The effects of supplementing grazing dairy cows with partial mixed ration on enteric methane emissions and milk production during mid to late lactation¹

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ABSTRACT

This study compared the enteric CH₄ emissions and milk production of cows offered various grass-based diets during mid to late lactation. Forty-eight spring-calving Holstein-Friesian dairy cows were randomly assigned to 1 of 3 nutritional treatments for 8 wk: (1) low grass allowance (LGA) + partial mixed ration (PMR), (2) high grass allowance (HGA), or (3) LGA. The PMR group received an allocation of 13.9 kg of grass dry matter (DM)/cow per day and in addition were offered 4.1 kg of PMR DM/cow per day. The HGA group received an allocation of 19.3 kg of grass DM/cow per day and the LGA group received an allocation of 14.4 kg of grass DM/cow per day. The PMR offered was composed of 450 g of maize silage/kg of DM, 450 g of concentrate blend/kg of DM, and 100 g of barley straw/kg of DM. Daily CH₄ emissions were determined using the emissions from ruminants using a calibrated tracer technique, using sulfur hexafluoride, for 5 consecutive days during 2 periods. Simultaneously, grass DM intake (DMI) was estimated using the n-alkane technique and the PMR DMI was also recorded. Cows offered PMR had higher DMI than either the HGA or LGA cows (16.5 vs. 14.9 and 13.9 kg of DM/d). The higher DMI of PMR cows increased milk production relative to HGA and LGA cows: milk yield (17.0 vs. 14.6 and 13.1 kg) and fat and protein yield (1.29 vs. 1.14 and 1.04 kg). Daily CH₄ emissions were higher for the PMR group than for the HGA and LGA groups (406 vs. 384 and 349 g/cow per day). The enteric CH₄ emissions intensity per unit of DMI, milk yield, solids-corrected milk yield, and fat and protein yield did not differ between treatments. Effects observed in the PMR

treatment were due to an increase in DMI rather than to any nutritional characteristic of the PMR.

Key words: enteric methane, dairy cow, grass, partial mixed ration

INTRODUCTION

Globally, in 2005, agriculture was responsible for 10 to 12% of greenhouse gas (GHG) emissions (Smith et al., 2007). In Ireland, the proportional contribution of agriculture to national GHG is much greater, estimated at 29% for 2009 (EPA, 2010). Although this is greatly reduced from 36% in 1990 (EPA, 2010), it still poses Irish agriculture with significant challenges. This is because under the Kyoto Protocol (UNFCCC, 1997) Ireland must limit the growth in its GHG to 13% above 1990 levels over the 2008 to 2012 period. Ireland is facing additional challenges under the EU Climate and Energy Package, which came into law in June 2009 (EU, 2009). The so-called effort sharing decision commits Ireland to reducing emissions from those sectors not covered by the emissions trading scheme, namely transport, agriculture, and residential, to 20% below 2005 levels by 2020 (EU, 2009). Ireland's unique position within the EU, as the country with the highest proportion of national emissions from agriculture, presents major challenges in limiting emissions and meeting future GHG targets.

The primary GHG are carbon dioxide, CH₄, and nitrous oxide. In ruminant animals, the production of CH₄ in the rumen and the exhalation of this CH₄ are necessary to remove excess hydrogen formed during the rumen fermentation process. The process of CH₄ production in the rumen is referred to as enteric CH₄ production. Enteric CH₄ directly emitted by ruminants, and other animals, accounts for 3 to 5% of global GHG emissions (Steinfeld et al., 2006). Due to Ireland's large ruminant population (5.9 million cattle; CSO, 2009) relative to its human population (4.2 million people; CSO, 2007), the production of CH₄ from enteric fermentation contributes approximately 13% of total GHG in Ireland (EEA, 2009). Hence, considerable

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pressure exists in the short to medium term to develop cost-effective and easily implemented measures to reduce enteric CH₄ emissions from ruminants.

Ninety percent of Irish dairy herds are spring calving (NMA, 2009), producing milk from grazed grass, with the mean calving date coinciding with the initiation of grass growth in early spring (Dillon et al., 1995). The reliance of the predominantly spring-calving Irish dairy herd on grazed grass necessitates the development of grass-based CH₄ mitigation strategies, which can be adopted in the short term by Irish dairy farmers. With a 50% increase in milk production by 2020 anticipated (DAFF, 2010) from the abolition of milk quota in 2015 (Lips and Rieder, 2005; EC, 2009) cow numbers will increase. This is evident in increasing numbers of dairy heifers being born in the last 4 yr (Shalloo, 2011). Consequently, stocking rate will increase on some farms, forcing those farmers to consider supplementary feeding [e.g., feeding partial mixed rations (**PMR**) during times of grass deficit]. Methane emissions are dependent on the amount of feed consumed and the composition of the diet (Johnson and Johnson, 1995). Changing the feeding strategy on farms can have a large effect on CH₄ production. For example, increasing the level of starch or rapidly fermentable carbohydrates will increase propionate production in the rumen, reducing hydrogen production, and thus reducing CH₄ formation (Monteny et al., 2006). Increasing the level of fibrous forages with slow digestibility produces less propionate in the rumen, utilizing less hydrogen and, as a result, allowing more hydrogen to be used in the formation of CH₄. The objective of the current study was to investigate the effects of offering dairy cows in mid to late lactation a diet composed of all grass offered at a high or low allowance, or a low grass allowance supplemented with a PMR, on CH₄ emissions and milk production.

MATERIALS AND METHODS

The study was conducted at Fermoy (Co. Cork, Ireland; 52°16' N, 8°25' W), on free-draining soils comprising acid brown earth with a sandy loam-to-loam texture.

Animals and Experimental Design

Forty-eight Holstein-Friesian cows were selected for the study. Eighteen were primiparous and 30 were multiparous. The study took place over an 8-wk period during mid to late lactation (beginning July 20, 2009). Cows were blocked on the basis of parity, BW, BCS, DIM, and milk yield (**MY**), and from within block were randomly assigned to 1 of 3 treatments: (1) low

grass allowance + PMR (**PMR**), (2) high grass allowance (**HGA**), or (3) low grass allowance (**LGA**). The study was a randomized complete block design with 16 cows per treatment.

Treatments

The diet offered to the PMR treatment was composed of 4 kg of DM/cow per day of a PMR and a target 15 kg of DM/cow per day of perennial ryegrass (*Lolium perenne* L. permanent pasture available >4 cm height). The HGA treatment was offered only perennial ryegrass (target 19 kg of DM/cow per day available >4 cm height). Cows assigned to the LGA treatment were offered perennial ryegrass (only) at the same allowance as the PMR treatment (target 15 kg of DM/cow per day available >4 cm height). All treatments were grazed to a target postgrazing sward height of 4 cm.

Experimental measurements were undertaken during 2 periods in wk 5 (August 16) and 8 (September 6) of the study. Mean DIM at the beginning of these 2 periods was 186 (SD = 21) and 207 (SD = 21), respectively.

Grazing Management and Grass Measurements

The experimental grazing area consisted of 7.8 ha. Cows were grazed in a rotational system and were allocated fresh grass daily after the morning milking. The grazing area was strip grazed using temporary fences. Nitrogen fertilizer (calcium ammonium nitrate) was applied following grazing to supply 34 kg of N/ha.

Pregrazing and postgrazing sward heights were calculated daily by averaging 60 measurements recorded along the 2 diagonals of the daily grazing area using a rising plate meter (Jenquip, Feilding, New Zealand). Herbage mass (>4 cm) was determined twice weekly by cutting 4 strips of grass from the grazing area for the following days grazing (1.2 × 10 m) using an Etesia mower (Etesia UK Ltd., Warwick, UK). Ten measurements of sward height were recorded before and after each strip was cut using the rising plate meter. Grass cut from each strip was weighed and sampled (0.3 kg). A subsample (0.1 kg) was oven dried at 95°C for 16 h to determine DM content (Binder FED 720 drying oven with mechanical convection; Binder GmbH, Tuttlingen, Germany). During the 2 measurement periods grass samples were collected to determine the chemical composition and alkane content of grass. Duplicate pooled samples were cut from 25 randomly selected transects in each daily grazing area immediately before grazing. These grass snips were made with hand shears (Accu 60; Gardena International GmbH, Ulm, Germany) to the previously recorded postgrazing height for the treatment group. Samples were stored at -20°C before

Table 1. Chemical composition of the partial mixed ration offered over the 8 wk of the study (mean $\pm$ SD)

Item	Maize silage	Straw	Concentrate	Partial mixed ration ¹
DM, %	26 $\pm$ 1	91 $\pm$ 1	90 $\pm$ 0	61
CP, g/kg of DM	82 $\pm$ 32	62 $\pm$ 4	225 $\pm$ 7	144
NDF, g/kg of DM	457 $\pm$ 35	773 $\pm$ 32	162 $\pm$ 2	356
Starch, g/kg of DM	179 $\pm$ 74	18 $\pm$ 9	170 $\pm$ 4	159
Ash, g/kg of DM	30 $\pm$ 18	31 $\pm$ 1	75 $\pm$ 1	50
OMD, ² g/kg of DM	720 ³	440 ³	861 $\pm$ 5	755
GE, ⁴ MJ/kg of DM	17.6 $\pm$ 0.3	17.3 $\pm$ 0.2	16.6 $\pm$ 0.1	17.1

¹Calculated from ingredient content of partial mixed ration (maize silage, straw, and concentrate) and ingredient chemical composition.

²Organic matter digestibility.

³Maize silage and straw OMD values taken from O'Mara (1996).

⁴Gross energy.

being freeze dried and ground for analysis of alkane content and chemical composition.

PMR Feeding and PMR Measurements

The PMR offered to the PMR group was composed of 450 g of maize silage/kg of DM, 450 g of concentrate blend/kg of DM, and 100 g of barley straw/kg of DM. The concentrate blend contained 300 g of soybean meal/kg of DM, 265 g of citrus pulp/kg of DM, 260 g of wheat/kg of DM, 100 g of maize gluten meal/kg of DM, 45 g of molasses/kg of DM, and 30 g of minerals and vitamins/kg of DM. The chemical composition of the PMR offered and its ingredients are presented in Table 1. The PMR was mixed daily using a diet feeder mixing wagon (Holaras; Hoopman Machines BV, Aalten, the Netherlands) and was offered to PMR cows following the morning milking. The PMR for each individual cow was fed using a Griffith Elder feeding system (Griffith Elder Ltd., Bury St. Edmunds, Suffolk, UK). All cows were acclimatized to the feeding system before the start of the study.

During the 2 measurement periods, samples of each ingredient used in the PMR were collected daily. Forage DM was determined by oven drying (Binder FED 720 drying oven with mechanical convection; Binder GmbH) at 40°C for 24 h and the PMR composition was adjusted weekly as necessary to maintain the correct composition. The dry samples were ground to pass through a 1-mm sieve (Cyclotec 1093 Sample Mill; Foss Electric A/S, Hillerød, Denmark) in preparation for chemical analysis.

Chemical Analysis

Grass samples were analyzed for DM, CP, NDF, ADF, ash, OM digestibility (OMD), and gross energy (GE) content. The grass samples were analyzed for DM content as previously described (95°C for 16 h). Grass

N content was determined using a Leco N analyzer (FP 428; Leco Australia Pty Ltd., NSW, Australia) via a method adapted by Sweeney (1989). Crude protein content was determined as N content $\times$ 6.25. The NDF and ADF content of the grass samples were analyzed using the Ankom fiber analyzer (Ankom Technology Corp., Macedon, NY) using the procedure of Van Soest et al. (1991). Sodium sulfite was used in the NDF analysis procedure. Grass ash content was determined following 16 h in a muffle furnace at 550°C. The OMD of the grass was determined using the *in vitro* neutral detergent cellulase method as described by Morgan et al. (1989) (Fibertec Systems, Foss, Ballymount, Dublin, Ireland). Grass GE content was determined from pelletized samples using a bomb calorimeter (Parr Instrument Co., Moline, IL). The maize silage, concentrate, and barley straw samples were analyzed individually for DM, CP, NDF, ash, and GE content using the methodologies described above. In addition, the starch content of the maize silage, concentrate, and barley straw samples was analyzed following treatment with hot dilute hydrochloric acid using an automatic polarimeter [Optical Activity Ltd., Cambridgeshire, UK; International Association for Cereal Science and Technology (IACST) standard method 123/1].

Animal Measurements

MY and Composition. Cows were milked twice daily at approximately 0800 and 1500 h. Individual MY were automatically recorded at each milking (Dairy-master, Co. Kerry, Ireland). Milk fat, milk protein, and milk lactose concentrations were determined weekly from 1 evening and 1 morning milk sample taken on successive days and pooled in proportion to MY. During the 2 measurement periods, a second evening and morning sample was also collected. The concentrations of milk constituents were determined via infrared spectroscopy (Milkoscan 203, Foss Electric A/S).

BW and BCS. Body weight was recorded weekly using electronic portable weighing scales and the WinWeigh software package (Tru-Test Ltd., Auckland, New Zealand). Body condition score was recorded every 2 wk by an experienced independent observer on a scale of 0 to 5 (Lowman et al., 1976). Body weight and BCS were measured at the same time at each measurement, namely after morning milking.

DMI. Individual grass DMI (**GDMI**) was estimated during the 2 measurement periods using the n-alkane technique (Mayes et al., 1986) as modified by Dillon and Stakelum (1989). Cows were dosed twice daily for 11 consecutive days with a paper bolus (Carl Roth GmbH and Co. KG, Karlsruhe, Germany) containing 500 mg of dotriacontane (C_{32}). From the seventh day of dosing onwards a fecal sample was collected twice daily from each individual cow (morning and evening). The 10 fecal samples were subsampled and pooled by cow (15-g subsamples resulting in a pooled sample of 150 g). Composite samples were oven dried for 48 h at 40°C, and ground in preparation for analysis of alkane concentrations. The grass grazed from d 6 to 11 of the intake measurement period was also sampled as previously described. The ratio of grass C_{33} (tritriacontane) to dosed C_{32} was used to estimate DMI. The n-alkane concentration was determined as described by Dillon (1993). Partial mixed ration intake was recorded manually by weighing out individual cows PMR allocation into a Griffith Elder feeding system and then weighing back any residual feed.

Enteric CH_4 Emissions. The daily CH_4 emissions of each cow were determined using the emissions from ruminants using a calibrated tracer (ERUCT) technique. This study used SF_6 tracer gas (Johnson et al., 2007), with equipment modifications for free-ranging dairy cattle.

Tracer gas permeation tubes were filled with approximately 2.5 g of SF_6 during January 2009. Linear SF_6 emissions was confirmed via gravimetric weighing to produce an 8-point regression curve ($R^2 > 0.999$) during incubation in 39°C air at the trial site. Tubes were blocked by emission rate (6.88 mg/d, SD = 0.60) and randomly allocated to both experimental treatment and cow within treatment. Tubes were administered to all cows in April, 136 d before the first measurement period. To ensure reliability of gas sampling during grazing, indoor housing, and milking, gas collection canisters were fitted on the back of each cow using a proprietary saddle apparatus, described by O'Neill et al. (2011). Expired and eructated gases along with ambient air were drawn into the evacuated gas collection canister via a halter-mounted tube looped above the cows mouth and nostrils. The rate of sample collection

was restricted to 0.5 mL/min via passage through a 50-mm length of stainless steel capillary tubing with internal diameter of 12.7 μ m (Valco Instruments Co. Inc., Houston, TX) crimped at several points and calibrated using a digital flow meter (Cole-Parmer Instrument Co., IL). Each precalibrated restriction tube was fixed into a proprietary aluminum brace to prevent loss of calibration during the collection period. The apparatus remained on the cows for 5 consecutive 24-h periods. The initial gas collection canister vacuum was 90 kPa below atmospheric pressure. After collection, the gas collection canisters were pressurized to 70 kPa with ultra pure N (99.995%; Air Products PLC, Cheshire, UK). Concentrations of SF_6 and CH_4 were determined via gas chromatography as described by Johnson et al. (2007) using a Varian 3800 gas chromatograph (Varian Inc., Palo Alto, CA).

Statistical Analysis

Statistical analysis was conducted using SAS 2002-2003 (SAS Institute Inc., Cary, NC). The average enteric CH_4 emissions, DMI, milk production, and change in BW and BCS for the 2 measurement periods were used in the analysis. These data were analyzed using general linear models (PROC GLM) in SAS with treatment and block included in the model. The CORR procedure was used to test for any influence of SF_6 permeation rate upon the CH_4 emission calculated for individual cows.

RESULTS

Climatic Conditions

The total rainfall for July, August, and September was 312 mm which was 75 mm above the previous 10-yr average. The mean daily temperature during these 3 mo was 14.2°C, which was lower than the 10-yr average of 14.9°C. The total hours of sunshine were 520 h over the 3 mo, which was greater than the 10-yr average of 443 h. During the measurement periods, the average weekly rainfall amounted to 22.4 mm, the mean temperature was 14°C, and there were 40 h of sunshine/wk.

Grass Measurements and Feed Chemical Analysis

During the measurement periods, the mean pregrazing herbage mass was 1,500 kg of DM/ha (SD = 327) for the PMR herd, 1,802 kg of DM/ha (SD = 374) for the HGA herd and 1,633 kg of DM/ha (SD = 314) for the LGA herd. The average pre- and postgrazing sward heights were 9.8 (SD = 1.5) and 4.6 cm (SD = 0.3),

Table 2. Chemical composition of the grass consumed during the measurement periods (mean $\pm$ SD) for cows offered a low grass allowance with partial mixed ration, a high grass allowance, or a low grass allowance

Item	Partial mixed ration	High grass allowance	Low grass allowance
DM, %	14.5 $\pm$ 1.4	14.5 $\pm$ 1.4	14.8 $\pm$ 2.9
CP, g/kg of DM	236 $\pm$ 17	225 $\pm$ 16	227 $\pm$ 17
NDF, g/kg of DM	411 $\pm$ 20	426 $\pm$ 27	417 $\pm$ 27
ADF, g/kg of DM	256 $\pm$ 22	255 $\pm$ 26	252 $\pm$ 19
Ash, g/kg of DM	73 $\pm$ 8	69 $\pm$ 4	74 $\pm$ 5
OMD, ¹ g/kg of DM	846 $\pm$ 9	841 $\pm$ 8	846 $\pm$ 10
GE, ² MJ/kg of DM	18.1 $\pm$ 0.2	18.1 $\pm$ 0.2	18.0 $\pm$ 0.2

¹Organic matter digestibility.²Gross energy.

11.0 (SD = 1.2) and 5.3 cm (SD = 0.2), and 10.0 (SD = 1.2) and 3.9 cm (SD = 0.3), respectively, for the PMR, HGA, and LGA herds.

The PMR offered and selected grass for each of the 3 treatments are presented in Tables 1 and 2. The grass was highly digestible and had a high mean CP concentration.

The PMR group received an allocation of 13.9 kg of grass DM/cow per day and in addition were offered 4.1 kg of PMR DM/cow per day. The HGA group received an allocation of 19.3 kg of grass DM/cow per day and the LGA group received an allocation of 14.4 kg of grass DM/cow per day.

Animal Performance

During the measurement periods, the 3 grazing treatments applied generated differences in GDMI and total DMI. The HGA herd had 1.0 kg greater GDMI compared with the LGA herd and 2.4 kg greater GDMI than the PMR herd ($P < 0.001$; Table 3). Total DMI was higher for the PMR herd than the HGA herd (+1.6 kg of DM, $P < 0.001$) and the LGA herd (+2.6 kg of DM, $P < 0.001$).

Grass GE intake (**GEI**) was lower ($P < 0.001$) for the PMR (−45 MJ/d) and LGA (−20 MJ/d) herds compared with the HGA herd (271 MJ/d). Offering the PMR increased the total GEI of the PMR treatment (296 MJ/d) by 8.8% relative to the HGA treatment (271 MJ/d), whereas the LGA treatment consumed the least feed energy (251 MJ/d; $P < 0.001$).

Initial BW and BCS were (mean $\pm$ SEM) 486 $\pm$ 14.2 and 2.94 $\pm$ 0.065, 511 $\pm$ 14.2 and 3.02 $\pm$ 0.065, and 495 $\pm$ 14.2 and 2.92 $\pm$ 0.065 for the PMR, HGA, and LGA treatments, respectively. The LGA treatment gained less BW from the start to the end of the study than both the HGA and PMR treatments ($P < 0.05$). No effect of treatment was observed on the change in BCS from the start to the end of the study ($P > 0.05$).

During the measurement periods, MY was influenced by the dietary treatments imposed. Cows from the HGA and PMR treatments produced 11.5% (1.5 kg/d) and 29.8% (3.9 kg/d) more milk respectively ($P < 0.001$) than cows from the LGA treatment (Table 4). Milk fat and protein concentration did not differ between the treatments ($P > 0.05$). This resulted in SCM and fat and protein yield (**FP**) differences mirroring the MY differences ($P < 0.001$).

Despite differences in feed and energy intake, and the resulting effect on milk production, MY per unit of DMI or per unit of GEI did not differ between treatments ($P > 0.05$).

Enteric CH₄ Emissions

Overall collection of the 480 individual gas samples was 92% successful. Samples were lost due to sampling tube blockages, broken collection tubes and occasional dismounting of saddles during the two 5-d sampling periods. The permeation rate of SF₆ tracer gas from tubes allocated to individual cows was not correlated ($P = 0.43$) with the daily CH₄ emission values determined in this study ($R^2 = 0.08$).

Table 3. The DMI, BW, and BCS of dairy cows in mid to late lactation offered a low grass allowance supplemented with partial mixed ration, a high grass allowance, or a low grass allowance during 2 measurement periods in wk 5 and 8 of the study

Item	Partial mixed ration	High grass allowance	Low grass allowance	SEM	<i>P</i> -value
Grass DMI, kg/d	12.5 ^b	14.9 ^a	13.9 ^a	0.37	<0.001
Partial mixed ration DMI, kg/d	3.91	0	0	NA ¹	NA
Total DMI, kg/d	16.5 ^a	14.9 ^b	13.9 ^b	0.37	<0.001
Grass gross energy intake, MJ/d	226 ^c	271 ^a	251 ^b	6.6	<0.001
Total gross energy intake, MJ/d	296 ^a	271 ^b	251 ^c	6.7	<0.001
Change in BCS from start (wk 1) to end (wk 8) of study	0.063	0.078	−0.047	0.0518	NS
Change in BW (kg) from start (wk 1) to end (wk 8) of study	35.0 ^a	44.5 ^a	19.5 ^b	3.55	<0.001

^{a-c}Within a row, means with different superscripts differ significantly ($P < 0.05$).¹NA = not applicable.

Table 4. The milk production performance of dairy cows in mid to late lactation offered a low grass allowance supplemented with partial mixed ration, a high grass allowance, or a low grass allowance during 2 measurement periods in wk 5 and 8 of the study

Item	Partial mixed ration	High grass allowance	Low grass allowance	SEM	P-value
Milk yield, kg/d	17.0 ^a	14.6 ^b	13.1 ^c	0.43	<0.001
Milk protein, %	3.28	3.39	3.43	0.053	NS
Milk protein yield, kg/d	0.598 ^a	0.518 ^b	0.463 ^c	0.0191	<0.001
Milk fat, %	4.12	4.06	4.11	0.132	NS
Milk fat yield, kg/d	0.702 ^a	0.622 ^b	0.569 ^b	0.0230	0.001
Milk lactose, %	4.56 ^a	4.53 ^{ab}	4.44 ^b	0.031	<0.05
Milk lactose yield, kg/d	0.775 ^a	0.661 ^b	0.579 ^c	0.0211	<0.001
SCM, kg/d	16.4 ^a	14.4 ^b	13.1 ^c	0.41	<0.001
Milk fat and protein yield, kg/d	1.29 ^a	1.14 ^b	1.04 ^c	0.033	<0.001
Milk yield/kg of DMI, kg	1.04	1.06	1.00	0.025	NS
Milk yield/100 MJ of gross energy intake, kg	5.86	5.83	5.55	0.001	NS

^{a-c}Within a row, means with different superscripts differ significantly ($P < 0.05$).

Relative to cows of the LGA restricted feed allocation, cows offered the HGA allocation emitted 10.0% more CH₄ (+35 g/d, $P < 0.001$). Cows of the PMR treatment emitted 16.3% more enteric CH₄ ($P < 0.001$) than LGA cows (Table 5). Overall, no effect of treatment was observed on the enteric CH₄ emissions intensity per unit of DMI, MY, SCM, or FP ($P > 0.05$).

DISCUSSION

The grazing management resulted in high-quality grass being consumed by the cows, as demonstrated by the high digestibility. The composition was similar to, or better than, that reported by some other experiments for similar grazing systems at similar times of the year (McEvoy et al., 2009; Curran et al., 2010). Cows were offered grass at the recommended pregrazing herbage mass and grazed to recommended postgrazing sward heights (O'Donovan, 2000). The LGA group consumed almost all of the grass offered to them (97%). The PMR and HGA groups received ad libitum grass, consuming 90 and 77%, respectively, of the grass offered to them. The PMR was formulated to balance the grazed grass diet, and maintain a high-quality total diet. This was achieved and the total diet for the PMR

group contained a high CP concentration (>210 g/kg), a high digestibility (>820 g/kg), and fiber levels were sufficient (>390 g/kg of NDF) to meet animal requirements (NRC, 2001).

Animal Performance

In general, cow DMI in the current study was in the range expected for the stage of lactation, time of year, and feed delivery method (Butler et al., 2003; Woodward et al., 2006). The PMR cows had the greatest total DMI but the lowest GDMI. They had a lower GDMI than the LGA group, even though both were offered a similar grass allowance. When supplements are consumed by grazing cows, GDMI decreases because the supplement is substituting for the grass (Kellaway and Porta, 1993; Holmes and Roche, 2007). However, in total, the PMR group had a greater feed allowance than the LGA cows, giving rise to a greater total DMI (Burke et al., 2008). The PMR group had a lower GDMI than the HGA group due to their lower grass allowance (Curran et al., 2010) and substitution rate effects (Kellaway and Porta, 1993; Holmes and Roche, 2007), but a greater total DMI, even though total feed offered was similar. The reason for the difference between the PMR

Table 5. The enteric CH₄ emissions and enteric CH₄ emissions intensity of dairy cows in mid to late lactation offered a low grass allowance supplemented with partial mixed ration, a high grass allowance, or a low grass allowance during 2 measurement periods in wk 5 and 8 of the study

Item	Partial mixed ration	High grass allowance	Low grass allowance	SEM	P-value
CH ₄ , ¹ g/d	406 ^a	384 ^b	349 ^c	7.3	<0.001
CH ₄ /kg of DMI, g	25.0	26.1	25.0	0.66	NS
Gross energy intake lost as CH ₄ , %	7.78	7.98	7.70	0.204	NS
CH ₄ /kg of milk yield, g	23.9	24.5	24.9	0.74	NS
CH ₄ /kg of SCM, g	25.2	26.1	26.5	0.83	NS
CH ₄ /kg of milk fat and protein yield, g	320	333	336	10.5	NS

^{a-c}Within a row, means with different superscripts differ significantly ($P < 0.05$).

¹CH₄ = (enteric) methane.

and HGA groups in terms of total DMI is that grazing cows are limited in the quantity of fresh forage that they can consume (Holden et al., 1994). The differences between treatments in GEI mirrored the differences in DMI.

Milk yield was also in the range expected for this type of system, at this time of the year, and stage of lactation (McEvoy et al., 2009). The higher MY and SCM supported by the PMR diet compared with the other 2 treatments is due to the greater DMI exhibited by these animals, as DMI has been identified as the main factor limiting MY by grazing cows (Leaver, 1985; Dillon, 2006). The LGA group had the lowest MY and SCM for the same reason. McEvoy et al. (2009) and Curran et al. (2010) demonstrated that over an entire lactation, cows offered a greater grass allowance had a higher MY. Woodward et al. (2006) found that MY produced by low-grass allowance cows was less than high-grass allowance cows, but when the low grass allowance was supplemented, MY increased. The data in the current study demonstrate that the MY per unit of DMI or per unit of GEI did not differ between treatments. This indicates that the partial supplementation of grazing dairy cows with PMR did not confer any beneficial increase in milk production per unit of feed intake—the greater milk production was simply due to the greater total DMI. The increased DMI of the PMR treatment relative to the HGA treatment does indicate that the addition of PMR to the diet promoted DMI, thereby enabling higher milk production per cow.

No effect of treatment was observed on the change in BCS from the start to the end of the study. This was expected, as cows at this stage of lactation are expected to have static BCS (McCarthy et al., 2007). Cows at this stage of lactation are expected to gain BW (McCarthy et al., 2007), and this was observed. The LGA cows gained less BW from the start to the end of the study than both the PMR and HGA cows, which was due to lower gut fill of the LGA cows due to lower DMI.

Enteric CH₄ Emissions

In a New Zealand study, Robertson and Waghorn (2002) examined the CH₄ emissions of dairy cows in early (60 DIM), mid (150 DIM), and late (240 DIM) lactation. The results of the current study are comparable in terms of stage of lactation to the Robertson and Waghorn (2002) mid and late lactation measurements, and the results from both studies are similar. In the current study, we found that CH₄ was highest for PMR cows and lowest for LGA cows, as DMI is the main driver of enteric CH₄ emissions (Hegarty et al., 2007).

Previous research from this center showed the effect of diet quality on enteric CH₄ emissions intensity

(Wims et al., 2010; O'Neill et al., 2011). In the current study, no effect of treatment was observed on CH₄/DMI. This is due to the high and similar diet quality (OMD) of all 3 treatments. As no significant difference in the total CH₄ emission per unit of feed intake was observed, it is clear that the PMR portion of the PMR diet contributed a similar amount of CH₄ as the grass consumed. Thus, the partial supplementation of grazing dairy cows with PMR did not confer any reduction in enteric CH₄ emissions per unit of feed intake. The CH₄ emissions per unit of feed intake in the current study were higher than those reported by Robertson and Waghorn (2002) because compared with the current study, they recorded higher DMI, but similar CH₄ emissions, per cow per day.

Methane is a loss of energy to the ruminant system (Chamberlain and Wilkinson, 1996) and, as a result, it is often expressed as CH₄ energy emitted as a percentage of GEI. The GEI lost as CH₄ is typically 6 to 7% in forage-based diets (Johnson and Johnson, 1995). The results from the current study are greater than this range. They are also greater than results from the same group of cows measured earlier in lactation in April (5.74% on a grass-only diet; O'Neill et al., 2011) and from a different group of cows measured in June (5.85% across 2 grass-only treatments; Wims et al., 2010). Results are slightly greater than the Wims et al. (2010) results for cows measured in July (6.9% across 2 grass-only treatments). This collection of results demonstrates that CH₄ emissions per unit of DMI and per unit of GEI increase as lactation progresses. Robertson and Waghorn (2002) found similar results. As expected from the CH₄/DMI results, no treatment effect was observed on the CH₄ emitted as a percentage of GEI.

Another measure of the enteric CH₄ emissions intensity is its expression as a proportion of MY and milk solids yield (Beauchemin et al., 2008). In the current study, we observed no effect of treatment on CH₄/MY, CH₄/SCM, or CH₄/FP. This is important because many dairy products are traded on the basis of FP (Hillers et al., 1980). These results are interesting compared with the early lactation results of O'Neill et al. (2011) who found that the greater CH₄ emissions by a group of cows offered a full TMR diet was not offset by greater milk production performance, resulting in a poorer CH₄/FP. Robertson and Waghorn (2002) found that in early lactation (60 DIM), New Zealand-type cows offered a pasture-only diet had the same CH₄/MY as those offered a TMR diet. Then, in mid (150 DIM) and late (240 DIM) lactation, the pasture cows had a greater CH₄/MY than the TMR cows. It seems that in the earlier stages of lactation a grass-only diet is advantageous. But, in later lactation, the ability of supplementary feeding to increase milk production is

beneficial from a CH₄ efficiency perspective. In general, the results obtained in the current study (23.9 to 24.9 g of CH₄/MY) are slightly higher than those observed in the study of Robertson and Waghorn (2002) for cows at 150 (19.4 g of CH₄/MY) and 240 (24.3 g of CH₄/MY) DIM. This is due to the higher milk production performance by the cows in that study.

CONCLUSIONS

In the current study, which was conducted on dairy cows in mid to late lactation, enteric CH₄ emissions per cow were greater on a PMR-supplemented diet than on a grass-only diet. When PMR was offered, DMI and milk production per cow also increased. The partial supplementation of a grazing diet with PMR did not confer any reduction in enteric CH₄ emissions per unit of DMI, MY, SCM, or FP. The PMR treatment effects were attributed solely to the increased DMI, rather than to any particular nutritional characteristic of the PMR. The full life-cycle assessment implications of supplementing grass-based diets should be investigated. Dairy farmers seeking to reduce the enteric CH₄ emissions intensity of their systems will not see a significant benefit by supplementing grazing dairy cows with PMR in mid to late lactation.

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