Production performance, nutrient use efficiency, and predicted enteric methane emissions in dairy cows under confinement or grazing management system

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ABSTRACT

There has been an intense debate regarding the economic, social, and environmental sustainability of confinement versus grazing dairy systems. Our goal was to conduct a meta-analysis to compare dry matter intake, milk yield and composition, nutrient use efficiency (i.e., feed efficiency, milk N efficiency), and predicted enteric CH4 emissions using studies that simultaneously evaluated confinement and grazing. We were able to include in the meta-analysis 8 peer-reviewed articles that met the following selection criteria: (1) publication between 1991 and 2021 in English language, (2) report either SEM or SD, (3) inclusion of at least 1 confinement [total mixed ration or fresh cut herbage fed indoors (i.e., zero-grazing)] and 1 grazing treatment in the same study, and (4) use of markers (internal or external) to estimate herbage dry matter intake. Two unpublished experiments were added to the data set resulting in a total of 10 studies for comparing confinement and grazing. The magnitude of the effect (i.e., effect size) was evaluated using weighted raw mean differences between grazing and confinement systems for a random effect model. Enteric CH4 production was predicted as follows: CH4 (g/d) = 33.2 (13.54) + 13.6 (0.33) × dry matter intake + 2.43 (0.245) × neutral detergent fiber. Dry matter intake (~9.5%), milk yield (~9.3%), milk fat yield (~5.8%), milk protein yield (~10%), and energy-corrected milk (~12%) all decreased in grazing versus confined dairy cows. In contrast, concentration of milk fat and feed efficiency (energy-corrected milk/dry matter intake) were not affected by management system. Whereas milk protein concentration increased, milk nitrogen (N) efficiency (milk N/N intake) tended to decrease in grazing compared with confinement. Predicted enteric CH4 production was 6.1% lower in grazing than confined dairy cows. However, CH4 yield (g/kg of dry matter intake) and CH4 intensity (g/kg of energy-corrected milk) did not change between confinement and grazing. In conclusion, while production performance decreased in grazing dairy cows, nutrient use efficiency and predicted enteric CH4 emissions were relatively similar in both management systems. Results of our meta-analysis should be interpreted with caution due to the small number of studies that met our inclusion criteria leading to a limited number of treatment mean comparisons. Key words: climate change, dairy cow, feed efficiency, greenhouse gas, milk nitrogen efficiency

INTRODUCTION

Pasture-based systems are known to perform multiple ecosystem services including food production, climate regulation, pollination, nutrient cycling, and erosion control (Sala et al., 2017; Tittonell, 2021), as well as use of marginal lands not suitable for tillage and crop production (Wang et al., 2021). Grazing ruminants can also express their natural behaviors while on pasture (Charlton et al., 2011), and previous research revealed that dairy cows were more motivated to go outside to graze than stay indoors and consume a total mixed ration (TMR) offered immediately after the afternoon milking (von Keyserlingk et al., 2017). Another benefit associated with pasture-based dairy is the reduction in production costs, which have been shown to decrease as the proportion of grazed herbage increases in the diet dry matter (DM; Kelly et al., 2020). Furthermore, consumers are willing to pay premiums for pasture-based milk and dairy products due to potential human-health benefits (Benbrook et al., 2018; Stampa et al., 2020; Peira et al., 2020) and the perception that grazing is more environmentally friendly and welfare sounder than confinement (Wong et al., 2010; Bir et al., 2020; Joubran et al., 2021). This opens opportunities to small dairies capitalize on organic certified and grassfed milk markets to remain economically viable (Brito and Silva, 2020; Snider et al., 2021). However, only 10 to 15% of milk produced worldwide comes from grazing operations (Shalloo et al., 2018) and, in Europe and Australia, inclusion of grazed herbage in dairy diets has been declining (Hennessey et al., 2020; Joubran et al., 2021). On the other hand, TMR-based, confinement dairy farms are more prolific not only in the United States (Winsten et al., 2010), but also globally (Joubran et al., 2021) mostly driven by greater milk output compared with grazing dairies (Fontanelli et al., 2005; Winsten et al., 2010; Joubran et al., 2021). Despite a growing interest in the economic and environmental sustainability of confinement and grazing enterprises, we are not aware of any meta-analysis that has compared experiments in which animal production and environmental impact metrics were concurrently measured in both systems.

There is an ongoing interest to better understand differences in nutrient use efficiency and environmental performance of confinement versus grazing dairy systems. However,
due to the limited number of studies that had simultaneously investigated the economic, social, and environmental outcomes associated with confinement and pasture-based farms (Titttonell, 2021), a head-to-head comparison between systems is challenging. O’Neill et al. (2011) reported reductions in CH₄ production (−37%), CH₂ yield (−11%), and CH₂ intensity (−13%) in dairy cows grazing perennial ryegrass (Lolium perenne L.) herbage compared with those fed TMR. However, these positive responses occurred at expense of DMI (DMI) and milk yield, which together decreased 27% with feeding the herbage diet (O’Neill et al., 2011). Further evaluations using a larger data set are needed to better understand how diets impact enteric CH₄ production in dairy cows under confinement or grazing management. We aimed, via a meta-analytical approach, to compare DMI, milk yield and composition, nutrient use efficiency (i.e., feed efficiency, milk nitrogen (N) efficiency), and precited enteric CH₄ production in studies that simultaneously used confined and grazing dairy cows.

METHODOLOGY

Literature Search, Study Eligibility Criteria, and Data Sets

A systematic literature search was conducted using the advanced search webtool of Web of Science (https://www.webofscience.com), Google Scholar (https://scholar.google.com), and Science Direct (https://www.sciencedirect.com). The original search used the key words “grazing” “confinement” “dairy cows” and “methane production” covering the years from 1991 through 2021 in each database. The terms “indoor” and “outdoor” and “milk production” were also used in a second literature search to obtain additional peer-reviewed papers. In the present meta-analysis, the grazing treatment was defined as cows having exclusively access to pasture (i.e., 100% grazed herbage diet) or cows having access to pasture supplemented with partial TMR (pTMR) or conserved forage (i.e., baleage) plus concentrate (Table 1). Confinement was defined as cows fed TMR or fresh cut herbage (i.e., zero grazing) indoors (Table 1).

The inclusion criteria for selected peer-reviewed papers were: (1) published between 1991 and 2021 (i.e., last 30 years) in English language, (2) report either SEM or SD for variables of interest, (3) inclusion of at least 1 confinement and 1 grazing treatment in the same study, and (4) use of markers (internal or external) to estimate herbage DMI. Our meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009), with the literature search protocol detailed below. We originally obtained 1,044 publications, with 198 excluded after an initial screening due to duplication of records. The remaining 846 records were screened, and 97 publications were removed because they were defined as systematic reviews, reviews, or meta-analyses. An additional 749 references did not meet the inclusion criterion of simultaneously comparing at least 1 confinement versus 1 grazing treatment in the same study and were excluded from our data set. Twenty-five full-text articles were selected, but further screening resulted in the removal of 17 publications as authors did not report SEM or have not used markers to estimate herbage DMI. Therefore, 8 peer-reviewed papers from the literature search were included in the final data set. Two studies (Brito et al., unpublished) conducted at the University of New Hampshire (Durham) were included to improve the robustness of the data set to detect differences in the variables used to compare confinement versus grazing.

Calculations

Dry matter intake, milk yield, and concentration and yield on milk components were obtained from treatment means reported in the selected studies (Table 1). Variables that were not reported in tables or text such as feed efficiency and milk N efficiency were calculated. Standard deviation presented herein was obtained from reported SD or computed from SEM multiplied by the square root of experimental units of individual studies. Energy-corrected milk (ECM) yield was calculated according to Orth (1992) as follows: ECM yield = [0.327 × milk yield (kg/d)] + [12.95 × milk fat yield (kg/d)] + [7.2 × milk protein yield (kg/d)]. Feed efficiency was calculated by dividing ECM yield by DMI. When not reported, crude protein intake (kg/d) was calculated by multiplying DMI (kg/d) by the respective treatment crude protein concentration and converted to N intake (g/d) using the 6.25 conversion factor. Milk N was obtained by dividing milk protein by 6.38, with milk N efficiency determined by the division between milk N yield and N intake (reported or calculated) multiplied by 100.

Only 4 studies (2 published and 2 unpublished) included in our data set reported enteric CH₄ production (O’Neill et al., 2011; Civiero et al., 2021; Brito et al., unpublished). Therefore, we used the intercontinental equation proposed by Niu et al. (2018), which is based on DMI and dietary neutral detergent fiber concentration to predict enteric CH₄ production for all selected studies including those that measured CH₄ production. The equation adopted from Niu et al. (2018) was: CH₄ (g/d) = 33.2 (13.54) + 13.6 (0.33) × DMI + 2.43 (0.245) × neutral detergent fiber. Methane yield was obtained by dividing predicted CH₄ production (g/d) by measured DMI (kg/d), and CH₄ intensity by the division between predicted CH₄ production (g/d) and calculated ECM (kg/d).

Statistical Analysis

Effect of management system on variable responses (i.e., DMI, N intake, milk yield, ECM yield, milk composition, feed efficiency, milk N efficiency, predicted CH₄ production, calculated CH₂ yield, calculated CH₂ intensity) was evaluated using weighted raw mean differences (WMD) comparing grazing and confinement treatment means (i.e., estimated effect size). The estimated effect size was weighted by the inverse of the variance in the respective studies using the method proposed by DerSimonian and Laird (1986) for a random effect model. Publication bias was assessed using funnel plot asymmetry (Light and Pillemer, 1984) and Egger’s regression method (Egger et al., 1997). The chi-squared (Q) test and F statistic, which measures the proportion of variation due to heterogeneity (Higgins et al., 2003), were both used to evaluate between-study variability (i.e., heterogeneity of effect size). Heterogeneity values of <25%, 25 to 50%, and >50% indicate low, moderate, and high between-study variability, respectively (Higgins et al., 2003). The metafor package of R Software (version 1.3-1093; Viechtbauer, 2010; https://cran.rproject.org/web/packages/metafor/metafor.pdf) was used for obtaining WMD, publication bias, F statistics, and forest plot.
Table 1. Summary of studies included in the meta-analysis to compare confinement versus grazing dairy systems

| Reference                  | n-cows | DIM | Exp. design | Treatments | Grazed herbage                                                                 |
|----------------------------|--------|-----|-------------|------------|--------------------------------------------------------------------------------|
| Civiero et al. (2021)      | 9      | 136 | 3 × 3 LS    | (1) TMR, (2) GRAZ + 75% pTMR, (3) GRAZ + 50% pTMR | Pearl millet (Pennisetum glaucum ‘Campeiro’)                                      |
| Soutto et al. (2020)       | 14     | 148 | RCBD        | (1) TMR, (2) GRAZ + CONC | Red oats (Avena byzantina)                                                         |
| Fajardo et al. (2015)      | 41     | -   | RCBD        | (1) TMR, (2) 6 h GRAZ + pTMR, (3) 9 h GRAZ + pTMR | Legume-grass mix [tall fescue (Festuca arundinacea), white clover (Trifolium repens), and birdfoot trefoil (Lotus corniculatus)] |
| O’Neill et al. (2011)      | 48     | 64  | RCBD        | (1) TMR, (2) 100% GRAZ | Perennial ryegrass (Lolium perenne)                                                 |
| Kaufmann et al. (2011)     | 14     | 38  | Crossover   | (1) Z-GRAZ + CONC, (2) GRAZ + CONC | 66% grass with 43% perennial ryegrass (L. perenne), 20% herbs with 18% dandelion (Tanaxacum officinale), and 14% white clover (T. repens) |
| Mohammed et al. (2009)     | 6      | 76  | 3 × 3 LS    | (1) Z-GRAZ + CONC, (2) grass silage + CONC, (3) GRAZ + CONC | Perennial ryegrass (L. perenne)                                                     |
| Bargo et al. (2002)        | 45     | 109 | RCBD        | (1) TMR, (2) GRAZ + CONC, (3) GRAZ + pTMR | 50% smooth bromegrass (Bromus inermis), 33% orchardgrass (Dactylis glomerata), 7% Kentucky bluegrass (Poa pratensis), and 10% weeds and dead herbage |
| Kolver and Muller (1998)   | 19     | 59  | CRD         | (1) TMR, (2) 100% GRAZ | 53% perennial ryegrass (L. perenne), 19% white clover (T. repens), 21% other grasses including orchardgrass (D. glomerata), Kentucky bluegrass (P. pratensis), smooth bromegrass (B. inermis), and tall fescue (F. arundinacea), 3% weeds, and 4% dead herbage |
| Brito et al. (Study 1)     | 18     | 153 | RCBD        | (1) TMR, (2) GRAZ + legume-grass mix baleage + CONC | 90% forage canola (Brassica napus), 4.4% grasses, 0.78% legumes, and 4.9% weeds |
| Brito et al. (Study 2)     | 20     | 161 | RCBD        | (1) TMR, (2) GRAZ + pTMR | 81.5% forage canola (B. napus), 16% weeds, 2.4% dead herbage                      |

1Studies included Holstein (n = 5), Holstein-Friesian (n = 2), Jersey (n = 2), and Holstein × Jersey cross (n = 1).
2DIM, days in milk.
3LS, Latin square; RCBD, randomized complete block design; CRD, completely randomized design.
4TMR, total mixed ration, GRAZ, grazing, pTMR, partial total mixed ration, CONC, concentrate, Z-GRAZ, zero-grazing (fresh cut herbage fed in confinement).
5Days in milk averaged 24 ± 10 d during herbage DMI measurements in wk 4 and 5 of the study, and milk yield was recorded during wk 0 to 10 in the study.
6Unpublished grazing studies conducted at the University of New Hampshire (Durham); diets were formulated to yield a 60:40 forage:concentrate ratio, with forage canola herbage set to replace 30% (Study 1) or 40% (Study 2) of legume-grass mix baleage in the diet dry matter.

We did not observe publication bias (P ≥ 0.08) for milk yield, concentrations of milk fat and protein, and milk protein yield based on funnel plot asymmetry (data not shown) and Egger’s regression asymmetry test (Table 3). In contrast, publication bias was detected for DMI (P = 0.03) and milk fat yield (P = 0.01) possibly because of the limited number of treatment mean comparisons (n = 14) and associated variation. Heterogeneity values ranged from low (I² = 22%; P = 0.21; milk fat concentration) to high (I² = 95.3%; P < 0.01; DMI) as shown in Table 3. Specifically, heterogeneity was considered high (>50%; mean I² = 88.3%) for all variables analyzed except milk fat concentration (Table 3), thus indicating large between-study variability.

Effect of management system on DMI, milk yield, and concentration and yield of milk fat and protein assessed via WMD between confinement and grazing is presented in Table 3. Dry matter intake decreased (P < 0.01) by 9.5% in grazing dairy cows compared with those under confinement management. Grazing cows spend more time searching and selecting food than confined dairy cows (Agnew and Yan, 2000), which

RESULTS AND DISCUSSION
This study was designed to compare production performance, nutrient utilization, and predicted enteric CH₄ production in dairy cows under confinement or grazing system via a meta-analysis using studies that simultaneously test both treatments. However, we did not aim to oppose both management systems, but rather to fill knowledge gaps while acknowledging the limitations and strengths of confinement and grazing.

Description of the experimental design and treatments from studies used in the meta-analysis is presented in Table 1, and descriptive statistics in Table 2. The same dairy breeds (i.e., Holstein, Holstein-Friesian, Jersey) and crossbred cows (Holstein × Jersey) were used within study (Tables 1 and 2), thus indicating that comparisons between confinement and grazing were not biased by differences in genetic potential. (data not shown). Differences were declared at P ≤ 0.05 and tendencies at 0.05 < P ≤ 0.10.
Table 2. Descriptive statistics of studies used in the meta-analysis to compare confinement versus grazing dairy systems

| Item                        | n-study | n-treatment | Mean   | ± SD  | Minimum | Maximum |
|-----------------------------|---------|-------------|--------|-------|---------|---------|
| **Confinement**             |         |             |        |       |         |         |
| Body weight, kg             | 10      | 3           | 567    | 61.8  | 460     | 660     |
| Days in milk                | 10      | 3           | 94.0   | 46.7  | 24.0    | 161     |
| DMI, kg/d                   | 10      | 11          | 21.9   | 3.45  | 15.6    | 26.7    |
| Milk yield, kg/d            | 10      | 11          | 30.2   | 9.01  | 16.1    | 44.1    |
| Milk fat, %                 | 10      | 11          | 4.06   | 0.66  | 3.30    | 5.32    |
| Milk fat, kg/d              | 10      | 11          | 1.15   | 0.23  | 0.58    | 1.56    |
| Milk protein, %             | 10      | 11          | 3.30   | 0.27  | 2.80    | 3.88    |
| Milk protein, kg/d          | 10      | 11          | 0.98   | 0.26  | 0.47    | 1.30    |
| ECM, kg/d                   | 10      | 11          | 31.6   | 7.42  | 15.9    | 43.2    |
| Feed efficiency, kg/kg     | 10      | 11          | 1.43   | 0.21  | 1.02    | 1.92    |
| N intake, g/d               | 10      | 11          | 583    | 104   | 342     | 720     |
| Milk N efficiency, %        | 10      | 11          | 25.2   | 4.27  | 16.6    | 30.6    |
| CH₄ production, g/d         | 10      | 11          | 420    | 39.3  | 369     | 473     |
| CH₄ yield, g/kg of DMI      | 10      | 11          | 20.7   | 3.05  | 17.6    | 26.9    |
| CH₄ intensity, g/kg of ECM  | 10      | 11          | 15.1   | 3.87  | 10.1    | 23.3    |
| **Grazing**                 |         |             |        |       |         |         |
| Body weight, kg             | 10      | 3           | 561    | 69.8  | 433     | 660     |
| Days in milk                | 10      | 3           | 94.0   | 46.7  | 24.0    | 161     |
| DMI, kg/d                   | 10      | 13          | 19.9   | 2.40  | 14.3    | 25.2    |
| Milk yield, kg/d            | 10      | 13          | 27.3   | 6.19  | 19.6    | 42.4    |
| Milk fat, %                 | 10      | 13          | 4.10   | 0.61  | 3.13    | 5.41    |
| Milk fat, kg/d              | 10      | 13          | 1.09   | 0.19  | 0.83    | 1.59    |
| Milk protein, %             | 10      | 13          | 3.40   | 0.31  | 2.82    | 4.03    |
| Milk protein, kg/d          | 10      | 13          | 0.88   | 0.17  | 0.64    | 1.32    |
| ECM, kg/d                   | 10      | 13          | 29.4   | 5.51  | 21.5    | 43.5    |
| Feed efficiency, kg/kg     | 10      | 13          | 1.48   | 0.22  | 1.23    | 2.03    |
| N intake, g/d               | 10      | 13          | 620    | 112   | 467     | 768     |
| Milk N efficiency, %        | 10      | 13          | 23.0   | 6.79  | 16.5    | 37.6    |
| CH₄ production, g/d         | 10      | 13          | 403    | 32.8  | 340     | 460     |
| CH₄ yield, g/kg of DMI      | 10      | 13          | 20.5   | 3.03  | 14.1    | 26.9    |
| CH₄ intensity, g/kg of ECM  | 10      | 13          | 15.5   | 3.40  | 9.70    | 20.9    |

1Studies included Holstein (n = 5), Holstein-Friesian (n = 2), Jersey (n = 2), and Holstein × Jersey cross (n = 1); confinement was defined as a management system with cows fed total mixed ration, fresh cut herbage (zero-grazing), or grass silage indoors, and grazing as a management system with cows having access to pasture and consuming herbage as the sole dietary ingredient, herbage supplemented with partial total mixed ration, or herbage supplemented with baleage plus concentrate.

2DMI (dry matter intake); ECM (energy-corrected milk) yield = [0.327 × milk yield (kg/d)] + [12.95 × milk fat yield (kg/d)] + [7.2 × milk protein yield (kg/d)] (Orth, 1992); feed efficiency = ECM yield/DMI; milk N efficiency = (milk N/N intake) × 100; predicted CH₄ production (g/d) = 33.2 (13.54 × 13.6 (0.33) × DMI + 2.43 (0.245) × neutral detergent fiber (Niu et al., 2018); CH₄ yield was obtained by dividing predicted CH₄ production by measured DMI; CH₄ intensity was obtained by dividing predicted CH₄ production by calculated ECM yield.

3Studies did not report days in milk and body weight by treatment.

can limit the amount of herbage consumed leading to less total DMI (Reis and Combs, 2000). It should be also noted that grazing cows are generally more exposed to heat and heat stress conditions resulting in less grazing activity and decreased herbage DMI.

Milk yield was 9.3% lower (P < 0.01; Table 3) in grazing versus confined dairy cows likely in response to a 9.5% drop in DMI leading to decreased energy intake. In 3 studies used in the data set (i.e., Fajardo et al., 2015; Soutto et al., 2020; Civiero et al., 2021), grazing cows received less concentrate than those in confinement, while in 2 other experiments (i.e., Kolver and Mullen, 1998; O’Neill et al., 2011), herbage was not supplemented with concentrate (100% grazing; Table 1). Therefore, decreased or no concentrate supplementation also contributed to the milk yield reduction in grazing dairy cows (Table 3). Furthermore, increased energy requirement due to grazing activity (i.e., energy spent to select and consume herbage) and walking back and forth from pasture to the milking parlor, shifts dietary energy away from milk synthesis to maintenance in pasture-based dairy cows (Agnew and Yan, 2000; NRC, 2001). Bargo et al. (2002) estimated, using equations reported in the NRC (2001), that compared with confined cows fed TMR, maintenance requirements increased by 5.4 and 2.4 Mcal/d in grazing dairy cows supplemented with concentrate or pTMR, respectively. According to Bargo et al. (2002), increased maintenance requirement accounted for 88 and 61% of the differences in milk yield between cows offered TMR versus herbage supplemented with concentrate or pTMR, respectively.
Management system did not affect the concentration of milk fat ($P = 0.38$) as shown in Table 3. In contrast, concentration of milk protein increased ($P = 0.03$) by 2.4%, whereas yields of milk fat ($P = 0.05$) and milk protein ($P < 0.01$) decreased by 5.8 and 10%, respectively, between grazing versus confined dairy cows (Table 3). Increased milk protein concentration can be explained by a dilution effect caused by increased milk volume. Decreased production of milk fat and protein followed the reduction in milk yield (−9.3%), with all linked to lowered DMI (−9.5%) in pasture-based diets. Overall, grazing decreased yields of milk and milk fat and protein, and these production losses may not be offset by less feed costs often associated with pasture-based diets as American dairy farmers receive premiums for shipping more fat and protein.

Hardie et al. (2014) demonstrated via a cluster analysis using 69 organic-certified dairy farms from Wisconsin that dairies feeding the least amount of concentrate and relying heavily on pasture had lower milk rolling herd average (mean = 3,632 kg/cow per year) and income over feed costs ($5.76/lactating cow per d) than those with greatest concentrate and least reliance on grazed herbage (mean = 6,878 kg/cow per year of milk rolling herd average and $10.2/lactating cow per d of income over feed costs). However, organic grass-fed milk markets can potentially counteract production losses due to additional premiums paid to farmers (Benbrook et al., 2018; Brito and Silva, 2020; Snider et al., 2021).

Effect of management system on ECM yield, feed efficiency, milk N efficiency, and predicted enteric CH₄ production evaluated through WMD between confinement and grazing is presented in Table 4. Response variables shown in Table 4 were all calculated or predicted to standardize comparisons between management systems and to obtain additional data such as enteric CH₄ production, which was reported in only 4 out of 10 studies [O'Neill et al., 2011; Civiero et al., 2021; Brito et al., unpublished (2 experiments)]. Therefore, the intercontinental equation [CH₄ (g/d) = 33.2 (13.54) + 13.6 (0.33) × DMI + 2.43 (0.245) × neutral detergent fiber] published by Niu et al. (2018) was used to predict CH₄ production. This equation was developed using a refined data set containing 2,566 individual observations of enteric CH₄ production obtained from 42 studies conducted in Europe ($n = 1,423$), 45 in the United States ($n = 1,084$), and 1 study from Australia ($n = 59$). Holstein was the predominant dairy breed, contributing with 68% ($n = 1,732$) of the total individual observations followed by Ayshire (19%; $n = 497$), Brown Swiss, Simmental, and crossbred dairy cattle 10% ($n = 249$), and Jersey (3%; $n = 88$). It should be noted that none of the experiments conducted in Europe or United States used grazing dairy cows, and only 1 pasture-based study (2.3%; $n = 59$) was included in the final data set, suggesting that equations reported by Niu et al. (2018) could be more accurate to
predict enteric \( \text{CH}_4 \) production from confined than grazing cows. We used 58 individual observations of enteric \( \text{CH}_4 \) production from 3 grazing studies in which diets were formulated to contain (DM basis) 30% or 40% of forage canola herbage (\textit{Brassica napus} L.; Brito et al., unpublished; Table 1), or 48% of cool season legume-grass mix herbage (Antaya et al., 2019) to assess the relationship between measured and predicted \( \text{CH}_4 \) production via regression (Figure 1). Despite the limited number of observation \((n = 58)\), there was a moderate relationship between measured and predicted \( \text{CH}_4 \) production \((R^2 = 0.36; P < 0.001)\) indicating that the equation of Niu et al. (2018), which is based on DMI and dietary neutral detergent fiber concentration, appears to be reliable to predict \( \text{CH}_4 \) production in grazing dairy cows consuming (actual intake) up to 51% of herbage (% of diet DM). It is also important to note that the prediction equation used herein had one the greatest concordance correlation coefficient (i.e., 0.75) and smallest mean absolute error (i.e., 48.5 g/d) indicating that \( \text{CH}_4 \) production can be reasonably predicted (Niu et al., 2018).

Energy-corrected milk yield decreased \((P < 0.01)\) by 12% in grazing versus confined dairy cows (Table 4), which is in line with reduced yields of milk and milk fat and protein (Table 3). Contrarily, management system did not affect feed efficiency \((P = 0.20)\). Nitrogen intake was not impacted by management system \((P = 0.52)\), but milk N efficiency tended \((P = 0.09)\) to decrease with grazing (Table 4), which may be associated with greater concentration of soluble crude protein in herbage than TMR (Bargo et al., 2002). In general, improved feed efficiency and milk N efficiency indicate that cows are more efficient in partitioning nutrients for production of milk and milk components than waste including enteric \( \text{CH}_4 \) and nitrogenous compounds such as urinary urea N. However, the lack of management system effect on feed efficiency, and only a trend for improving milk N efficiency with confinement implies similar nutrient use efficiency between confined cows and those with access to pasture.

Predicted enteric \( \text{CH}_4 \) production was 6.1% lower \((P < 0.01)\) in grazing than confined dairy cows (Table 4), thus in line with reduced DMI (Table 3). In fact, it is well known that DMI is positively correlated with enteric \( \text{CH}_4 \) production in lactating dairy cows (Hristov et al., 2013, 2018). Neither \( \text{CH}_4 \) yield \((\text{g/kg of DMI})\) nor \( \text{CH}_4 \) intensity \((\text{g/kg of ECM})\) changed \((P \geq 0.23)\) in response management system (Table 4). We detected a more pronounced reduction in \( \text{CH}_4 \) production \((i.e., -19\%)\) in grazing \((\text{mean} = 368 \text{ g/d})\) versus confinement \((\text{mean} = 453 \text{ g/d} \text{ data not shown})\) when using data from selected studies \((n = 4; O’Neill et al., 2011; Civiero et al., 2021; Brito et al., unpublished)\) whereby enteric \( \text{CH}_4 \) production was directly measured. Furthermore, \( \text{CH}_4 \) yield \((7.2\%)\) and \( \text{CH}_4 \) intensity \((6.2\%)\) were both lower in cows under grazing than confinement management in these 4 studies \(\text{data not shown}\). In 3 out of 4 studies from this smaller data set, cows grazed high quality herbage in the form of perennial ryegrass \((\text{mean} = 24.1\% \text{ crude protein}; \text{mean} = 46.5\% \text{ neutral detergent fiber}; O’Neill et al., 2011)\) or forage canola \((\text{mean} = 24.5\% \text{ crude protein}; \text{mean} = 16.1\% \text{ ash-free neutral detergent fiber}; Brito et al., unpublished)\), which likely contributed to the larger reduction in enteric \( \text{CH}_4 \) emissions compared with the complete data set \((n = 10 \text{ studies})\). Forage canola also contains glucosinolates that have been shown to be negatively correlated with \( \text{CH}_4 \) production in continuous culture (Dillard et al., 2018). Overall, the enteric \( \text{CH}_4 \) production data reported in Table 4 should be interpreted cautiously because we used an equation to predict enteric \( \text{CH}_4 \) production as discussed previously.

Enteric \( \text{CH}_4 \) accounts for approximately 27% of total \( \text{CH}_4 \) emissions in the United States (EPA, 2019). Even though the atmospheric half-life of \( \text{CH}_4 \) (~10 years) is much shorter than that of other greenhouse gases such as \( \text{N}_2\text{O} \) (~110 years) and \( \text{CO}_2 \) (~1,000 years), its global warming potential is about 28 times greater compared with that of \( \text{CO}_2 \) (Lashof et al., 1990; IPCC, 2013). In addition to its effects on global warming, enteric \( \text{CH}_4 \) represents energy losses ranging from 2.7% to 9.8% of gross energy intake in lactating dairy cows (Niu et al., 2018). Therefore, dietary and management strategies to mitigate enteric \( \text{CH}_4 \) emissions in ruminants can improve both the carbon footprint of dairy farms and milk yield of dairy cows. Our meta-analysis revealed only a small difference in predicted \( \text{CH}_4 \) production between confinement and grazing systems, and no changes in \( \text{CH}_4 \) yield and \( \text{CH}_4 \) intensity (Table 4).

However, a fair comparison and evaluation of dairy management systems should also consider greenhouse gas emissions from crop production, transportation, and manure management, as well as ecosystem services provided by grazing dairies (Fredeen et al., 2013; Tittonell, 2021), which was beyond the scope of our study. Nevertheless, results from studies that have compared the carbon footprint of grazing and confinement dairy systems are not consistent. For instance, whereas some studies reported reduced whole-farm greenhouse gas emissions in grazing versus confinement (Flysjø et al., 2011; O’Brien et al., 2014), others showed increased emissions with grazing management (Capper et al., 2009; Léis et al., 2015). In contrast, Aguirre-Villegas et al. (2017) reported comparable whole-farm greenhouse gas emissions across different grazing and confinement scenarios using Wisconsin dairies in their modeling simulations.
CONCLUSIONS

Our meta-analysis provided a snapshot of production performance, nutrient use efficiency, and predicted enteric CH\textsubscript{4} emissions of confinement versus grazing dairy systems using studies that simultaneously compared these 2 management approaches. We showed that yields of milk, milk fat and protein, and ECM were all lower (ranging from −5.8 to −12%) in grazing than confinement, with these responses mostly driven by decreased DMI (−9.5%) in cows with access to pasture. Feed efficiency did not change, and milk N efficiency tended to decrease with grazing, thus indicating similar nutrient utilization between both systems. Predicted CH\textsubscript{4} production decreased by 6.1% in grazing dairy cows due to reduced DMI. However, CH\textsubscript{4} yield (g/kg of DMI) and CH\textsubscript{4} intensity (g/kg of ECM) were not affected by management system. In general, results of our meta-analysis should be interpreted cautiously due to the limited number of studies (n = 10) and associated treatment mean comparisons (n = 14) that met inclusion criteria. We also used a published equation based on DMI and dietary neutral detergent fiber concentration to predict CH\textsubscript{4} production because only 4 studies used in the data set directly measured CH\textsubscript{4}. Whole-farm greenhouse gas emissions and ecosystems services provided by grazing should be considered in future assessments of confinement and pasture-based dairy systems.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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