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Symposium Review
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Enteric methane emissions in grazing dairy systems*

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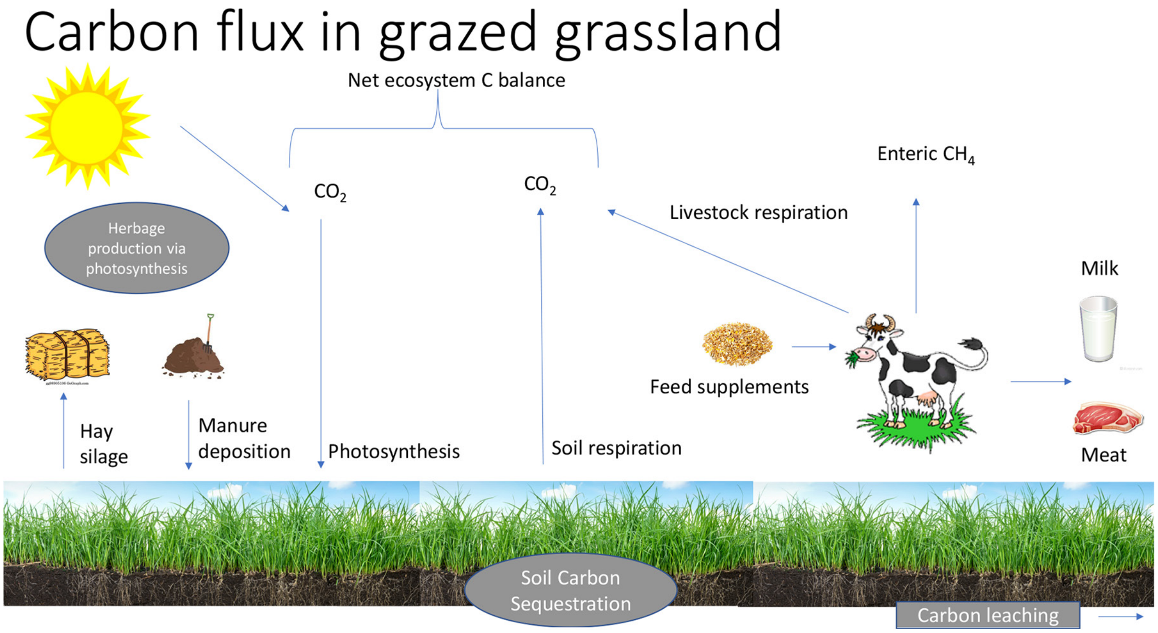
Graphical Abstract

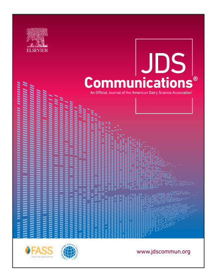


Summary

Quantifying and mitigating enteric CH_4 from pastoral dairy systems is challenging. A variety of dietary- and husbandry-management strategies are being evaluated to mitigate enteric CH_4 emissions in dairy cattle. Some strategies may not be applicable to pastoral dairy systems. Further research is needed to identify protracted strategies for reducing CH_4 emissions that do not require frequent vaccination or constant feeding, particularly for grazed herds that do not receive supplementation. Breeding animals for reduced CH_4 emissions shows promise, as long as the purchase of such animals is not cost-prohibitive and animal production is not impaired. More robust data sets are needed to develop life cycle assessments that account for all inputs and outputs on the farm that affect carbon and nitrogen cycling.

Highlights

- Quantifying and mitigating enteric CH_4 from pastoral dairy systems is challenging.
- Low-input, long-acting strategies such as vaccines and selective breeding are needed.
- Life cycle assessments are required to fully assess pastoral dairy farms in all environments.



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Enteric methane emissions in grazing dairy systems*

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Abstract: Approximately 80% of agricultural CH_4 comes from livestock systems, with 90% of that derived from enteric CH_4 production by ruminants. Grazing systems are used worldwide to feed dairy cattle. Although quantifying enteric CH_4 emissions in grazing systems has unique challenges, emerging technologies have made gaseous data collection more feasible and less laborious. Nevertheless, robust data sets on enteric CH_4 emissions under various grazing conditions, as well as effective and economic strategies to mitigate CH_4 emissions in grazing dairy cows, are still in high demand because data collection, feeding management, and milk market regulations (e.g., organic certification, grassfed) impose more challenges to grazing than confinement dairy systems. This review will cover management strategies to mitigate enteric CH_4 emissions and applicability to pastoral dairy systems. The effects of enteric CH_4 in the broader context of whole-system assessments will be discussed, which are key to assess the overall environmental impact of grazing dairies.

Approximately 80% of agricultural CH_4 comes from livestock systems, with 90% of that derived from enteric CH_4 production by ruminants (Gerber et al., 2013). Reduction of enteric CH_4 emissions has been a major research focus (Hristov et al., 2013; Beauchemin et al., 2020). While grazing systems are used worldwide, quantifying and mitigating enteric CH_4 emissions from these systems present unique challenges. For example, in countries such as New Zealand, the dairy industry is primarily pasture based, yet has the lowest C footprint for milk in the world (DairyNZ, 2022). In other countries such as the United States, the dairy sector only contributes 1.3% of total national greenhouse gas (**GHG**) emissions (Rotz, 2018) with grazing systems comprising <25% of dairy operations (Winsten et al., 2011).

The term "grazing system" has different meanings worldwide, which may affect GHG emissions and practical mitigation strategies due to widely varying feeding and management systems. For example, regions such as New Zealand and Ireland have grazing systems where there is very limited use of feeds other than fresh forage. South America and North Australia have tropical and subtropical grazing systems with forages that differ greatly from many other parts of the world. The United States has a wide range of systems from no-grain grazing systems to hybrid systems that feed higher amounts of stored forages and concentrates. The purpose of this paper is to summarize potential strategies to mitigate enteric CH_4 emissions in grazing dairy systems, including practical applications and whole-system considerations.

Reduction of enteric CH_4 emissions worldwide is challenged by the development and application of mitigation strategies that are economically viable and practical to be adopted across a wide variety of pasture-based systems (Beauchemin et al., 2020; Vargas et al., 2022). While many factors such as DMI can affect enteric CH_4 emissions (Molano and Clark, 2008), diet quality also plays a significant role (Knapp et al., 2014). Forage-based diets are often assumed to result in greater CH_4 yield (g/kg of DMI) than diets that contain increased amounts of highly fermentable carbohydrates such as concentrates (Thompson and Rowntree, 2020), in part due to shifts in ruminal VFA profile toward propionate, when supplementing starch-based concentrates to grazing dairy cows (Beauchemin et al., 2009). However, differences in ruminal propionate are expected to narrow if replacing concentrate with highly digestible forage species.

Increasing the forage component of the diet can favor production of acetate and butyrate, which release hydrogen ions, whereas propionate serves as a net hydrogen sink. Consequently, diets that increase propionate and decrease acetate in the rumen are often associated with a reduction in ruminal methanogenesis, as less hydrogen is available to methanogens to reduce CO_2 to CH_4 (Beauchemin et al., 2009). It is important to distinguish the GHG emission potential between grazing systems that rely on highly digestible temperate forages (i.e., C3 pathway) from those that are not well managed, yielding poor quality grazed forages, as well as from tropical grazing systems in which cows grazed more lignified warm-season grasses (i.e., C4 pathway). O'Neill et al. (2011) reported that compared with TMR, dairy cows grazing high-quality perennial ryegrass (*Lolium perenne* L., 21.8% CP and 38.8% NDF) had lower enteric CH_4 production (251 vs. 397 g/d), CH_4 yield (18.1 vs. 20.3 g/kg of DMI), and CH_4 intensity (defined as g/kg of ECM; 174 vs. 200 g/kg of fat and protein yield). Archimède et al. (2011) demonstrated via a meta-analysis that ruminants offered C4 grasses had greater (+17%) CH_4 yield (L/kg of OM intake) than those receiving C3 grasses. They also showed that ruminants fed warm-season legumes had the lowest CH_4 yield followed by C3 grasses, cool-season legumes, and C4 grasses, possibly due to greater presence of plant secondary metabolites (Archimède et al., 2011).

Grazing systems have opportunities to increase diet digestibility and feed efficiency through adoption of improved forage species and forage mixtures and advanced grazing management (Vargas et al., 2022). For example, CH_4 emissions were lower when ruminants were fed legumes compared with grasses (McCaughey et al., 1999; Waghorn et al., 2002), which may be a result of more rapid fermentation of plant cell walls in legumes (Coulman et al.,

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Table 1. Summary of studies in which grazing dairy cows were supplemented with varying amounts of concentrate

Reference	Country	No. of cows	Grazed forage	Concentrate level (kg/d)	Concentrate composition	CH_4 (g/d)	CH_4 (g/kg DMI)	CH_4 (g/kg ECM)
Lovett et al. (2005)	Ireland	24	Perennial ryegrass (*Lolium perenne*), meadow grass (*Poa trivialis*), annual meadow grass (*Poa annua*), and white clover (*Trifolium repens*)	0.87, 5.24	Fibrous byproducts, barley, wheat	Increased	No change	No change[1]
Jiao et al. (2014)	Northern Ireland	40	Perennial ryegrass	2, 4, 6, 8	Soyhulls, corn, wheat, soybean meal, others	No change	Decreased	Decreased
Muñoz et al. (2015)	Chile	24	Perennial ryegrass	1, 5	Steam-rolled corn, ground corn, rolled barley, wheat bran, others	Increased	No change	No change
Muñoz et al. (2018)	Chile	24	Perennial ryegrass	4, 8	Steam-rolled corn, ground corn, rolled barley, wheat bran, others	Increased	Decreased	No change[2]
van Wyngaard et al. (2018a)	South Africa	60[3]	Perennial ryegrass	0, 4, 8	Ground corn, soybean oilcake, sugarcane molasses	No change	No change	Tendency to decrease linearly
van Wyngaard et al. (2018b)	South Africa	60[4]	Kikuyu grass (*Pennisetum clandestinum*)	0, 4, 8	Corn, soybean oilcake, sugarcane molasses	Increased linearly	Decreased linearly	Decreased linearly

[1]CH_4 intensity (g/kg of FCM).

[2]CH_4 intensity (g/kg of milk yield).

[3]10 cows per treatment used for measurements of enteric CH_4 production.

[4]11 cows per treatment used for measurements of enteric CH_4 production.

2000) or the presence of secondary compounds such as condensed tannins (**CT**) in the tissues of some legumes (Roca-Fernández et al., 2020; Billman et al., 2022). Forages at advanced stages of maturity result in reduced concentration of soluble carbohydrates and increased NDF content, thereby elevating acetate production in the rumen and increasing CH_4 produced per unit of forage digested (Pinares-Patiño et al., 2007). However, reduced forage quality can also decrease DMI, which is highly correlated with CH_4 production (Molano and Clark, 2008). Therefore, decreases in CH_4 production may simply be a matter of decreased DMI and not forage quality (Brito and Silva, 2020). Nevertheless, a study done in New Zealand using lactating dairy cows grazing perennial ryegrass and white clover (*Trifolium repens* L.) showed lower CH_4 production in spring (288 g/d) than in summer (361 g/d), despite similar DMI across both seasons (Robertson and Waghorn, 2002). The authors attributed this difference to the high-quality spring forage, which resulted in lower CH_4 production compared with more mature summer forages. Results could also have been affected by the advancing stage of lactation as the study progressed (50 DIM at the beginning of the study vs. 240 DIM at the last sampling) and the small number of animals sampled (5/treatment). A recent review by Eugène et al. (2021) stated that increased forage quality results in increased DMI, which consequently increases CH_4 production. However, when milk yield was considered, CH_4 intensity (g/kg of milk) decreased with increased forage digestibility. Furthermore, Eugène et al. (2021) reported that equations that use digestible OM may be more accurate than those that use DMI, as using digestible OM considers both quantity and quality of forage.

Due to the relatively high fiber component of most grazing diets, energy is typically the most limiting nutrient in grazing dairy systems (Bargo et al., 2002). Therefore, concentrate supplementation, particularly starch-based sources, can be used to improve milk yield due to increased energy intake and shift of ruminal fermentation toward propionate. However, effects on enteric CH_4 emissions are mixed. Table 1 summarizes the effect of various concentrate levels and types on enteric CH_4 emissions in dairy cows grazing different forage sources. Enteric CH_4 production increased in 4 out of 6 studies likely caused by increased concentrate DMI or total DMI. Methane yield and CH_4 intensity did not change in Lovett et al. (2005) and Muñoz et al. (2015) despite supplementing approximately 5 kg/d of concentrate. In contrast, CH_4 yield and CH_4 intensity decreased when grazing cows were supplemented with up to 8 kg/d of concentrate (Jiao et al., 2014; van Wyngaard et al., 2018a,b). These discrepant results in enteric CH_4 emissions across studies might be explained by differences in the type and proportion of grazed forage in the basal diet, type and amount of concentrate supplementation, stage of lactation, production level, and grazing management.

Another method to increase energy intake in dairy cattle is to supplement lipids such as oilseeds, which have been shown to decrease CH_4 emissions by up to 60% in grazing beef and dairy cattle (Vargas et al., 2022). Lipid supplementation can be costly, is not practical for grazing ruminants that are not otherwise supplemented, and can negatively affect ruminal fiber digestibility with highly variable results (Beauchemin et al., 2020), particularly when total lipids exceed 5% to 6% of the diet DM.

Nitrate supplementation may mitigate enteric CH_4 emissions in lactating dairy cows in confinement (van Wyngaard et al., 2018c, 2019). However, data are limited under grazing conditions. Studies conducted in South Africa with grazing dairy cows supplemented with varying levels of nitrate (up to 15.2 g/kg of DMI) showed marginal effects on enteric CH_4 emissions using both warm-season (van Wyngaard et al., 2018c) and cool-season (van Wyngaard et al., 2019) grasses. High-quality forages often (e.g., Bargo et al., 2002) contain CP levels well in excess of nutrient needs for lactating dairy cows. Addition of nitrate to the diet could cause excessive urinary N, which in turn could increase N leaching and nitrous oxide emissions (Marshall et al., 2021).

Algal-based feeds such as seaweed have gained interest as an additive in ruminant diets to reduce enteric CH_4 emissions (Beauchemin et al., 2020) while improving animal health (Antaya et al., 2015). However, there is limited information on the impact of seaweed on CH_4 suppression in grazing dairy cows. One study in which dairy cows were supplemented with 113 g/d of the brown seaweed *A. nodosum* showed a significant diet × period interaction, with CH_4 production decreasing by 10.9% during period 1, but no change was detected in the remaining 2 periods (Antaya et al., 2019). Note that the concentrations of CP and NDF ranged from 13.9% to 17.5% and 50.9% to 66%, respectively, in the cool-season legume-grass mix forage grazed by cows, with supplement DMI (partial TMR plus pelleted grain) averaging 49% of the total DMI in Antaya et al. (2019) study, thus not representing many other grazing systems worldwide (e.g., O'Neill et al., 2011). Overall, for algae-based feed to be adopted by dairy producers, enteric CH_4 emissions must be substantially decreased without negatively affecting milk yield and milk composition. In addition, seaweed anti-methanogenic effects would need to persist over time, which depends on the stability of bioactive compounds and on how harvesting, processing, and seasonality affect their concentrations in algal tissues. The potential for elevated iodine and bromoform concentrations in milk must also be considered in future research (Beauchemin et al., 2020; Brito, 2020).

Condensed tannins, or proanthocyanidins, are secondary polyphenolic compounds naturally produced by some legumes, forbs, and other forages and grains as a defensive mechanism against herbivory (Patra and Saxena, 2010). Feeding CT-containing legumes to ruminants is of interest due to their direct inhibitory effect on ruminal archaea and protozoa, and indirectly by depressing ruminal fiber digestibility (Patra and Saxena, 2010), which may also reduce CH_4 emissions. Condensed tannins are classified as having low to medium CH_4 mitigation potential (Beauchemin et al., 2020), with most research to date done in vitro. Woodward et al. (2004) reported that, whereas CH_4 production was similar in dairy cows grazing perennial ryegrass or birdsfoot trefoil (*Lotus corniculatus*), both CH_4 yield and CH_4 intensity decreased with birdsfoot trefoil. Cows grazing birdsfoot trefoil also had greater milk yield (18.5 and 24.4 kg of milk/d for ryegrass and trefoil, respectively), possibly associated with increased RUP flow in response to CT-dietary protein complexes. The grazed forages used by Woodward et al. (2004) had high nutritive value (mean = 26.5% CP, 9.91% soluble sugars, and 21.9% ADF), suggesting that, in general, forage quality had a minor impact on enteric CH_4 emission responses. However, birdsfoot trefoil had lower NDF concentration (28.4% vs. 41%), which, combined with the presence of CT (2.62%; DM basis), accounted at least partially for the observed decrease in CH_4 yield.

While supplements or compounds found naturally in some forages and concentrates can help mitigate CH_4, chemical inhibitors such as 3-nitroxypropanol (**3-NOP**) may have high potential to suppress enteric CH_4 emissions (Beauchemin et al., 2020). Hristov et al. (2022) reported a consistent reduction in enteric CH_4 production, CH_4 yield, and CH_4 intensity without a negative effect on production performance of confined dairy cows in a meta-analysis. However, they also reported that the efficacy of 3-NOP seems to decrease over time and has a very short-lived active period in the rumen; therefore, Hristov et al. (2022) called for further research to investigate its long-term effects. For these reasons, 3-NOP may not be practical for grazing-based dairies unless other delivery methods (e.g., long-lasting bolus) or long-term efficacy improve.

Development of vaccines that target methanogen reduction would be especially useful on grazing farms where cows cannot be supplemented continuously. However, commercial availability may still be 5 to 10 years away. Although all major components of a vaccine chain have been demonstrated, including genome sequencing of methanogens and the production of antibodies by host animals that suppress pure cultures of methanogens in vitro, the efficacy, immune memory, and cost effectiveness have yet to be fully investigated (Reisinger et al., 2021).

Low-CH_4-emitting sheep have been shown to reduce CH_4 emissions by approximately 10% to 15% after 3 generations without adversely affecting production (Rowe et al., 2019). Animals expressing the low-CH_4 trait are expected to be commercially available to sheep producers in New Zealand in the next few years (Reisinger et al., 2018). Cattle show similar potential for breeding strategies (e.g., Teagasc, 2021), but progress is slower due to greater research costs and longer generation intervals than sheep. Research on proxies such as milk constituents or ruminal microbiota profile may enable less expensive and rapid identification of low-CH_4-emitting dairy cattle (Reisinger et al., 2021). Genetic of selection of animals with lower enteric CH_4 emissions would be advantageous as the reduction would be permanent and additive. Additionally, adoption of breeding programs must rely heavily on the balance between the opportunity cost and policy incentives for curbing emissions. Considering that only a few sires are used across dairy herds in many countries, efficacy could be high if these bulls also possessed other positive production traits.

While the above CH_4-mitigating strategies can help reduce enteric CH_4, whole-system approaches must also be considered. Pastoral dairy systems that make use of perennial crops and permanent pastures that provide a variety of ecosystem services may help offset enteric CH_4 emissions (Guyadar et al., 2016). Such services include C sequestration (Skinner and Dell, 2016), improved soil fertility by retaining plant biomass in the soil, which builds soil OM (Bolinder et al., 2007; Glover et al., 2010), and reduced soil erosion (Russell and Bisinger, 2015; Teague, 2015).

Although well-managed perennial pastures sequester C, they may not be an infinite C sink because permanent pastures that have been established for decades may have reached a saturation point for soil C and no longer sequester additional C (Guyadar et al., 2016). However, while not capturing additional C each year, these pastures do withhold C from the atmosphere, which benefits net soil C retention (Smith et al., 2008). Nevertheless, this notion of C saturation of soils has been challenged by a handful of regional, long-term studies that showed C sequestration may continue, particularly when management is improved (Liebig et al., 2010; Rowntree et al., 2020). Such management practices include converting annual crops to perennial pastures, improving soil fertility with precision technologies, or improving grazing management to increase soil C storage (Skinner and Dell, 2016; Rowntree et al., 2020).

Dietary changes designed to mitigate GHG often increase production costs. Therefore, for these changes to be adopted commercially, there must be a positive economic impact such as increased milk yield or more efficient growth (Beauchemin et al., 2009). Evaluating net GHG emissions from any farming enterprise requires a life cycle assessment that seeks to describe the entire farm system (Liebig et al., 2010; Thompson and Rowntree, 2020). However, such studies are limited. For example, while feeding increased levels of concentrate in the dairy diet may reduce enteric CH_4 intensity, total CH_4 production was not changed (Jiao et al., 2014). Alternatively, total CH_4 production could even increase due to the concomitant need to increase stocking rate to improve pasture utilization, thereby improving milk produced per hectare (O'Brien et al., 2012).

Ecosystem services provided by perennial pasture systems may reduce or negate enteric CH_4 emissions in grazing dairy systems. Fully describing a farm system through a life cycle assessment can be quite complex due to the number of components that interact, including soils, plants, feeds, animals, and manure. However, considering a wider perspective will allow for more integrated forage-animal management systems to produce food and fiber while fostering a wide range of ecosystems services to improve sustainable intensification of pasture-based dairies. The challenge to scientists, and ultimately producers, is how to leverage these plant-animal-soil relationships to improve sustainable intensification of dairy production systems.

In summary, a variety of dietary and husbandry management strategies are being evaluated to mitigate enteric CH_4 emissions in dairy cattle. However, some strategies may not be applicable to pasture-based dairy systems due maintaining constant levels in the rumen through frequent supplementation (which is not practical in many grazing systems), differences in forage quality compared with confinement or across different regions of the world, or specialty market restrictions (e.g., organic or grassfed certification). Further research is needed to identify strategies of reducing CH_4 emissions that do not require frequent vaccination, particularly for grazed herds that do not receive supplementation continuously. Research is also needed on slow-release delivery technologies that provide a constant supply of CH_4-inhibiting activity in the rumen for cows not supplemented continuously. Breeding animals for reduced CH_4 emissions shows promise, as long as purchase of such animals is not cost prohibitive and animal production is not impaired. More robust data sets are needed to develop life cycle assessments that affect C and N cycling.

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Notes

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