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Greenhouse gas emissions of confinement and pasture-based dairy farms: Implications for mitigation

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ABSTRACT

Despite extensive research on the environmental effects of dairy farming, comparative GHG emissions from confinement and pasture-based systems remain unclear due to inconsistent findings from prior studies, which were often specific to the local conditions of each system and overlooked carbon sequestration by trees. The present study aimed to compare the GHG emissions of 2 Australian milk production systems (confinement and pasture-based) using a life cycle assessment approach that incorporates C sequestration by trees. The confinement system used a TMR, whereas the grass-based system primarily relied on grazed forage with concentrate supplementation. The Australian Dairy Carbon Calculator, a Tier 3 tool, predicted emission intensity using the National Greenhouse Gas Inventory and Intergovernmental Panel on Climate Change methods, as reported to the United Nations Framework Convention on Climate Change. Emission intensity was calculated as net GHG exchange in CO_2 equivalents (CO_{2eq}), allocated to milk and meat. Animal emissions dominated: 85% of total emissions in confinement systems (54% enteric CH_4, 31% manure) and 71% in pasture-based systems (58% enteric CH_4, 13% manure). The confinement system showed 13% lower enteric CH_4 intensity and 88% lower prefarm embedded intensity (kg CO_{2eq}/kg fat- and protein-corrected milk [FPCM]) but 129% higher manure-related GHG intensity than the pasture-based system. Emission intensities for milk (1.02 ± 0.038 vs. 1.07 ± 0.069 kg CO_{2eq}/kg FPCM) and meat (5.51 ± 0.779 vs. 6.76 ± 0.868 kg CO_{2eq}/kg liveweight) were similar between systems. The emission offset by tree C sequestration (kg CO_{2eq}/kg FPCM) was relatively low in both systems, contributing about 1% of total CO_{2eq} emissions in confinement systems and up to 6% in pasture-based systems. Targeted mitigation should address manure emissions in confinement systems, prefarm embedded, and fertilizer emissions in pasture-based systems, and enteric CH_4 in both.
Key words: dairy, manure, methane, milk yield

INTRODUCTION

The livestock sector faces the dual challenge of increasing productivity while reducing GHG emissions and adapting to a changing climate (Gerber et al., 2013). Livestock currently contributes 34% of global protein intake and 17% of calorie consumption, with demand continuing to rise due to population growth, urbanization, and increasing incomes (FAO, 2022). Dairy products alone contribute 11% of global protein and 5% of calorie intake (FAO, 2022). However, livestock is responsible for 14.5% of global anthropogenic GHG emissions, with ruminants accounting for 75% of these (IPCC, 2019). Dairy farming plays a substantial role in these emissions, contributing 4.0% of global GHG emissions (2.7% from milk production and 1.3% from meat from dairy cattle), accounting for 20% of total global livestock emissions (Gerber et al., 2013). In Australia, the dairy sector contributes 2% of total national and 14% of agricultural emissions (Australian Government, 2023). Addressing the effect of livestock production on climate change is urgent because rising temperatures, variable precipitation, and increased CO_2 concentration negatively affect livestock performance and feed supply (FAO, 2019). In addition, the global demand for both animal- and plant-based foods is projected to double by 2050 (FAO and GDP, 2018; Enahoro et al., 2021; van Dijk et al., 2021) and sustainable intensification of food production may be required (Muscat et al., 2021).

In dairy farming, confinement is one form of intensification, but one key debate concerns its environmental effect compared with pasture-based systems. Confinement systems, which include any type of contained housing such as freestall, loose housing, compost barns, and dairy dry lots (Dairy Australia, 2024), are often considered more efficient in terms of emissions per unit of output due to improved feed conversion and animal productivity

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(Gerber et al., 2011). However, concerns arise regarding feed production or off-farm feed purchases and energy consumption, and competition for arable land that could otherwise be used for grain production for human consumption (Van Zanten et al., 2018). In contrast, pasture-based systems are often perceived as more environmentally friendly, as they typically rely on land unsuitable for arable crops, although this view overlooks the potential for such land to support biodiversity or C sequestration (Wuepper et al., 2020).

Extensive research has been conducted globally on the environmental effects of dairy farming. However, due to the inconsistent results, there remains a lack of clear evidence regarding the comparative sources of GHG in pasture-based and confinement systems. For instance, Flysjö et al. (2011), Belflower et al. (2012), and O'Brien et al. (2014), reported that grass-based and confinement dairy systems have similar C footprints per ton of ECM if grassland C sequestration is not considered. However, O'Brien et al. (2014) and Belflower et al. (2012) found that grass-based systems showed 5% and 14% lower C footprints, respectively, when grassland C sequestration was included compared with confinement systems. Conversely, other authors argue that intensive dairy systems have lower GHG emissions per unit of milk produced due to better feed efficiency and higher productivity (Capper et al., 2009; Gerber et al., 2011, 2013). Although extensive research has been conducted internationally, much of it focused on production systems where most of the feed is sourced off-farm, as is common in confinement systems. In contrast, production systems that rely primarily on feed produced on-farm, such as those prevalent in Australia, remain underexplored in terms of the environmental implications, highlighting the need for further investigation to address this knowledge gap. Notably, previous studies (Flysjö et al., 2011; Belflower et al., 2012; O'Brien et al., 2014) have overlooked the potential role of trees on C sequestration to mitigate dairy farm GHG emissions. Therefore, the present study aimed to address this gap comparing GHG emissions from confinement and pasture-based dairy farms and identifying key emission sources within systems using the Australian Dairy Carbon Calculator (Christie-Whitehead and Dairy Australia, 2024). The findings provide valuable insights for producers, industry organizations, policymakers, and businesses seeking to balance productivity with environmental sustainability in the dairy sector.

MATERIALS AND METHODS

Data

Data were collected from 10 commercial dairy farms (5 pasture-based and 5 confinement) in New South Wales (**NSW**), Australia, during the 2022 to 2023 fiscal year. The farms represented the diversity of the industry in terms of milk production, milking herd size, farm input usage, and production system but not ecological region or weather. The selection process involved identifying farms that were representative of typical management practices within each system (pasture-based and confinement) in NSW, ensuring a balanced sample for comparative analysis. Given the limited sample size of 5 farms per system, this study represents a focused exploratory approach, and caution should be exercised when generalizing findings beyond the specific contexts of these farms. Ethical approval was not required for this study as it was based on farm data collection without direct animal experimentation.

Farm Characteristics

The study comprised 2 dairy production systems (confinement and pasture-based) with Holstein-Friesian, Jersey, and Holstein-Jersey crossbreeds. However, 1 confinement farm exclusively raised Jersey. Confinement farms mainly produced wheat (*Triticum aestivum*) and corn (*Zea mays*) as the major crops for silage, grain, and green feeding, with lucerne (*Medicago sativa*) and vetch (*Vicia sativa*) also grown for hay and silage. Confinement farms primarily fed cows a TMR, with some farms allowing grazing for nonlactating animals, while 1 farm practiced zero-grazing, keeping the entire herd fully confined. The dominant pasture species in the grazing system included Kikuyu grass (*Cenchrus clandestinus*), ryegrass (*Lolium multiflorum* L.), and legumes, such as clover species (*Trifolium* spp.). The TMR was formulated from silage, hay, straw, concentrate, and minerals in varying proportions. Concentrates were made from grains, such as barley (*Hordeum vulgare*) and wheat, supplemented with protein-rich ingredients, such as canola (*Brassica napus*) meal, lupin (*Lupinus* spp.) seed, and cotton (*Gossypium* spp.) seed. Silage was primarily derived from corn, lucerne, and vetch. Hay consisted of vetch, lucerne, and oats (*Avena sativa*). Cereal straw came from wheat, barley, and oats. Some farms also incorporated almond (*Prunus amygdalus*) husk into the TMR. To balance the diet and provide essential nutrients, minerals, such as lime, magnesium sulfate, copper, and selenium, and vitamin-mineral premixes were added to the TMR in most farms.

Lactating and dry cows, along with heifers, grazed year-round in the pasture-based system. The pasture was divided into irrigated sections (utilizing center-pivot units, travelers, and solid-set guns) and nonirrigated systems, further subdivided into individual paddocks using high-tensile electric fences. For the pasture-based farming systems, the percentage of area under irrigation ranged from 13% to 92%, with a mean of 61%. In contrast, the confinement farming systems had a higher percentage of irrigated areas, ranging from 67% to 98%, with a mean of 84%. The pastures contained a variety of grass and legume species, including Kikuyu grass, annual ryegrass, oats, Bermuda grass (*Cynodon dactylon*), Setaria (*Setaria* spp.), fescue (*Festuca arundinacea* L.), clover (*Trifolium* spp.), lucerne, Rhodes grass (*Chloris gayana*), prairie grass (*Bromus wildenowii*), chicory (*Cichorium intybus* L.), and Paspalum (*Paspalum* spp.). In this system, cows were also fed silage and hay. The silage was primarily made from forage crops, such as ryegrass, Kikuyu, millet (*Pennisetum glaucum*), sorghum (*Sorghum sudanense*), soybean (*Glycine max*), and corn, whereas hay consisted of a mix of legumes and grasses, including lucerne, vetch, oats, Kikuyu, and ryegrass. Additionally, pellets formulated from blended grains, byproducts, and protein supplements, provided a consistent source of energy and protein. Minerals, including calcium, phosphorus, and magnesium, were incorporated into the pellets or added to the concentrate. Cows received grain during milking, consisting mainly of corn, wheat, barley, and Triticale (*Triticosecale*), supplemented with canola meal, minerals, and pellets, with average daily concentrate intake varying from 4.30 to 7.80 kg/cow day among the farms.

Feed Nutritional Content

The nutritional quality of feed for the milking cow herd is presented in Table 1. Feed nutritional analysis was conducted using wet chemistry (Dumas, AOAC 990.03; AOAC International, 2000). The results were averaged based on the proportion of each ingredient in the diet to represent the nutritional content of various feed categories. For instance, feeds classified as concentrates, such as grains and grain byproducts, were averaged according to their proportion in the diet to determine the nutritional value of concentrates. Feed samples for concentrate, hay, minerals, and silage were collected 1 time per farm during the 2022 to 2023 fiscal year. Pasture samples were collected and analyzed monthly, with results averaged to account for seasonal variations.

Functional Unit and Global Warming Potential

The global warming potential for 100 years horizon (**GWP100**) index was used to assess the contribution of different gases to total GHG emissions. According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2019), the GWP100 characterization factors are 1 for carbon dioxide (CO_2), 28 for methane (CH_4), and 265 for nitrous oxide (N_2O). All areas used for dairy-related activities, including the milking platform and support areas, and runoff areas for raising

Table 1. Nutritional content of feeds (mean ± SD; % DM) used on commercial dairy farms to estimate GHG emissions

	Confinement						Pasture-based				
Nutrient[1]	Concentrate	Silage	Hay	Cereal straw	Almond husk	TMR	Concentrate	Silage	Hay	Pasture	Pellet
NDF	39.7 ± 7.437	42.3 ± 6.834	53.0 ± 5.663	74.4 ± 0.460	31.8 ± 0.884	35.7 ± 4.080	23.7 ± 6.543	56.4 ± 9.160	46.8 ± 8.620	52.5 ± 2.456	23.1 ± 7.354
ADF	26.1 ± 3.958	27.8 ± 4.944	32.9 ± 3.865	45.0 ± 0.134	22.1 ± 0.915	20.6 ± 2.232	10.1 ± 5.911	30.7 ± 5.299	31.5 ± 4.649	24.5 ± 1.108	10.2 ± 6.364
CP	22.6 ± 11.52	16.4 ± 2.862	16.5 ± 4.397	5.80 ± 1.556	5.13 ± 0.351	17.0 ± 0.908	16.4 ± 9.810	13.8 ± 6.836	16.3 ± 6.806	23.0 ± 1.724	17.1 ± 4.009
WSC	6.23 ± 3.285	2.74 ± 1.734	8.57 ± 8.631	2.75 ± 2.192	24.6 ± 0.252	4.46 ± 0.673	5.39 ± 1.999	4.38 ± 2.354	9.40 ± 7.568	7.60 ± 2.150	4.5 ± 0.919
DMD	80.1 ± 11.17	63.6 ± 8.928	66.5 ± 5.089	40.8 ± 2.475	60.0 ± 3.430	74.7 ± 3.969	82.9 ± 8.134	67.0 ± 8.962	60.4 ± 4.771	72.0 ± 2.391	84.0 ± 7.787
DOMD	67.9 ± 9.098	60.6 ± 8.435	61.1 ± 1.041	40.4 ± 3.394	59.8 ± 3.315	70.0 ± 3.795	81.8 ± 7.816	58.9 ± 7.030	58.0 ± 4.060	67.7 ± 2.007	79.5 ± 6.647
Ash	5.73 ± 2.117	11.6 ± 6.019	12.9 ± 8.058	11.9 ± 1.344	10.3 ± 4.139	8.71 ± 0.483	5.40 ± 5.243	12.1 ± 2.641	9.35 ± 1.066	10.8 ± 1.196	7.55 ± 0.354
OM	94.3 ± 2.117	88.4 ± 6.019	87.1 ± 8.058	88.2 ± 1.344	89.7 ± 4.139	91.3 ± 0.483	94.6 ± 5.243	87.9 ± 2.641	90.6 ± 1.066	89.1 ± 1.281	92.4 ± 0.354
ME	13.2 ± 1.300	9.70 ± 1.349	9.40 ± 0.265	5.00 ± 0.990	9.70 ± 0.346	11.9 ± 0.596	12.9 ± 1.023	9.42 ± 1.113	8.78 ± 0.854	10.7 ± 0.410	12.3 ± 0.919
EE	10.3 ± 8.436	2.98 ± 0.901	1.83 ± 0.757	0.90 ± 0.424	2.20 ± 0.557	5.14 ± 0.577	2.60 ± 1.149	2.88 ± 0.742	—	—	1.80 ± 0.000

[1]DMD = DM digestibility; DOMD = digestible OM in DM; EE = ether extract; WSC = water soluble carbohydrate; all units are in %, except for ME, which is in MJ/kg DM.

replacement stock and growing pastures and crops for forage conservation or grain production, were included in the total farm usable area. The milking platform is the portion of the farm's land specifically dedicated to supporting the milking herd. The present study reports GHG emissions in CO_2 equivalents (**CO_{2eq}**) per kilogram of liveweight for meat at the farm gate. The percentage contribution of each animal class to total farm GHG emissions was based on their enteric CH_4, manure CH_4, and N_2O. Fat- and protein-corrected milk (**FPCM**) was calculated according to the formula provided by Seven-ster and Jong (2008), as follows:

$$\text{FPCM (kg)} = \text{M (kg)} \times (0.337 + 0.116 \times \text{fat content [\%]} + 0.06 \times \text{protein content [\%]}),$$

where M is the raw milk mass (kg), calculated as milk volume (L) × 1.03.

Australian Dairy Carbon Calculator

The Australian Dairy Carbon Calculator (**ADCC**) version 5.2 (https://www.dairyaustralia.com.au/climate-and-environment/greenhouse-gas-emissions/australian-dairy-carbon-calculator) was employed to estimate GHG emissions. The ADCC was constructed in Microsoft Excel and consists of 10 user forms and 19 worksheets. These worksheets include algorithms, emission factors, and methodologies to calculate CO_2 emissions from embedded prefarm inputs, as well as on-farm CH_4, N_2O, and CO_2 emissions. The sources of GHG emissions considered in the present study were CO_2 from electricity (scopes 2 and 3), diesel (scopes 1 and 3), urea and lime (scope 1), prefarm gate embedded sources (scope 3: purchased grain, concentrate, forages, and fertilizers), CH_4 from enteric fermentation and manure (scope 1), and N_2O (scope 1) from direct emissions from dung and urine voided onto pastures, direct emissions from manure (storage and spreading), indirect N waste, and direct and indirect N_2O from fertilizers. Indirect N_2O emissions result from N in urine, dung, effluent, or N-based fertilizers being lost to the environment, redeposited onto soils or watercourses, and subsequently transformed into N_2O through nitrification and denitrification. The ADCC calculated enteric CH_4 and manure N_2O and CH_4 for each farm using required data on livestock (number and weight of animals), average lactation length in days, milk production, milk composition (milk fat and protein content in percentage), and feed DM digestibility and CP. Manure CH_4 and N_2O emissions were calculated based on the proportion of time (d/yr) animals spent grazing versus in confinement yards, accounting for systems with both grazing growing stock and confined milking cows. All input data for the ADCC were collected directly from the farms. Carbon sequestration by trees was accounted for as a sink based on the local environmental conditions, tree species, age, and tree area recorded for each farm using the ADCC method. The annual C sequestered by trees was then subtracted from the total gross GHG emissions to calculate the net farm emissions. Only woody vegetation in permanent or semipermanent tree areas was included in the estimation. The major tree species grown by the farms included honey locust (*Gleditsia triacanthos*), sweet osmanthus (*Osmanthus fragrans*), eucalyptus (*Eucalyptus* spp.), blackwood (*Acacia melanoxylon*), and Australian silky oak (*Grevillea robusta*). Dry matter intake was calculated by the ADCC using a series of algorithms and methodologies from the Australian Agricultural Council (1990). All prediction equations used to estimate DMI, enteric CH_4, and manure N_2O and CH_4 are provided as supplemental files (see Notes) and can also be found in our previous publication (Dida et al., 2024).

System Boundary

On- and off-farm GHG sources associated with dairy production, from production inputs to the point where milk is sold from the farm, were estimated in kilogram of CO_{2eq}. In the ADCC, emissions were allocated between milk and meat production based on their respective energy demand proportions (Christie-Whitehead and Dairy Australia, 2024). Emissions from electricity and prefarm embedded emissions (from concentrates) were solely attributed to milk, whereas emissions from other livestock (<1 yr of age) were fully attributed to meat production. For shared emissions, such as those from the milking herd, replacement heifers, and general farm activities, the allocation was based on the proportion of total energy requirements for milk and meat production. Greenhouse gas emissions from housing construction, cleaning agents, antibiotics, and pharmaceuticals are excluded due to their minimal contribution, typically less than 5% of total farm emissions (Gerber et al., 2011; Rotz and Thoma, 2017).

Statistical Analysis

The ADCC was run for each of the 10 farms mentioned previously, and the output estimates were then exported and consolidated for all farms, along with the input data, for statistical analysis. Feed ingredient proportions and DMI results apply to the milking herd only, whereas emission intensities per unit of milk, land area, and cow were based on total farm emissions. Enteric and manure emissions per cow were calculated by dividing total emissions from all herd compositions by the number of milking cows, reflecting total farm emissions per milking cow. Before analysis, the normality of the data distribution was assessed using the Shapiro–Wilk test. A *t*-test was used to compare GHG emissions, milk production, and feed intake between confinement and pasture-based production systems. Untransformed data were analyzed for normally distributed variables. Results are reported as mean ± SE for each production system, along with the *P*-value from the *t*-test. All statistical analyses were performed using R software, version 4.4.2 (R Core Team, 2020).

RESULTS

Farm Area, Herd Size, and Production Metrics of Farms

The farm area, herd size, and production performance metrics of the farms are presented in Tables 2 and 3. For the total per-farm values, *P*-values were included for descriptive reference only, as they are not based on standardized or directly comparable metrics. The average total usable area was 72% larger ($P = 0.044$), and the milking platform area was 90% smaller ($P = 0.002$) on confinement than pasture-based farms (Table 2). The irrigated farm area ($P = 0.025$), support area ($P = 0.033$), sulfur fertilizer rate (t/ha per year; $P = 0.012$), and diesel use per total usable area (L/ha per year; $P = 0.005$) were larger on confinement farms. However, there were no significant differences ($P > 0.05$) in nonirrigated farm area, tree area, electricity uses per total usable area (kWh/ha per year), diesel consumption per hectare, nitrogen, phosphorus, potassium fertilizer rates (t/ha per year), or feed inputs (Table 2). The number of milking cows ($P = 0.018$), milk solids (kg/cow per year; $P = 0.002$), and 2-yr-old replacement heifers ($P = 0.042$) was also larger in the confinement farms (Table 3). Furthermore, calves from confinement farms were sold heavier at sale ($P = 0.007$), and the proportion of silage in the milking herd's diet was also higher ($P = 0.004$) in confinement compared with the pasture-based farms. In contrast, there were no differences ($P > 0.05$) in the milking herd liveweight, lactation length, number of

Table 2. Key farm input for confinement and pasture-based dairy production systems used to estimate GHG emissions[1]

Key farm input	Pasture-based	Confinement	*P*-value
Total usable area (ha)	233 ± 47.32	609 ± 150.5	0.044
Milking platform area (ha)	98.2 ± 19.28	10.0 ± 1.715	0.002
Farm area – irrigated (ha)	115 ± 21.97	370 ± 90.56	0.025
Farm area – nonirrigated (ha)	118 ± 46.27	239 ± 118.2	0.368
Support area (ha)	133 ± 30.40	602 ± 149.2	0.033
Tree area (ha)	11.9 ± 3.896	18.9 ± 8.536	0.485
Tree area (% usable area)	6.08 ± 0.283	2.77 ± 0.058	0.246
Electricity use (thousands of kWh/yr)	150 ± 30.08	287 ± 115.09	0.308
Electricity use (kWh/ha/yr)	693 ± 224.3	561 ± 116.9	0.117
Diesel use (thousands of L/yr)	31.8 ± 6.650	236 ± 132.0	0.199
Diesel use (L/ha/yr)	165 ± 50.41	447 ± 239.9	0.005
Nitrogen fertilizer (t/yr)	41.1 ± 2.452	45.5 ± 17.16	0.815
Nitrogen fertilizer rate (t/ha/yr)	0.21 ± 0.037	0.09 ± 0.032	0.051
Phosphorus fertilizer (t/yr)	9.14 ± 3.357	6.66 ± 2.916	0.592
Phosphorus fertilizer rate (t/ha/yr)	0.05 ± 0.021	0.02 ± 0.009	0.234
Potassium fertilizer (t/yr)	6.17 ± 3.002	0.44 ± 0.392	0.129
Potassium fertilizer rate (t/ha/yr)	0.03 ± 0.016	0.001 ± 0.0007	0.139
Sulfur fertilizer (t/yr)	2.81 ± 0.508	1.12 ± 0.734	0.099
Sulfur fertilizer rate (t/ha/yr)	0.01 ± 0.003	0.003 ± 0.0018	0.012
Lime fertilizer (t/yr)	11.0 ± 7.404	26.5 ± 10.10	0.282
Lime fertilizer rate (t/ha/yr)	0.05 ± 0.038	0.08 ± 0.037	0.629
Purchased concentrates (t DM/yr)	763 ± 91.34	5,455 ± 2,863	0.177
Home-grown concentrates (t DM/yr)	19.3 ± 15.12	396 ± 396.0	0.396
Home-grown concentrates (t DM/ha/yr)	0.11 ± 0.078	0.65 ± 0.396	0.511
Purchased silage (t DM/yr)	21.2 ± 8.692	70.0 ± 70.00	0.526
Home-grown silage (t DM/yr)	443 ± 150.7	8,039 ± 3,302	0.083
Home-grown silage (t DM/ha/yr)	2.03 ± 0.505	15.2 ± 6.198	0.100
Purchased hay (t DM/yr)	195 ± 75.69	1,254 ± 863.4	0.288
Home-grown hay (t DM/yr)	61.4 ± 49.07	189 ± 156.4	0.473
Home-grown hay (t DM/ha/yr)	0.20 ± 0.124	0.30 ± 0.184	0.679
Purchased other feeds (t DM/yr)	108 ± 50.54	2,948 ± 2021	0.233

[1]All reported land areas (milking platform, irrigated and nonirrigated farm areas, support area, and tree area) are components of the total usable area. The fertilizers (N, P, K, S, and lime) and home-grown feed (concentrate, hay, and silage) values presented per hectare may not reflect the true values because they were calculated by simply dividing the total amounts by the total usable area; therefore, the results should be interpreted with caution. Values are given as mean ± SE.

Table 3. Key herd structure and inputs of confinement and pasture-based dairy production systems used to estimate GHG emissions[1]

Herd size and input[2]	Pasture-based	Confinement	*P*-value
Milking herd size (number of cows)	335 ± 13.56	1,073 ± 247.2	0.018
Milking herd average liveweight (kg)	568 ± 13.56	627 ± 37.27	0.197
Lactation length (d)	304 ± 8.718	322 ± 10.07	0.214
Milk solids (kg/cow/yr)	472 ± 41.73	876 ± 70.62	0.002
Number of cows sold per year	43.0 ± 10.57	155 ± 71.82	0.160
Liveweight of cow at point of sale (kg)	578 ± 21.07	675 ± 165.5	0.330
Herd size of 1-yr-old replacement heifers	107 ± 12.83	708 ± 263.8	0.052
1-yr-old replacement heifers sold	1.00 ± 0.400	17.0 ± 17.00	0.491
Herd size of 2-yr-old replacement heifers	103 ± 16.23	602 ± 205.0	0.042
2-yr-old replacement heifers sold	1.00 ± 0.400	8.00 ± 8.000	0.396
Mature bull's herd size	2.00 ± 0.748	36.0 ± 34.96	0.351
Number of mature bulls sold	2.00 ± 0.400	19.0 ± 18.80	0.412
Other stock <1 yr of age	33.0 ± 24.26	123 ± 60.37	0.201
Other stock, <1 yr of age, sold	0.00	42.0 ± 42.00	—
Other stock >1 yr of age	1.00 ± 0.200	88.0 ± 50.56	0.121
Other stock, >1 yr of age, sold	6.00 ± 6.00	55.0 ± 55.00	0.425
Number of calves sold per year	152 ± 50.02	225 ± 67.40	0.195
Liveweight of calves at point of sale (kg)	45.5 ± 0.289	50.0 ± 0.577	0.007
Stocking rate (cows/ha)	1.67 ± 0.281	2.13 ± 0.505	0.457
Concentrate (% of DMI, milking herd)	32.5 ± 2.704	38.6 ± 3.702	0.219
Silage (% of DMI, milking herd)	19.2 ± 5.574	44.5 ± 2.867	0.004
Hay (% of DMI, milking herd)	8.72 ± 1.352	6.44 ± 2.525	0.448
Pasture (% of DMI, milking herd)	35.1 ± 6.159	0.00	—
DMD of the milking herd diet (g/kg DM)	719 ± 1.684	747 ± 1.120	0.654
CP of the milking herd diet (g/kg DM)	171 ± 1.173	189 ± 0.941	0.281

[1]The stocking rate is calculated based solely on the milking herd size. Values are given as mean ± SE.

[2]DMD = DM digestibility; other stock <1 yr age = young bulls, steers, and nonreplacement heifers that are 0 to 1 yr of age; other stock >1 yr age = replacement bulls, and for steers and nonreplacement heifers that are 1 to 2 yr of age.

cows sold, 1-yr-old replacement heifers, other stock and mature bull herd size, stocking rate, dietary components, and other production-related metrics.

DMI, Milk Yield, and Composition

Estimated DMI, milk yield, and composition of the pasture-based and confinement systems are shown in Table 4. Predicted total DMI ($P = 0.013$), concentrate ($P = 0.024$), and silage ($P = 0.002$) were higher in the confinement than in the pasture-based system, while the intake of hay and other feed types was similar ($P > 0.05$). Greater milk yield ($P = 0.014$) resulted in >70% greater FPCM ($P = 0.007$), and milk fat, protein, and milk solids yield per cow ($P = 0.006$) on confinement compared with pasture-based farms. However, there was no difference in milk fat and protein concentration between production systems ($P > 0.05$). Confinement farms also showed 23% higher ($P = 0.029$) milk yield per unit of DMI (kg FPCM/kg DMI) and a substantial 140% increase in milk yield per hectare of total usable area.

Farm GHG Emissions and Emissions Sources

Net total farm emissions were higher ($P = 0.017$) in the confinement than in the pasture-based system (Table 5). However, C sequestered by trees and the proportion of net emissions allocated to milk and meat were similar ($P > 0.05$) in both systems. Carbon sequestration by trees was consistent with similar tree areas leading to no differences between production systems ($P > 0.05$). The current tree coverage offsets ~4.5% of GHG emissions in the pasture-based system and about 0.8% in the confinement system.

Enteric fermentation was the most important source of CO_{2eq} in both production systems, accounting for more than half of the total GHG emissions. Total CH_4 emissions were higher in the confinement system ($P = 0.003$), driven by higher manure CH_4 emissions ($P = 0.002$), whereas enteric CH_4 emissions were higher in the pasture-based system ($P = 0.013$). The next 2 largest sources differed between systems, with emissions from manure (CH_4 and N_2O) accounting for 31% in confinement, followed by prefarm embedded emissions. Comparatively, pasture-based systems had prefarm embedded emissions as the second largest source, followed by manure emissions. The proportion of total emissions from fertilizer, urea, and lime in the present study was ~5-fold greater in pasture-based compared with confinement systems ($P = 0.001$). Emissions from energy (electricity and fuel) constituted the fourth largest source of GHG emissions in both production systems. Confinement farms had a

Table 4. Effects of dairy production system on milk production and composition and predicted DMI of milking cows

Parameter[1]	Pasture-based	Confinement	*P*-value
Predicted feed intake, kg DM/cow per day			
Total DMI	18.0 ± 0.650	25.4 ± 1.837	0.013
Pasture	6.22 ± 1.049	0.00	—
Concentrate	5.88 ± 0.626	9.85 ± 1.173	0.024
Silage	3.54 ± 1.163	11.4 ± 1.313	0.002
Hay	1.58 ± 0.258	1.54 ± 0.537	0.944
Others	0.78 ± 0.399	2.59 ± 1.135	0.193
Milk yield			
Milk (L/cow per day)	21.6 ± 1.814	36.6 ± 3.840	0.014
FPCM yield (kg/cow per day)	22.1 ± 1.992	38.1 ± 3.553	0.007
Milk fat (kg/cow per day)	0.85 ± 0.082	1.48 ± 0.137	0.006
Milk protein (kg/cow per day)	0.71 ± 0.067	1.25 ± 0.116	0.006
Milk solids (kg/cow per day)	1.56 ± 0.146	2.73 ± 0.249	0.006
Milk constituents, g/kg milk			
Milk fat	3.92 ± 0.136	4.10 ± 0.259	0.560
Milk protein	3.27 ± 0.064	3.45 ± 0.106	0.198
Milk production efficiency			
FPCM/DMI (kg/kg)	1.22 ± 0.080	1.50 ± 0.065	0.029
Milk yield per usable area (t FPCM/ha)	10.6 ± 1.269	25.4 ± 6.766	0.094

[1]Values are given as mean ± SE. FPCM = fat and protein-corrected milk; others feed = minerals, byproducts.

Table 5. Total farm GHG emissions, with a breakdown by source, the contribution of herd composition to total GHG emissions, and the proportion allocated to meat and milk

Parameter[1,2]	Pasture-based	Confinement	*P*-value
Net total farm emissions (t CO_{2eq}/yr)	2,591 ± 200.78	15,218 ± 4,221	0.017
Carbon sequestered by trees (t CO_{2eq}/yr)	117 ± 39.29	128 ± 29.10	0.819
Net emissions allocated to milk (%)	91.2 ± 1.158	92.2 ± 1.020	0.535
Net emissions allocated to meat (%)	8.80 ± 1.158	7.80 ± 1.020	0.535
Breakdown by source, % of total CO_{2eq}			
Total CH_4 (manure plus enteric CH_4)	62.2 ± 0.735	74.2 ± 2.035	0.003
Enteric CH_4	58.2 ± 1.020	53.6 ± 1.030	0.013
Manure CH_4	4.00 ± 1.517	20.6 ± 2.874	0.002
Total N_2O from manure management	9.20 ± 0.730	10.4 ± 0.678	0.002
Direct N_2O from urine and feces voided to pasture	4.00 ± 0.601	0.90 ± 0.270	0.004
Direct N_2O from manure storage	1.40 ± 1.158	6.30 ± 1.068	<0.001
Indirect N_2O animal waste	3.80 ± 0.374	3.20 ± 0.200	0.206
Total manure ($N_2O + CH_4$) emissions	13.2 ± 1.241	31.0 ± 2.966	0.002
Total N_2O N fertilizer (on-farm)	4.60 ± 0.400	1.20 ± 0.490	<0.001
Direct N_2O N fertilizer	2.40 ± 0.245	0.60 ± 0.245	<0.001
Indirect N_2O N fertilizer	2.20 ± 0.200	0.60 ± 0.245	0.001
CO_2			
Urea and lime from the soil	2.20 ± 0.200	0.60 ± 0.245	0.001
Energy consumption	8.20 ± 1.158	5.20 ± 1.068	0.093
Diesel	3.52 ± 0.678	3.54 ± 0.690	0.987
Electricity	4.69 ± 0.763	1.51 ± 0.550	0.006
Prefarm embedded	13.6 ± 0.510	8.40 ± 1.503	0.023
Concentrate	5.50 ± 0.576	4.09 ± 1.017	0.273
Forage	1.55 ± 0.496	2.89 ± 2.036	0.554
Fertilizers	6.56 ± 0.709	1.42 ± 0.581	<0.001
Breakdown by herd composition, % of total CO_{2eq}			
Milking cows	58.8 ± 1.393	68.0 ± 2.950	0.032
Heifers >1 yr age	7.60 ± 1.503	9.20 ± 1.158	0.425
Heifers <1 yr age	3.40 ± 0.400	4.40 ± 0.600	0.208
Mature bulls	0.15 ± 0.076	0.61 ± 0.597	0.488
Other stock <1 yr age	0.80 ± 0.583	0.80 ± 0.374	1.00
Other stock >1 yr age	0.01 ± 0.010	1.80 ± 0.800	0.889
Total emissions from the animals	71.4 ± 1.030	84.6 ± 2.293	0.002
On-farm emissions (%)	86.4 ± 0.510	91.6 ± 1.503	0.023

[1]The percentage contribution of each animal class to total farm GHG emissions is calculated as the sum of their enteric CH_4, manure CH_4, and N_2O emissions. Values are given as mean ± SE.

[2]CO_2 emissions from energy consumption = CO_2 emissions from diesel and electricity; CO_2 emissions from prefarm embedded sources = CO_2 emissions from concentrate, forage, and fertilizers; CO_{2eq} = CO_2 equivalents; total N_2O from manure management = direct N_2O + indirect N_2O from manure management; total N_2O from N fertilizer (on-farm) = direct N_2O + indirect N_2O from N fertilizer (on-farm).

lower (P = 0.023) proportion of the total emissions associated with pre-embedded emissions despite higher concentrate and silage use. On-farm activities accounted for a higher (P = 0.023) proportion of total emissions in the confinement compared with the pasture-based system. Milking cows contributed more significantly (P = 0.032) to total farm emissions in the confinement than in the pasture-based system (Table 5). Other yearling stock and stock over 1 yr showed similar (P > 0.05) contributions to total GHG emissions in both systems. The total contribution from animals through enteric CH_4 and direct manure emissions to total farm emissions was greater (P = 0.002) in the confinement compared with the pasture-based system. Animal emissions dominated both systems, representing 85% (enteric CH_4 and manure CH_4 and N_2O) of total emissions in confinement and 71% in pasture-based systems.

GHG Emissions Intensity per Hectare of Total Usable Area

The emission intensity per unit of usable area (t CO_{2eq}/ha) was higher on confinement farms for most GHG sources (Table 6). Total CH_4 emissions (from both manure and enteric fermentation) per unit of area were over 2-fold greater on confinement compared with pasture-based farms (P = 0.053). Methane (P = 0.003) and direct N_2O (P = 0.011) emissions from manure storage per unit of area were also higher on confinement farms. Total manure-related emissions (CH_4 + N_2O) per unit of area were over 4-fold greater (P = 0.006) in confinement farms. In contrast, C sequestered by trees, CO_2 emissions from urea and lime application and energy-related emissions, including those from diesel and electricity, prefarm emissions, and emissions from purchased concentrate and forage per unit of area were not different (P > 0.05) between farming systems. However, fertilizer-related emissions intensity was 51% lower (P = 0.043) on confinement compared with pasture-based farms.

GHG Emissions Intensity per Cow

Total farm GHG emissions intensity per cow per year was higher (P = 0.004) on confinement compared with pasture-based farms (Table 7). Total CH_4 emissions (including manure and enteric CH_4) per cow per year were more than 2 times as high (P < 0.001) in confinement farms. Furthermore, confinement farms exhibited higher (P = 0.002) total manure-related emissions (N_2O + CH_4), including CH_4 from manure, total N_2O emissions, and

Table 6. Greenhouse gas emissions intensity (t CO_{2eq}/ha; of total usable area) in confinement and pasture-based dairy production systems[1]

GHG source[2]	Pasture-based	Confinement	P-value
Total farm emissions	12.5 ± 1.729	28.3 ± 7.349	0.098
Carbon sequestered by trees	0.64 ± 0.283	0.23 ± 0.058	0.223
CH_4			
Total CH_4 (manure plus enteric CH_4)	7.78 ± 1.040	21.0 ± 4.697	0.053
Enteric fermentation	7.28 ± 1.084	15.20 ± 4.334	0.144
Manure management	0.50 ± 0.198	5.83 ± 0.816	0.003
N_2O			
Total N_2O from manure management	1.15 ± 0.174	2.94 ± 0.688	0.071
Direct N_2O from urine and feces voided to pasture	0.50 ± 0.112	0.26 ± 0.129	0.237
Direct N_2O from manure storage	0.17 ± 0.032	1.78 ± 0.341	0.011
Indirect N_2O from N waste	0.48 ± 0.086	0.91 ± 0.224	0.195
Total manure (N_2O + CH_4) emissions	1.65 ± 0.173	8.77 ± 1.239	0.006
Total N_2O from N fertilizer (on-farm)	0.58 ± 0.097	0.34 ± 0.122	0.081
Direct N_2O from N fertilizer	0.30 ± 0.059	0.17 ± 0.061	0.076
Indirect N_2O from N fertilizer	0.28 ± 0.042	0.17 ± 0.061	0.097
CO_2			
Urea and lime from the soil	0.28 ± 0.042	0.17 ± 0.061	0.097
Energy consumption	1.03 ± 0.233	1.47 ± 0.818	0.493
Diesel	0.44 ± 0.144	1.00 ± 0.648	0.305
Electricity	0.59 ± 0.106	0.43 ± 0.211	0.584
Prefarm embedded	1.70 ± 0.285	2.38 ± 1.388	0.483
Concentrate	0.69 ± 0.162	1.16 ± 0.385	0.366
Forage	0.19 ± 0.040	0.82 ± 0.771	0.356
Fertilizers	0.82 ± 0.174	0.40 ± 0.144	0.043

[1]Values are given as mean ± SE.

[2]CO_2 emissions from energy consumption = CO_2 emissions from diesel and electricity; CO_2 emissions from prefarm embedded sources = CO_2 emissions from concentrate, forage (emissions from purchased silage, hay, and other feeds), and fertilizers (CO_2 emissions from nitrogen, phosphorus, sulfur, potassium, and lime); CO_{2eq} = CO_2 equivalents; total N_2O from manure management = direct N_2O + indirect N_2O from manure management; total N_2O from N fertilizer (on-farm) = direct N_2O + indirect N_2O from N fertilizer (on-farm).

Table 7. Greenhouse gas emissions per milking cow (t CO_{2eq}/cow per year) in confinement and pasture-based dairy production systems[1]

GHG source[2,3]	Pasture-based	Confinement	*P*-value
Total farm emissions	7.70 ± 0.364	13.5 ± 1.065	0.004
Carbon sequestered by trees	0.36 ± 0.127	0.12 ± 0.023	0.125
CH_4			
Total CH_4 (manure plus enteric CH_4)	4.79 ± 0.239	10.0 ± 0.552	<0.001
Enteric fermentation	4.48 ± 0.141	7.24 ± 0.397	0.013
Manure management	0.31 ± 0.136	2.78 ± 0.404	0.003
N_2O			
Total N_2O from manure management	0.71 ± 0.043	1.43 ± 0.136	0.016
Direct N_2O from urine and feces voided to pasture	0.31 ± 0.019	0.12 ± 0.010	<0.001
Direct N_2O from manure storage	0.11 ± 0.018	0.85 ± 0.105	0.003
Indirect N_2O from N waste	0.29 ± 0.017	0.43 ± 0.035	0.205
Total manure (N_2O + CH_4) emissions	1.02 ± 0.119	4.16 ± 0.493	0.002
Total N_2O from N fertilizer (on-farm)	0.35 ± 0.028	0.14 ± 0.060	0.022
Direct from N_2O N fertilizer	0.18 ± 0.015	0.07 ± 0.030	0.017
Indirect from N_2O N fertilizer	0.17 ± 0.016	0.07 ± 0.030	0.029
CO_2			
Urea and lime from the soil	0.17 ± 0.016	0.08 ± 0.030	0.029
Energy consumption	0.63 ± 0.107	0.70 ± 0.174	0.716
Diesel	0.27 ± 0.051	0.48 ± 0.138	0.199
Electricity	0.36 ± 0.074	0.22 ± 0.073	0.102
Prefarm embedded	1.05 ± 0.034	1.13 ± 0.253	0.679
Concentrate	0.42 ± 0.032	0.55 ± 0.141	0.331
Forage	0.12 ± 0.041	0.39 ± 0.312	0.406
Fertilizers	0.51 ± 0.047	0.19 ± 0.068	0.004
Liveweight (kg CO_{2eq}/kg liveweight/yr)	6.76 ± 0.868	5.51 ± 0.779	0.316

[1]Values are given as mean ± SE.

[2]The GHG emission intensity per cow is calculated based on the total farm emissions. This includes all enteric and manure emissions from other herd compositions, which are added to the milking herd's enteric and manure emissions and then divided by the number of milking cows. Therefore, these results represent the total farm emissions distributed per cow.

[3]CO_2 emissions from energy consumption = CO_2 emissions from diesel and electricity; CO_2 emissions from prefarm embedded = CO_2 emissions from concentrate, forage, and fertilizers; CO_{2eq} = CO_2 equivalents; total N_2O from manure management = direct N_2O + indirect N_2O from manure management; total N_2O from N fertilizer (on-farm) = direct N_2O + indirect N_2O from N fertilizer (on-farm).

direct N_2O emissions from manure per cow. In contrast, there was no difference ($P > 0.05$) in indirect N_2O emissions from N waste between the 2 systems. Nitrous oxide emissions per cow from N fertilizer were higher ($P = 0.022$) on pasture-based farms, driven by both direct ($P = 0.017$) and indirect ($P = 0.029$) N_2O emissions per cow. Additionally, emissions intensity from urea and lime applied to soil was higher ($P = 0.029$) on pasture-based farms. In contrast, C sequestered by trees, energy-related (diesel and electricity), and prefarm embedded emissions did not differ ($P > 0.05$) between the systems. Similarly, the total farm GHG emissions intensity per kilogram of liveweight per year showed no difference ($P > 0.05$) between the systems.

GHG Emissions Intensity of FPCM

Results revealed that GHG intensity of FPCM (kg CO_{2eq}/kg FPCM), did not differ ($P = 0.610$) between systems (Table 8). However, FPCM emission intensity from manure CH_4 ($P = 0.003$), total manure (N_2O + CH_4) emissions ($P = 0.004$), direct N_2O from urine and feces voided to pasture ($P = 0.007$), and manure storage ($P < 0.001$) was higher on confinement farms. In contrast, FPCM emission intensity from prefarm embedded sources was lower on confinement ($P = 0.023$) compared with pasture-based farms. Despite the higher electricity usage in confinement farms, the FPCM emission intensity from electricity consumption (kg CO_2/kg FPCM) was lower ($P = 0.002$) in the confinement system. The FPCM emission intensity from N fertilizer, urea, and lime (g CO_{2eq}/kg FPCM) was higher ($P < 0.001$) on pasture-based farms.

DISCUSSION

The comparison of GHG emissions from confinement and pasture-based dairy systems remains debated, with studies offering conflicting evidence on their relative emission intensities. In this study, which included a detailed appraisal of all possible emission sources, we observed no difference in the intensity of C emissions between pasture- and confined-based systems, albeit C sequestration in soil was not accounted for. Confinement systems are often credited with lower GHG emissions

Table 8. Greenhouse gas emissions intensity (kg CO_{2eq}/kg FPCM) in confinement and pasture-based dairy production systems[1]

GHG source[2]	Pasture-based	Confinement	*P*-value
Total farm emissions	1.07 ± 0.069	1.02 ± 0.038	0.610
Carbon sequestered by trees	0.06 ± 0.021	0.01 ± 0.002	0.086
CH_4			
Total CH_4 (manure plus enteric CH_4)	0.66 ± 0.040	0.76 ± 0.036	0.108
Enteric fermentation	0.62 ± 0.043	0.55 ± 0.022	0.188
Manure management	0.04 ± 0.019	0.21 ± 0.036	0.003
N_2O			
Total N_2O from manure management	0.10 ± 0.011	0.11 ± 0.008	0.809
Direct N_2O from urine and feces voided to pasture	0.04 ± 0.008	0.01 ± 0.003	0.007
Direct N_2O from manure storage	0.02 ± 0.004	0.06 ± 0.005	<0.001
Indirect N_2O from N waste	0.04 ± 0.006	0.03 ± 0.003	0.086
Total manure (N_2O + CH_4) emissions	0.14 ± 0.014	0.32 ± 0.037	0.004
Total N_2O from N fertilizer (on-farm)	0.05 ± 0.009	0.01 ± 0.007	<0.001
Direct N_2O from N fertilizer	0.03 ± 0.003	0.01 ± 0.003	<0.001
Indirect N_2O from N fertilizer	0.02 ± 0.003	0.01 ± 0.003	<0.001
CO_2			
Urea and lime from the soil	0.02 ± 0.002	0.01 ± 0.003	<0.001
Energy consumption	0.09 ± 0.013	0.05 ± 0.011	0.104
Diesel	0.04 ± 0.010	0.04 ± 0.009	0.861
Electricity	0.05 ± 0.006	0.01 ± 0.007	0.002
Prefarm embedded	0.15 ± 0.015	0.08 ± 0.015	0.023
Concentrate	0.06 ± 0.009	0.04 ± 0.013	0.279
Forage	0.02 ± 0.006	0.03 ± 0.022	0.571
Fertilizers	0.07 ± 0.009	0.01 ± 0.006	<0.001

[1]Values are given as mean ± SE.

[2]CO_2 emissions from energy consumption = CO_2 emissions from diesel and electricity; CO_2 emissions from prefarm embedded sources = CO_2 emissions from concentrate, forage (emissions from purchased silage, hay, and other feeds), and fertilizers (CO_2 emissions from nitrogen, phosphorus, sulfur, potassium, and lime); CO_{2eq} = CO_2 equivalents; total N_2O from manure management = direct N_2O + indirect N_2O from manure management; total N_2O from N fertilizer (on-farm) = direct N_2O + indirect N_2O from N fertilizer (on-farm).

per unit of milk due to enhanced feed efficiency and productivity (Capper et al., 2009; Gerber et al., 2011, 2013). Conversely, pasture-based systems may achieve lower net emissions when grassland C sequestration is considered (Belflower et al., 2012; O'Brien et al., 2014). Without accounting for grassland C sequestration, the C footprint of both systems was comparable in agreement with previous studies (Flysjö et al., 2011; Belflower et al., 2012; O'Brien et al., 2014). Amidst this debate, the dairy industry's shift from pasture- to confinement-based systems seems to be driven by frequent drought, water scarcity, floods, inconsistent pasture growth, and higher cow productivity and efficiency (Wales et al., 2013; Wilkinson et al., 2020; Moscovici Joubran et al., 2021). The present study found similar stocking rates and tree-covered areas between systems, despite confinement systems having larger usable areas and herd sizes compared with pasture-based systems. However, it is uncertain whether the farms used in the present study are an accurate representation of the broader population of Australian dairy systems or only reflect characteristics specific to the 10 farms accessed, and caution is warranted when interpreting the results beyond this context. Although extensive research has been conducted internationally, much of it focuses on confinement systems that rely on off-farm feed (Belflower et al., 2012; O'Brien et al., 2014), whereas production systems that are primarily dependent on home-grown feed, such as those common in Australia and the present study, remain underexplored. Additionally, C sequestration by trees was not accounted for in prior research (e.g., Belflower et al., 2012; O'Brien et al., 2012, 2014). Therefore, the present study filled that knowledge gap to better understand the environmental implications of such confinement systems with large farm areas and on-farm feed production compared with pasture-based systems using a life cycle approach incorporating tree C sequestration.

The total farm GHG intensity, per unit of area (t CO_{2eq}/ha) and FPCM (kg CO_{2eq}/kg FPCM), were similar between the 2 systems. This lack of difference is largely attributed to total manure (N_2O + CH_4) emissions, which were 5.3-fold higher per unit of area (t CO_{2eq}/ha) and 2.3-fold higher per FPCM (kg CO_{2eq}/kg FPCM) in the confinement compared with the pasture-based system. This result is consistent with Flysjö et al. (2011), Belflower et al. (2012), and O'Brien et al. (2014), who reported that grass-based and confinement dairy systems have similar C footprints per ton of ECM without accounting for grassland C sequestration. The lack of a significant difference in emission intensity for milk between confinement and pasture-based dairy production systems of the present study indicates that enhancing dairy productivity alone may not substantially reduce the emission intensity for milk production. This is because other factors such as manure management systems may play an important role, as reflected by a 72% and 140% increase in FPCM milk production per cow and per hectare of usable land, respectively, in confinement systems. This emphasizes the necessity for supplementary strategies targeting reductions in animal GHG emissions and addressing prefarm embedded emissions. Confinement systems showed higher GHG emission intensity per cow (t CO_{2eq}/cow per year) than pasture-based systems, driven by 109% higher enteric CH_4 and 308% higher total manure (N_2O + CH_4) emissions, whereas milk production was 72% higher. Consequently, manure-related emission intensities (kg CO_{2eq}/kg FPCM, t CO_{2eq}/ha, t CO_{2eq}/cow per year) were greater in confinement, reflecting increased CH_4 and direct N_2O emissions from manure storage compared with pasture-based systems. Total N_2O emissions from animal waste per cow (t CO_{2eq}/cow per year) were higher in confinement, likely due to greater manure storage. Additionally, the higher DMI of confinement cows likely led to increased manure N_2O emissions due to greater N intake and fecal excretion, as reflected in greater direct emissions of manure per cow in the present study. The N_2O emissions are closely linked to the amount of N ingested by ruminants with ~2% of the N excreted by the animals being released as N_2O (Hao et al., 2004). In contrast, despite higher manure-related emissions, confinement systems provide more opportunities to capture, handle, store, and apply advanced manure treatment strategies such as acidification, anaerobic digestion, nitrification–denitrification, or chemical inhibitors (Chadwick et al., 2011; Montes et al., 2013), which can help mitigate the environmental effect compared with pasture-based systems, where most manure is excreted directly on the paddocks.

Enteric CH_4 emissions from milking cows were consistent with total DMI and milk production. This relationship is expected, given experimental studies demonstrating a positive correlation between enteric CH_4 production, DMI, and milk yield per cow (Ulyatt et al., 2002a,b; Lovett et al., 2005; O'Neill et al., 2011; Hardan et al., 2022). Emission intensity (t CO_{2eq}/kg FPCM and t CO_{2eq}/cow per year) from N fertilizer (N_2O) was higher in pasture-based systems, which could be attributable to larger usable areas in confinement farms and use of stored liquid and slurry effluent as fertilizer, reducing reliance on inorganic fertilizers (Garnett and Eckard, 2024). However, the present study did not record data on the amount of manure storage and utilization as fertilizers, and further research in this field is recommended. The result for total N_2O from N fertilizer falls within the range of 0.4 to 2.0 t CO_{2eq}/ha per year, as reported in previous studies based on field measurements (Eckard et al., 2003; Phillips et al., 2007). Despite higher energy use (electricity and diesel) in confinement, emission intensities from energy (kg CO_{2eq}/kg FPCM, t CO_{2eq}/ha, t CO_{2eq}/cow per year) did not differ between systems, partly because 2 confinement farms sourced 50% of their electricity (53,507 kWh/yr total) from solar power (data not shown).

Carbon sequestration, particularly through tree vegetation, emerged as an important factor in mitigating net GHG emissions from dairy production and warrants careful consideration in system comparisons (Ghale et al., 2022; Christie-Whitehead and Dairy Australia, 2024). In the present study, C sequestration by trees (kg CO_{2eq}/kg FPCM) was relatively low in both systems. Tree sequestration offset (kg CO_{2eq}/kg FPCM) ~6% of total emissions in pasture-based systems and less than 1% in confinement systems because the proportion of tree area over the total usable area was 1.6-fold lower and C sequestration per hectare was 1.4-fold lower in the latter. Pasture-based farms of the present study sequestered 9.41 t CO_{2eq}/ha and confinement farms 7.05 t CO_{2eq}/ha according to the ADCC model (data not shown), which may be partly explained by regional and weather differences.

The larger total usable area and irrigated farm area in the confinement system align with its higher reliance on home-grown feed production. These findings support the notion that confinement systems are designed for high production efficiency, often at the expense of higher input use (Rotz et al., 2010). The higher yield of milk solids per cow, DMI, and milk production efficiency in confinement compared with the pasture-based system support the concept that confinement systems often achieve higher productivity per animal due to optimized nutrition (Capper et al., 2009). In contrast, the lower yield of milk solids per cow in the pasture-based system may indicate a trade-off between lower input use and reduced productivity (Hristov et al., 2022).

Notably, the stocking rate in our study, calculated per total usable area, was similar between systems, albeit with a large variability. This contrasts with the definitions by FAO (2020) and O'Brien et al. (2014), which express stocking rate per grazed area. Under this definition, confinement systems typically have higher stocking rates than pasture-based systems because animals are concentrated in smaller, intensively managed areas. However, confinement dairy farms of the present study had a significant portion of the area used for forage cropping to support grain and silage production, which may contribute to this deviation from the global norm. These results highlight the importance of considering the structure of domestic dairy industries to develop mitigation strategies that are suitable and effective to reduce GHG emissions.

Despite confinement farms showing numerically higher total amounts of home-grown silage, hay, and concentrates, average N fertilizer used per farm (t N/yr) was similar between systems, yet N fertilizer usage per hectare of total usable land tended to be significantly higher in pasture-based farms. The present study was not designed to unravel the reasons for this finding, including potential differences in N fertilizer use efficiency, and, thus, it is difficult to draw firm conclusions. However, it is plausible that the lower N use in confinement systems could be partly explained by frequent utilization and recycling of manure. This includes liquid manure and sediments from lagoons, as well as fresh or composted manure, which are applied to cropping areas to supplement or partially replace synthetic N fertilizers. Such practices could improve N use efficiency (Garnett, 2024). In contrast, pasture-based systems rely on excretion of manure on the grazing paddocks and often require consistent N applications to sustain pasture productivity under frequent grazing throughout the year (Gourley et al., 2012a,b), particularly in regions with seasonal fluctuations in pasture growth. However, these results should be interpreted with caution, as we lack quantitative data on grazed pasture, which may also affect total N use.

The predicted total DMI of cows in the confinement system was higher than that of cows in the pasture-based system, and these results are partly explained by the greater observed milk production and cow BW, which are the key predictors of DMI in the ADCC model (Dida et al., 2024). The TMR provides balanced and consistent nutrients, energy, and fiber, throughout the year enhancing DMI compared with pasture, which constantly varies in nutrient quality (NRC, 2001). The greater milk yield in confinement systems is consistent with O'Brien et al. (2014), who reported a 74% increase in milk production in confinement systems versus pasture-based systems in Europe. This may be attributed to genetic selection for milk production (heavier BW with greater production potential), as well as the use of TMR diets in confinement systems (O'Brien et al., 2014), with associated higher DMI per cow (Bargo et al., 2002, 2003). Consistent with our findings, O'Brien et al. (2014) also reported 20% greater milk yield efficiency (kg ECM/kg DMI) for confinement than pasture-based systems. Milk yield per usable area tended to be higher in the confinement compared with pasture-based systems. Although not statistically significant, this tendency suggests the confinement system may enhance milk production efficiency (milk yield per hectare), potentially due to controlled feeding strategies. The higher number of animals per hectare in confinement systems can contribute to higher milk output per hectare, provided that nutrition and management are optimized (Macdonald et al., 2008).

Total yearly net farm emissions were 6-fold greater in confinement compared with pasture-based systems, mainly due to the larger scale of the business, including more land area and larger herds. In both production systems, enteric fermentation emerged as the dominant source of GHG emissions, contributing more than half of the total emissions. This finding is consistent with Flysjö et al. (2011) and Kristensen et al. (2011), who reported that enteric methane contributed a greater share of total farm GHG emissions in pasture-based systems (62% and 54%, respectively) compared with confinement systems (54% and 52%, respectively). The second largest emission sources differed between production systems, with manure emissions being the second largest in confinement systems and prefarm embedded emissions in pasture-based systems. The higher GHG emissions from manure in confinement systems can be attributed to the reliance on lagoon storage, which has higher CH_4 production than manure deposited on grazing paddocks (Montes et al., 2013). Pasture systems allow more manure recycling back into the soil and the feces dry faster to reduce microbial activity, reducing the overall GHG emissions associated with manure storage. These findings partly agree with O'Brien et al. (2012), who reported that emissions from manure accounted for 31% of total farm emissions in confinement systems and 8.3% in grass-based systems, with similar trends observed in this study.

Milking cows were the largest source of emissions in both systems, as previously reported (Christie et al., 2012), representing a higher percentage in confinement compared with those in pasture-based systems. Consistent with these findings, previous studies (Christie et al., 2012; Christie-Whitehead and Dairy Australia, 2024) have reported that animals account for ~75% (71% to 83%) of total farm GHG emissions across various Australian dairy farms. The present study expands on these results by demonstrating that the contribution of animals is even greater in confinement systems, due to higher enteric CH_4, manure CH_4, and N_2O emissions per animal, as well as a higher proportion of replacement heifers in confinement compared with pasture-based systems.

These findings highlight the need for targeted mitigation strategies tailored to the specific GHG emission profiles of each dairy production system. For confinement dairy production systems, manure management strategies, such as covered storage, anaerobic digesters (which can also generate renewable energy and reduce emissions from energy usage), acidification, aeration, antimicrobial agents, and solid-liquid separation, may help reduce emissions (Smith et al., 2008; Guzmán-Luna et al., 2022; Ambrose et al., 2023). For instance, acidifying cattle slurry to a pH of 5.5 can reduce its CH_4 emissions by up to 99% (Ambrose et al., 2023), whereas covering effluent storage, along with burning or harvesting the methane, can lower whole-farm emissions by 5% to 10% (Garnett and Eckard, 2024). Additionally, feed management options, such as CH_4-reducing additives, can help lower enteric CH_4 emissions in both production systems and improve feed efficiency (Eckard and Clark, 2018; Hristov et al., 2022). Furthermore, reducing prefarm embedded emissions through sustainable feed sourcing and improving the efficiency of fertilizer use could be more relevant to pasture- compared with confinement systems. Most of the grain, concentrate, and hay used in pasture-based systems of the present study were purchased. Therefore, reducing wastage and growing more forage on-farm could help substitute supplements and decrease prefarm embedded emissions. Both systems should also explore the potential to reduce energy-related emissions by adopting renewable energy sources, such as solar and wind power, and biodigesters which are feasible for confinement systems (Garnett and Eckard, 2024).

One limitation of this study is that concentrate, hay, and silage feed samples were collected only once and at different times from each farm. Therefore, this approach provides a snapshot of feed quality at specific points, rather than reflecting whole-year averages. This limitation is particularly relevant for silage and hay, as their composition can vary by season. Future research should assess the effects of more accurate and frequent diet information on the estimation of yearly GHG emissions. Additionally, the present study did not account for C sequestered by pastures and soils, which could have provided a more comprehensive understanding of the environmental benefits associated with different farming practices. Future research should address synchronized feed sampling throughout the year and consider C sequestration in soil to provide a more complete analysis of farm-level effects.

CONCLUSIONS

The results of the present study revealed that enteric CH_4 emissions were the largest source of GHG emissions in both confinement and pasture-based systems, while manure (N_2O and CH_4) and prefarm embedded emissions were the second largest sources in confinement and pasture-based systems, respectively. Despite a 72% increase in daily milk production per cow in the confinement compared with the pasture-based system, milk emission intensity was similar in both systems. This underscores the need for additional strategies to reduce GHG emissions from animals and address prefarm embedded emissions and fertilizer emissions. The emission offset by tree C sequestration (kg CO_{2eq}/kg FPCM) was relatively low in both systems; however, a greater potential to offset livestock emissions was observed in pasture-based systems (6% vs. 1%). In conclusion, targeted mitigation strategies tailored to specific dairy production systems should be implemented because the sources of GHG emissions differ between the systems, with feed being the primary source of emissions in both systems and manure management a significant contributor in the confinement system.

NOTES

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Nonstandard abbreviations used: ADCC = Australian Dairy Carbon Calculator; CO_2 emissions from energy consumption = CO_2 emissions from diesel and electricity; CO_2 emissions from prefarm embedded sources = CO_2 emissions from concentrate, forage, and fertilizers; CO_{2eq} = CO_2 equivalents; DMD = DM digestibility; DOMD = digestible OM in DM; EE = ether extract; FPCM = fat and protein-corrected milk; GWP100 = global warming potential for 100 yr horizon; NSW = New South Wales; total N_2O from N fertilizer (on-farm) = direct N_2O + indirect N_2O from N fertilizer (on-farm); WSC = water soluble carbohydrate.

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