewardship in dairy systems.

9.8. Future Research Opportunities

- Repeat sampling to measure soil C change over time.
- Expand assessments to other states and production systems.
- Integrate soil data into whole-farm C-neutrality models.
- Develop improved nutrient-management tools for confinement systems.

10. Subproject 5: Validation of the Soil and Landscape Grid of Australia

Research team: Prof. Luciano González (University of Sydney), Mulisa Dida (University of Sydney), Prof. Sergio García (University of Sydney), Budiman Minasny (University of Sydney), and Ho Jun Janga (University of Sydney).

10.1. Background

Digital soil products such as the Soil and Landscape Grid of Australia (SLGA) are increasingly used for C accounting and environmental reporting, but their accuracy for dairy farms has not been validated. Dairy landscapes have complex land-use patterns and high nutrient turnover, which may challenge model performance. This subproject tested SLGA predictions against measured soil data at farm and sub-farm scales.

10.2. Objectives

- Evaluate the accuracy of SLGA predictions for soil C, nitrogen, and phosphorus at both sub-farm (individual Carbon Estimation Areas, CEAs, i.e., paddocks or groups of paddocks with similar land use and management within a farm) and farm scales (aggregated across all CEAs within a farm).

10.3. Materials & Methods

The Soil and Landscape Grid of Australia (SLGA) was evaluated using the same soil dataset from the study of soil C and nutrient stocks across dairy land use types. SLGA predictions for soil C, nitrogen, and phosphorus were compared with laboratory measurements from 810 soil samples collected across nine NSW dairy farms at both point and farm scales. Standard accuracy and error metrics were used to assess the suitability of SLGA for farm-level C accounting.

10.4. Key Findings

- Moderate accuracy for soil C and nitrogen: SLGA captured broad differences between farming systems.
- Poor accuracy for phosphorus: Large errors and weak correlations make SLGA unsuitable for P-related decisions.
- Unreliable for sub-farm planning: SLGA resolution is too coarse for paddock-level management.
- Useful for broad baselines: SLGA can support preliminary assessments where direct sampling is not possible.

10.5. Applications & Impacts

Farm-level:

- SLGA can provide a starting point for understanding soil C and nitrogen.
- Ground-truthing is essential for phosphorus and for paddock-level decisions.

Industry-level:

- Results clarify when national digital tools are appropriate.
- Findings support development of improved digital soil products.

Environmental:

- Better soil information supports C accounting and nutrient stewardship.

10.6. Limitations

- •SLGA predictions were evaluated using soil samples from a limited number of NSW dairy farms, reducing national representativeness.
- The resolution of SLGA products is coarse relative to paddock-scale variability, limiting fine-scale comparison.
- SLGA models were not calibrated specifically for dairy landscapes, which have high nutrient turnover and complex land-use patterns.
- Soil samples and SLGA predictions were not always matched under identical temporal or environmental conditions.
- The study assessed SLGA accuracy at one point in time; temporal changes in soil properties were not evaluated.

10.7. Key Outputs

- First dairy-specific validation of SLGA using real farm soil data.
- Peer-reviewed publication under review in Environmental Technology & Innovation.
- Practical guidance for using digital soil tools in dairy systems.

10.8. Future Research Opportunities

- Improve digital soil mapping for nutrient-specific accuracy.
- Develop dairy-system-specific calibration datasets.
- Integrate digital tools with targeted soil sampling strategies.
- Support industry training on appropriate use of digital soil products.

11. Subproject 6: Greenhouse gas fluxes from C3 and C4 pastures

Research team: Prof. Luciano González (University of Sydney), Milad Bagheri Shirvan (University of Sydney), and Feike A. Dijkstra (University of Sydney).

11.1. Background

Pasture systems influence whole-farm carbon balances through CO_2 exchange, yet empirical data on greenhouse gas fluxes from C3 and C4 dairy pastures in Australia are limited. Differences in species, growth patterns, and management may affect short-term carbon dynamics. This subproject quantified GHG fluxes from ryegrass and kikuyu pastures and evaluated methodological factors affecting flux measurement.

11.2. Objective

This project included two studies examining methodological and ecological aspects of GHG flux measurement in pastures:

- To examine the effect of different mathematical models on GHG flux estimation and identify the optimal chamber closure period in both C_3 and C_4 pastures,
- To investigate the relationship between GHG fluxes and aboveground biomass changes in C_3 and C_4 pastures.

11.3. Methods

These studies were conducted in two pasture types in Western Sydney, NSW, a ryegrass (C_3) pasture and a kikuyu (C_4) pasture. An area of 12 × 12 m was selected as trial site in each pasture. The measurements were performed in spring in C_3 pasture, and in summer in C_4 pasture. The C_3 pasture was dominated by annual ryegrass (*Lolium multiflorum L.*), and the C_4 pasture by kikuyu (*Pennisetum clandestinum* Hoschst. ex Chiov). Eight automated chambers connected to a gas analyser (G2508, Picarro Inc., USA) were used to measure CO_2, CH_4, and N_2O concentrations.

The fluxes were estimated by fitting linear and non-linear models to gas concentrations recorded over closure time. Each measurement was divided into three closure periods to examine the effect of closure period on flux estimation. To assess the effect of grazing, each trial site was divided into two areas, one exposed to cattle grazing (grazed) and one fenced to exclude cattle grazing (ungrazed), with four chambers located in each area.

Aboveground biomass was sampled at the beginning of the measurement period, following the grazing event, and at the end of the measurement period to quantify change in aboveground biomass.

11.4. Key findings

Chamber effects on measurement accuracy

- Closed chambers can alter the micro-environment by changing temperature, humidity, and light, which can influence gas measurements.
- Shorter closure periods minimise these artefacts and improve data quality.
- At longer closure periods, CO_2 concentrations became increasingly non-linear ($p < 0.001$), meaning non-linear models were more appropriate for estimating CO_2 fluxes.
- This non-linearity occurred in both pasture types but was more pronounced in C4 (kikuyu) pasture.
- For short closure periods, a simple linear model was sufficient and reliable.

Effects on CH_4 and N_2O

- Closure period length did not significantly affect CH_4 or N_2O fluxes in either pasture type.
- Longer closure periods may still be useful because CH_4 and N_2O fluxes are highly variable, and extended measurement time can improve detection.
- Greenhouse gas dynamics in C3 vs C4 pastures
- Kikuyu (C4) pasture produces surplus biomass that often requires slashing, and during this period the pasture acted as a net source of GHG emissions.
- Ryegrass (C3) pasture acted as a net sink of CO_2, capturing carbon during regrowth.

Carbon capture per kg of aboveground biomass change:

- C3 grazed: 0.85 kg CO_2-eq/kg
- C3 ungrazed: 3.25 ± 0.31 kg CO_2-eq/kg
- C4 grazed: 0.41 ± 0.252 kg CO_2-eq/kg
- C4 ungrazed: 0.73 ± 0.218 kg CO_2-eq/kg

11.5. Applications and Impacts

Farm-level:

- Understanding when C3 and C4 pastures act as carbon sinks or sources supports better grazing and slashing decisions.

Industry-level:

- Results help refine GHG measurement protocols can be used in research and extension programs.
- Findings support more accurate carbon-accounting models for pasture-based dairy systems.

Environmental:

- Improved measurement practices strengthen confidence in reported GHG reductions.
- Identifying carbon-sink periods in pastures supports climate-smart pasture management.

11.6. Limitations

- Further research over longer periods of time and multiple pasture species are required to generate the information for estimating the full carbon balance of livestock production.

11.7. Key Outputs

- Dataset of CO_2, CH_4, and N_2O fluxes across C3 and C4 pastures.
- Evidence on optimal chamber closure periods and modelling approaches.
- Peer-reviewed publication in Agriculture, Ecosystems & Environment (Bagheri Shirvan et al., 2025).

11.8. Future Research Opportunities

- Extend flux measurements across seasons and additional pasture types.
- Quantify long-term carbon sequestration potential under different grazing strategies.
- Integrate pasture flux data into whole-farm carbon models.
- Evaluate mitigation options (e.g., biomass removal, grazing timing) to reduce GHG emissions from C4 pastures.

12. Project-wide Dissemination

The project's findings were disseminated through multiple channels, including a PhD thesis, peer-reviewed journal publications, newsletter, and presentations at national and international conferences (ADSA, AARN, NZSSS/SSA, DRF Symposium). Industry engagement occurred through Dairy UP communication channels, workshops, and direct interactions with producers and stakeholders. These activities ensured the research reached researchers, farmers, and policymakers, supporting knowledge exchange on sustainable dairy practices.

Table 1. Peer-reviewed publications.

Author	Title	Journal	Year Published	Citations (to May 13)
Dida et al., 2026	Environmental impacts of dairy farming intensification and land use on soil organic carbon stocks and physicochemical properties	Environmental Impact Assessment Review	2026	
Dida et al., 2025	Potential applications of a low-cost gas sensor to monitor enteric methane emission from ruminant animals	Smart Agricultural Technology	2025	3
Dida et al., 2025	Greenhouse gas emissions of confinement and pasture-based dairy farms: Implications for mitigation	Journal of Dairy Science	2025	5
Bagheri et al., 2025	Short-term effect of grazing on net ecosystem exchange and fluxes of greenhouse gases in C3 and C4 pastures during the growing season	Journal of Agriculture, Ecosystems & Environment	2025	1
Dida et al., 2024	Dietary concentrate supplementation increases milk production and reduces predicted greenhouse gas emission intensity in pasture-based commercial dairy farms	Journal of Dairy Science	2024	14

13. Conclusions and Recommendations

The findings of this Dairy UP project demonstrate that achieving carbon-neutral dairy production in Australia is possible but requires coordinated, system-specific strategies that address the major sources of GHG emissions while supporting productivity and economic resilience. Across confinement and pasture-based systems, emissions intensity was broadly similar, with enteric CH_4 consistently the dominant source.

This confirms that meaningful progress toward carbon neutrality will depend on effective enteric CH_4 mitigation across all production systems. System-level differences highlight the need for tailored approaches. Confinement systems require improved manure management to reduce CH_4 and N_2O emissions from stored effluent, while pasture-based systems benefit most from optimising nitrogen fertiliser use and improving nutrient efficiency. Moderate concentrate supplementation (2–3 t DM/cow/year) emerged as a practical strategy to improve emissions intensity through productivity gains, although over supplementation increases costs and manure-related emissions without proportional benefits.

The project also demonstrated the importance of enabling technologies and natural resource stewardship. Low-cost CH_4 sensors showed promising potential for future on-farm CH_4 monitoring, although further development is required. Soil assessments revealed that pasture-based systems store substantially more C and nitrogen than confinement systems, particularly under permanent pasture and tree cover, while confinement systems accumulate higher phosphorus stocks, underscoring the need for targeted nutrient management. Validation of the Soil and Landscape Grid of Australia (SLGA) showed moderate accuracy for carbon and nitrogen at whole-farm scales but insufficient precision for phosphorus or paddock-level decision-making.

Pasture-level GHG flux measurements further highlighted that species composition and management influence short-term C dynamics, with ryegrass acting as a CO_2 sink during regrowth and kikuyu becoming a source when surplus biomass is removed. Together, these findings show that no single mitigation strategy is sufficient. Instead, progress toward C-neutral dairy systems requires integrated actions across feeding, manure and fertiliser management, soil and vegetation stewardship, and improved emissions measurement.

Recommendations

1. Prioritise enteric CH_4 mitigation across all dairy systems
    - Support adoption of proven CH_4-reducing feed additives, genetics, and diet optimisation.
    - Invest in research and extension to accelerate commercial readiness of emerging technologies.
2. Implement system-specific mitigation strategies
    - Confinement systems: Improve manure storage, handling, and effluent treatment to reduce CH_4 and N_2O.
    - Pasture-based systems: Optimise nitrogen fertiliser use through soil testing, timing, and precision application.
3. Promote productivity-enhancing feeding strategies
    - Encourage 2–3 t DM/cow/year concentrate supplementation where economically viable.
    - Avoid over supplementation that increases emissions and costs without improving milk solids.
4. Strengthen soil and nutrient stewardship
    - Maintain permanent pastures and tree areas to enhance soil carbon and nitrogen stocks.
    - Improve phosphorus management in confinement systems to prevent nutrient accumulation and environmental risk.
5. Improve emissions measurement and monitoring capacity
    - Continue development and validation of low-cost CH_4 sensors for scalable on-farm use.
    - Integrate sensor data into digital decision-support tools for benchmarking and mitigation verification.
    - 6. Use digital soil products cautiously
    - Apply SLGA for broad, whole-farm baseline assessments where direct sampling is not feasible.
7. Expand integrated research and industry adoption pathways
    - Conduct multi-site trials combining feeding, manure, fertiliser, and land-use strategies.
    - Develop training, extension programs, and carbon-accounting tools tailored to diverse production systems.

14. Annexes

Table 2. Conference presentations, abstracts and other meetings

Authors	Title	Presentation Type	Conference/Event	Location	Year	Audience
Mulisa D.	Greenhouse Gas Emissions and Soil Carbon Stocks in Dairy Farming Systems	Final PhD Presentation (oral)	SOLES HDR Showcase (USYD)	Sydney	2025	40
Luciano G.	Are we understanding the “hoofprint” of pastures?	Oral presentation	DRF Symposium	Wollongong	2025	150
Luciano G.	Towards net zero dairy production in NSW: a case study approach for a deeper understanding of carbon emissions in NSW dairy farms	Oral presentation	Carbon workshop	Online (Zoom)	2025	25
Mulisa D.	Greenhouse Gas Emissions of Confinement and Pasture-Based Dairy Farms: Implications for Mitigation	Refereed abstract/poster presentation	ADSA Annual Meeting	Louisville, USA	2025	1000
Mulisa D.	Dairy Farming System and Land Use Influence Soil Organic Carbon Stocks	Refereed abstract/poster presentation	ADSA Annual Meeting	Louisville, USA	2025	1000
Mulisa D.	Dietary Concentrate Supplementation Increases Milk Production and Reduces Predicted Greenhouse Gas Emission Intensity in Pasture-Based Commercial Dairy Farms	Oral presentation	Australian Association of Ruminant Nutrition (AARN)	Melbourne	2024	100
Milad B.	Fluxes of greenhouse gases from pastures and methane emissions from beef cattle in Australia.	Oral presentation	ASAS Annual Meeting	Calgary, Canada.	2024	500
Mulisa D.	Farming System and Land Use Type Influence Soil Organic Carbon Stocks of Dairy Farms	Refereed abstract/poster presentation	Joint Conference of the NZSSS and SSA	Rotorua, New Zealand	2024	500
Luciano G.	Pasture alive! Towards net-zero in Kikuyu-based pasture systems – is it possible?	Oral presentation	DRF Symposium	Camden	2023	100
Mulisa D.	Dietary Concentrate Supplementation Benefits Both Dairy Farmers and the Climate: Evidence from the Australian Dairy Farms.	Oral presentation	DRF Symposium	Camden	2023	100

Milad B.	Effect of grazing on net ecosystem exchange and carbon balance in ryegrass pasture	Oral presentation	Soil Science Australia Conference	Darwin, Australia	2023	200
Mulisa D.	Does Dietary Concentrate Supplementation Benefit Both Dairy Farmers and Climate: Evidence from the Australian Dairy Farms	Poster presentation (Intermediate PhD)	SOLES HDR Showcase (USYD)	Sydney	2023	100
Mulisa D.	Greenhouse Gas Emissions and Carbon Soil Stocks in Dairy Farming Systems	Oral presentation (Introductory PhD)	SOLES HDR Showcase (USYD)	Sydney	2022	50
Milad B.	How are carbon dioxide and methane fluxes mediated by grazing in Kikuyu pastures?	Poster presentation	DRF Symposium	Forster, Australia	2022	100

Table 3. Technical reports, pamphlets, published material and other media engagements

Authors	Title	Place Published	Year
Luciano G.	A path to carbon-neutral dairy	Dairy UP Website	2025
Mulisa Dida	Sustainable Dairy Farming: Insights from My PhD Research	Sydney Institute of Agriculture, AgriCola	2025
Luciano G.	Carbon emissions and dairy systems	Dairy UP Website	2025
Luciano G.	Carbon on NSW dairy farms	Dairy UP Website	2023

15. References

Arndt, C., A.N. Hristov, W.J. Price, S.C. McClelland, A.M. Pelaez, S.F. Cueva, J. Oh, J. Dijkstra, A. Bannink, A.R. Bayat, and others. 2022. Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 C target by 2030 but not 2050. Proc. Natl. Acad. Sci. 119:e2111294119.

Bagheri Shirvan, M., F. A. Dijkstra, and L. A. Gonzalez. 2025. Short-term effect of grazing on net ecosystem exchange and fluxes of greenhouse gases in C3 and C4 pastures during the growing season. Agriculture, Ecosystems & Environment 383:109538.

Christie, K. 2019. Greenhouse gas emissions and potential mitigation options for the Australian dairy industry. PhD thesis, University of Tasmania, Australia

Eckard, R.J., and B.R. Cullen. 2011. Impacts of future climate scenarios on nitrous oxide emissions from pasture based dairy systems in south eastern Australia. Anim. Feed Sci. Technol. 166:736–748.

Garnett, L.M., and R.J. Eckard. 2024. Greenhouse-gas abatement on Australian dairy farms: what are the options?. Anim. Prod. Sci. 64.

Guo, L.B., and R.M. Gifford. 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Chang. Biol. 8:345–360. doi:10.1046/j.1354-1013.2002.00486.x.

Hammond, K.J., G.C. Waghorn, and R.S. Hegarty. 2016. The GreenFeed system for measurement of enteric methane emission from cattle. Anim. Prod. Sci. 56:181–189.

Hristov, A.N., E. Kebreab, M. Niu, J. Oh, A. Bannink, A.R. Bayat, T.M. Boland, A.F. Brito, D.P. Casper, L.A. Crompton, and others. 2018. Symposium review: Uncertainties in enteric methane inventories, measurement techniques, and prediction models. J. Dairy Sci. 101:6655–6674.

Joubran, A.M., K.M. Pierce, N. Garvey, L. Shalloo, and T.F. O'Callaghan. 2021. Invited review: A 2020 perspective on pasture-based dairy systems and products. J. Dairy Sci. 104:7364–7382.

Liang, M., N. G. Smith, J. Chen, Y. Wu, Z. Guo, E. S. Gornish, and C. Liang. 2021. Shifts in plant composition mediate grazing effects on carbon cycling in grasslands. Journal of Applied Ecology 58(3):518-527.