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A comparison of milk yields and methane production from three contrasting high-yielding dairy cattle feeding regimes: cut and carry, partial grazing and total mixed ration

Running title: Adding grass to TMR reduced methane from dairy cattle

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ABSTRACT

There have been reductions in grazing cattle and corresponding increases in mixed diets across many regions. Mixed diets consist of silage, grains, legumes and other herbaceous plants (termed total mixed ration, TMR). TMR has been associated with increased milk yields but has also been linked to increased enteric methane production. We measured milk yields and methane production from high yielding Holstein-Friesian cattle after substituting 29–36% of a TMR diet with grass. Two feeding treatments were compared with a diet of TMR: grass grazed at pasture and grass cut in the field and delivered to housed cattle (termed cut and carry). Each feeding treatment was fed to 15 cattle and the experiment was conducted in South-west Scotland. Using a laser methane detector, we measured a two- and four-fold decline in enteric methane production for the cut and carry and grazing groups, respectively, when the animals consumed grass. TMR was consumed by both grass-fed groups overnight, so daily values were adjusted to include elevated methane production during this period. This revealed that methane production for the cut-and-carry and grazing groups were 17% and 39% lower than for the TMR-fed group, respectively. Milk yields were maintained for all three groups and the efficiency of milk production per unit of methane was substantially greater for the two grass-fed groups. A shift away from exclusively feeding TMR by adding fresh grass to the diets of cattle could contribute to meeting emissions targets and could also represent an economically sustainable climate-change mitigation strategy.

Keywords

Cut and carry; enteric methane; forage; greenhouse gases; total mixed ration; zero grazing.

1. INTRODUCTION

Atmospheric methane concentrations have risen in the period between 2007 and 2013. The expansion of tropical wetlands during periods of high rainfall, the extraction and processing of fossil fuels, livestock farming and other meteorological factors likely to be the principal causes (Nisbet et al., 2016; Turner et al., 2016). These increases have been recorded on a global scale, but a rapid rise in livestock numbers and changes to feed and husbandry across southern and southeast Asia and India, Europe, North and South America, and savanna Africa has created hotspots of emissions (FAO, 2013; Robinson et al., 2014). Livestock farming, including feed production, land use change, enteric sources and manure decomposition produce approximately 7.1 gigatonnes of carbon dioxide equivalents (GT CO_2eq) annually (FAO, 2013). Enteric fermentation by livestock produces 2.8 GT CO_2eq of methane each year, with 77% being produced by cattle (FAO, 2013). This is a pressing issue because methane is the second most important contributor to anthropogenic climate change, with a radiative forcing of more than 25 times CO_2eq (IPCC, 2013). However, the relatively short residence time of methane in the atmosphere (approximately 15 years) means that methane reduction strategies may offer the best opportunities to mitigate climate change in the short-term (IPCC, 2013).

Globally there has been a rise in the livestock inventory, with meat production increasing from 74 to 118 million tonnes and milk production increasing from 83 to 114 million tonnes in the period between 1990 and 2014 (FAOSTAT, 2016). Productivity is increasing across many regions, with animal nutrition and economic factors driving a trend away from grazed grass at pasture and towards more productive mixed diets fed to housed animals (Herrero et al., 2013; March, Haskell, Chagunda, Langford, & Roberts, 2014). Mixed diets may contain grass or maize silage, grains, forage legumes and other herbaceous plants, as well as supplements including salt, fat or protein (hereafter referred to as Total Mixed

Ration; TMR). Recent increases in TMR-fed cattle have contributed to the global rise in milk and meat production, but may also be linked to the rise in atmospheric methane emissions (Thornton, Jones, Ericksen, & Challinor, 2011; Wollenberg et al., 2016). Life cycle assessments are used to assess the emissions intensities of different livestock management systems; however, these assessments require many field measurements to parameterize the models (Ross, Topp, Ennos, & Chagunda, 2017).

Enteric methane is produced in the rumen by methanogenic microorganisms which utilize hydrogen and carbon dioxide to form methane. Methane is released as a by-product; approximately 97% by mouth and 3% from the rectum (Grainger et al., 2007; Muñoz, Yan, Wills, Murray, & Gordon, 2012). Methane production serves no contribution to animal productivity and instead leads to a loss in energy, ranging from 2 to 12% (Johnson & Johnson, 1995). Enteric methane is therefore a cost to both the farmer and environment. The magnitude of enteric methane production by livestock is influenced by breed, age, genotype, husbandry and diet (Havlík et al., 2014). Studies have shown that cattle consuming TMR increase methane production by 58% compared with those grazing grass (O'Neill et al., 2011). Increased enteric methane may have been caused by the increased availability of methane precursors, reduced feed particle sizes (and increased surface:area ratios) or increased total feed intakes. There has been recent interest in modifying high yielding livestock diets to reduce emissions of methane, either by reducing methane intensity (the amount of methane produced per unit of milk yield), by reducing total methane production or by increasing milk yields.

TMR has a higher cost of production than grass and there is emerging evidence that optimal profitability in the UK and elsewhere may be achieved by replacing a proportion of TMR with cheaper fresh grass and accepting a moderate milk yield loss (Lee and Roberts, 2015). Studies have shown that high milk yields may be retained by incorporating some fresh, immature grass into cattle diets if the grass is of high nutritive quality (Steinshamn & Thuen, 2008; Zebeli, Mansmann, Ametaj, Steingaß, & Drochner, 2010). Grass can be fed either through direct grazing at pasture or by cutting grass and delivering it to permanently housed cattle, known as 'cut and carry' or 'zero grazing' feeding regimes (Delaby & Peyraud, 2009). Feed supplements including tannins (Woodward, Waghorn, Ulyatt, & Lassey, 2001) and macroalgae (Machado, Magnusson, Paul, De Nys, & Tomkins, 2014) can also reduce methane production. However, introducing fresh grass into the diets of high yielding dairy cattle may be the most readily achievable methane-mitigation strategy if farm profitability can be maintained.

There has been a steady increase in the use of cut-and-carry systems, particularly in the UK, Germany, Holland and USA. However, there have been few studies which have compared the productivity and environmental impacts of cut and carry with other, more common, feeding regimes. We sought to contribute to this knowledge gap by investigating whether methane production would be reduced, and milk yields from high yielding dairy cattle maintained, by replacing a moderate proportion of a TMR-based diet with freshly cut and delivered grass (hereafter termed cut and carry) or grass grazed at pasture (hereafter termed partial grazing).

2. MATERIAL AND METHODS

The study was conducted at the SRUC Dairy Research Centre, Dumfries, South West Scotland (55° 2′ N, 3° 35′ W), during May and June 2015. The animals were milked and weighed three times each day at 09:00, 15:00 and 22:00 with individual cattle milk yields simultaneously recorded at each milking. Milk was sampled three times each week during the morning, afternoon and evening milking and assessed for milk protein and butterfat content. The landscape was open grassland dominated by diploid perennial ryegrass (*Lolium perenne*), which had been reseeded two years previously. White clover (*Trifolium repens*) and creeping buttercup (*Ranunculus acris*) were minor sward constituents. The soil type was free-draining with a sandy-loam texture. Over the study, weather data were collected by an automated Decagon datalogger (Decagon, USA). The mean temperature and precipitation during the period was 11.5 °C and 2.3 mm per day, respectively.

2.1 Animals and experimental design

A group of 45 spring-calving, lactating Holstein-Friesian dairy cattle were divided into triplicates of the most similar individuals using mean milk yield, milk butterfat and protein content and liveweights over the previous month, as well as lactation number. One of the three triplicate animals was randomly assigned to one of the three experimental treatments. This ensured that each of the three groups was balanced prior to commencing the experiment (Table 1). Prior to the commencement of the experiment all of the animals had been permanently housed in the shed in which the experiment took place. During this period they had been provided with TMR *ad libitum* for a target milk yield of 40 L day^{-1}.

➔ Table 1

2.2 Experimental treatments

Treatments were (i) permanenly housed dairy cattle fed a diet consisting of total mixed ration delivered to the animals each day (the TMR treatment), (ii) permanently housed dairy cattle fed a diet consisting of grass delivered to the animals each day (the cut-and-carry treatment) and (iii) dairy cattle housed overnight but allowed to graze at pasture during the day (the partial grazing treatment). Treatments were enforced between the morning and evening milking (09:00 - 22:30). All three cattle groups were housed overnight and provided with TMR *ad libitum*, following the evening milking. TMR comprised predominantly grass and maize silage which was formulated for a target milk yield of 40 kg d^{-1} per animal (Dry matter content = 600 g kg^{-1}, crude protein = 154 g kg^{-1}, neutral detergent fibre = 245 g kg^{-1}, metabolizable energy = 12 MJ kg^{-1}, starch = 345 g kg^{-1}, sugars = 55 g kg^{-1}, fat = 45 g kg^{-1}).

The cut-and-carry group were provided with fresh grass every morning, indoors, following the morning milking. Grass was harvested daily at 08:00 with a self-loading forage wagon with front disk mower (Bonino; Alessandria, Italy). Grass for the cut-and-carry group was harvested from adjacent plots to the partial grazing group to ensure forage was of comparable nutritive quality. The grazing group were sent to pasture immediately after milking at 09:00 and at that time the other treatment groups had access to their rations. The amount of grass made available to the cut-and-carry group was adjusted daily according to the dry matter (DM) content of the grass. Target grass consumption per animal for this group was 8 kg DM day^{-1} (approximately 40 kg of fresh grass). Grass DM content was measured daily using a microwave oven according to the methods of Lee and Roberts (2015).

The paddock was divided in half, with one half used to provide grass for the partial grazing group and the other half used to provide grass for the cut-and-carry group. The total paddock area of 8 ha was allocated to ensure sufficient grass was available to sustain the 15 cattle in each group throughout the experiment. This was done by dividing the paddock into four sub-sections, one for each week of the study. Before commencing the study, each sub-section was reduced to a residual sward of 1,500 kg ha^{-1} on a staggered weekly basis. This was assessed using a sward stick with a target mean grass height of 4 cm. Sub-section 1 was cut to the residual height four weeks before the start of the experiment, with sub-sections 2, 3 and 4 cut to the target residual in each of the next three weeks. In week one, sub-section 1 was divided in half and used to provide grass for the partial grazing group and cut-and-carry group. The remaining sub-sections were then used in each subsequent week so that there was always four weeks of regrowth in each sub-section. The aim of this cutting regime was to provide a consistent quality and quantity of grass between weeks and between treatment groups.

2.3 Methane production measurements

Methane production was measured with a hand-held laser methane detector (LMD), model SA3C06A (Toyoto Gas Engineering, Japan). During methane measurements the LMD was held 1 m from the animal while they were feeding and immediately following milking, with the laser aimed at the animals' nostrils. Taking measurements of methane production immediately following milking has been shown to correlate strongly with total methane production by individual dairy cattle (Garnsworthy, Craigon, Hernandez-Medrano, & Saunders, 2012). The LMD has been designed to function normally in the temperature range of 0 – 40° C and humidity range of 20 – 90%. A sampling duration of five minutes was used to capture the full eructation cycle. This method has been validated in previous studies (Chagunda et al., 2013; Chagunda, Ross, & Roberts, 2009).

Methane produced by the animals was measured each week on Monday and Tuesday between the hours of 09:00 and 15:00. The LMD measured the methane plume emitted by each individual animal with the concentration recorded as parts per million-metre (ppm-m^{-1}). Values were then converted to daily methane production based on equations derived by Chagunda et al (2009) at this site and using this LMD. Daily methane production measurements by LMD have been shown to correlate strongly with measurements taken by an open-circuit respiration calorimetric chamber (Chagunda & Yan, 2011).

One week prior to the experimental start date (week 0), baseline methane measurements were collected when all of the animals were eating the same TMR-based diet. This provided an opportunity to confirm whether the groups were balanced for methane production at the beginning of the experiment and to measure the rate at which methane production diverged from these baseline values.

2.4 Feeding rate and rumination time

Feeding rates were also measured for each treatment by observing the animals' feeding behaviour. A single chew was counted as an up and down jaw movement and the frequency of chews were counted over one minute. From each treatment, a subset of four individual cattle was selected at random and their feeding rate was recorded. The feeding rate testing was carried out in weeks 2, 3 and 4 of the study, with feeding rate monitored immediately following methane-production measurements.

The proportion of time spent ruminating was also recorded for the TMR and cut-and-carry groups. Behavioural information was not gathered from the partial grazing group because all of the individuals could not be accurately monitored at the same time. Ruminating behaviour was monitored for a total of three days, during one day of weeks 2, 3, and 4. Whether the animals were ruminating or not was recorded every fifteen minutes following the morning milking, between the hours of 09:00 and 15:00.

2.5 Feed intakes

Every morning, all of the TMR which had not been eaten by the animals in the TMR, partial grazing and cut-and-carry groups was weighed. The total daily amount of feed consumed was calculated by dividing the total weight of fresh feed consumed in 24 hours by the number of cattle in each treatment. To estimate grass intakes for both the cut-and-carry and partial grazing groups, the animals were assumed to adjust their feed intake to achieve an approximately constant total daily DM intake, and therefore total intakes for all groups was assumed to be in line with the TMR group. This is consistent with another study at this site where there was no difference in total DM intakes when comparing cattle fed a ration of 50% grass:50% TMR, 25% grass: 75% TMR or 100% TMR (Lee and Roberts, 2015).

2.6 Statistical analysis

Linear regressions were used to test for relationships between methane production and milk yields over time within each treatment group, and to test for a relationship between methane production and feeding rate. T-tests were used to identify differences between the DM content of TMR and grass, and to test for differences in feed intakes between the treatment groups. Analysis of variance (ANOVA) tests were performed to identify treatment effects for methane production, milk yields, milk composition, methane intensity (methane production per unit of milk), animal behaviour (the amount of time spent engaged in different behaviours) and feeding rates. These variables were included in separate models as the response variable with the three treatments (TMR, partial grazing and cut and carry) included in the models as the explanatory variables. Time was also included as a co-variate in these analyses. Each of the 15 cows were experimental replicates (N = 15). Separate analyses were also carried out for each study week to avoid temporal pseudo-replication and to assess changes to the magnitude and direction of the treatment effects during the study. Tukey's honest significant difference (HSD) tests were then used to describe individual treatment effects for each response variable. A Shapiro-Wilks test was conducted to test for normality in methane production across all of the animals (Crawley, 2013). All statistical analyses were carried out using R (www.r-project.org, version 3.2.3).

3. RESULTS

3.1 Feed intake and milk yields

The mean DM content of TMR was approximately double the DM content of grass over the four weeks of the experiment (t = 11.5, p< 0001; table 2). TMR intakes by FW for the cut and carry group (t = 8.9, $p < 0.001$) and partial grazing group (t = 9.4, $p < 0.001$) were lower than the group fed solely TMR, with the cut-and-carry group consuming moderately more TMR than the partial grazing group overnight, though the difference between the cut-and-carry and grazing groups was not significant ($p > 0.05$). TMR intakes by DM showed the same patterns as FW, with both the cut-and-carry (t = 9.0, $p < 0.001$) and partial grazing group (t = 8.1, $p < 0.001$) having lower TMR intakes than the TMR group, but again the two grass-fed groups were not significantly different from each other ($p > 0.05$). The cut-and-carry group and the partial grazing group consumed means of 6.5 kg DM d^{-1} (30%) and 8 kg DM d^{-1} (36%) of their diet as grass, respectively. These values were approximately in line with the target of 8 kg DM d^{-1}.

➔ Table 2

Mean milk yields from all three treatments groups was 37 kg d^{-1} prior to commencing the treatments. Across all weekly sampling intervals there was no significant difference in milk yields between treatment groups (all $p > 0.05$). Milk yields did not change over time and in the final week mean milk yields across all three treatment groups was also 37 kg d^{-1}. Although there were absolute treatment differences in mean milk butterfat across all weeks - for the TMR group mean butterfat was 4.1 g kg^{-1} compared with 3.8 g kg^{-1} and 3.4 g kg^{-1} for the cut-and-carry and partial grazing groups, respectively - these differences were not significant (Figure 1a). Mean milk protein content across all weeks was 3.2, 3.3 and 3.1 for the TMR, cut-and-carry and partial grazing groups, respectively, but these differences were also not significant (Figure 1b).

➔ Figure 1

3.2 Methane production

Across all treatments and all sampling intervals, methane production was consistent with a normal distribution (mean = 400 g d^{-1}) with 79% of measurements falling between 200 g d^{-1} and 500 g d^{-1}. Prior to the commencement of the treatments, mean methane production by the animals in all three treatment groups was equal: 573 g d^{-1} ($p > 0.05$, Figure 2a). After treatments commenced, linear regression analyses revealed that methane production declined over time for both of the grass-fed groups (both $p < 0.05$), but there was no change over time in the amount of methane produced by the TMR-fed group ($p > 0.05$). Overall, there was a significant treatment effect for methane production between groups (F = 8.0, $p < 0.01$) and for methane intensity between groups (F = 7.9, $p < 0.01$).

Methane produced by cows within the cut-and-carry group was lower than the TMR fed group after one week of treatments, with this difference continuing throughout the four weeks. Methane production from the partial grazing group was only significantly different from the other two groups after four weeks of treatments. It should be noted that measurements could not be taken from the partial grazing group in week 1 due to adverse weather conditions. In the final week the partial grazing group produced the least methane, with the TMR-fed group producing approximately double the amount of methane compared with the cut-and-carry group and approximately four times the amount of methane compared with the partial grazing group.

Methane per unit of milk production followed a similar pattern to absolute methane production, with the amount of methane produced per unit of milk production declining for both grass-fed groups, whereas the methane intensity of the TMR group did not change over time (Figure 2b). There were no differences in methane intensity prior to commencing treatments ($p > 0.05$) and at week 0 mean methane intensity was 16 g CH_4 kg^{-1}. Methane intensity improved for the cut-and-carry group in week 1 but there were no differences between treatments in week 2. In the final week the partial grazing group had the lowest methane intensity, followed by the cut-and-carry group, whilst the TMR-fed group produced the most methane per unit of milk.

➔ Figure 2

3.3 Feeding rate and rumination time

Methane production was linearly related to the rate of chewing across all three treatments ($p < 0.05$, Figure 3). As the rate of chewing increased, methane production also increased across the range 68 – 120 chews min^{-1}. Chewing rates were greatest for the TMR-fed group, with a mean of 100 chews min^{-1}, and lower for both grass-fed groups, with a mean of 78 chews min^{-1}. The proportion of time spent ruminating also varied between groups, with the TMR-fed group spending a mean of 27% of their time ruminating compared with the mean of 42% for the cut-and-carry group ($p < 0.05$).

➔ Figure 3

4. DISCUSSION

Enteric methane production was reduced considerably in both grass-fed groups by week 4 compared with the TMR-fed group. The magnitude of methane production we measured was broadly consistent with a meta-analysis collected from cattle across Australia, Europe, New Zealand and North America (158 g d^{-1} – 597 g d^{-1}), which comprised grazed, cut and carry and TMR-based diets (Appuhamy, France, & Kebreab, 2016). Treatment effects in our study may have been driven by the maize- or grass-silage TMR component (Waugh, Clark, Waghorn, & Woodward, 2005) or other TMR components adding methane precursors (such as acetate and butyrate) or reducing feed particle sizes, and increasing particle surface area, for the TMR-fed group (Knapp, Laur, Vadas, Weiss, & Tricarico, 2014). Methane production when the cattle were consuming TMR was two- and four-times greater than animals consuming grass in both the cut-and-carry and partial grazing groups, respectively, in week 4 of the experiment.

The maintenance of high milk yields and reduced enteric methane production for both grass-fed groups resulted in improved methane production efficiencies for these two groups. In the final week of the experiment, methane intensity was lower for the cut-and-carry and partial grazing groups than the TMR-fed group. The range of values was broadly consistent with the range of values measured across several regions and feeding regimes (8 - 40 g CH_4 kg^{-1}) (Appuhamy et al., 2016). It should be noted that TMR was consumed overnight by both of the grass-fed groups (64 – 71% of total DM intake). We adjusted our estimates of methane production for the grass-fed groups by including rates of methane production for the TMR group and applying it to 64% and 71% of the daily values for the partial grazing and cut-and-carry groups, respectively (according to DM intakes). This conservative calculation produced estimated daily methane production for the cut-and-carry group of 431 g d^{-1} and partial grazing groups of 365 g d^{-1}; 17% and 39% lower than methane produced by the TMR-fed group, respectively.

TMR is considerably more expensive to produce than grass (Delaby & Peyraud, 2009), and so diets exclusively comprising TMR may be less efficient from an environmental and economic perspective in some cases. We show that milk yields can be maintained by replacing approximately 29 – 36% of the diet of high yielding dairy cattle with grass, over a four-week period, without a detectable change in milk quality. A previous study at this site has shown that when cattle are fed 25% or 50% of their diet as grass, the milk yields from grass-fed cattle may eventually decline over a longer time frame (16 weeks) when compared with TMR-fed cattle (Lee and Roberts, 2015). However, Lee and Roberts (2015) also demonstrated that 50% grass-fed cattle can be more profitable than those fed only TMR, depending on production costs and milk prices, due to savings from improved costs of production compared with moderate losses in milk sales. Further studies are needed to measure the longer-term effects of a modified diet on methane production. Care must be taken in the extrapolation of these results more broadly, since they were dependent on market conditions and grass nutritive quality. In particular, this study was conducted during a period when grass nutritive values will have been high in this region of South-west Scotland. Despite these caveats, the economic advantages of replacing a proportion of TMR with fresh grass, as well as an associated reduction in methane production, may mean that the costs of any longer-term reductions in milk yields may be outweighed by the benefits of improved farm profitability and reduced greenhouse gas emissions.

An alternative to increasing the proportion of grass to reduce methane production may be to adjust the composition of TMR. There is evidence that increasing TMR digestibility by reducing the proportion of fibre or non-structural carbohydrates, or increasing the proportion of fatty acids and proteins, may reduce methane production (Ellis et al., 2007; Moraes, Strathe, Fadel, Casper, & Kebreab, 2014; Nielsen et al., 2013). In this study, fibre and carbohydrate concentrations were relatively high, but protein and fat concentrations were relatively low in the TMR formulation and these are components which could be manipulated to limit methane production. Feed supplements, such as tannins (Woodward et al., 2001), fats (Beauchemin & McGinn, 2006; McGinn, Beauchemin, Coates, & Colombatto, 2004), starchy cereal grains (McAllister & Cheng, 1996) and macroalgae (Machado et al., 2014) may also be introduced to reduce methane production. However, production costs and milk yields must be considered when making any changes to TMR composition and the introduction of many feed supplements is not practicable for many farmers. The introduction of a greater proportion of fresh grass into the diets of high yielding cattle may therefore be a more realistic methane abatement measure. However, future climate-driven changes to grass nutritive quality and productivity must also be taken into account when designing future feeding regimes (M. A. Lee, Davis, Chagunda, & Manning, 2017; M. Lee, Manning, Rist, Power, & Marsh, 2010).

The regime used in this study to introduce grass into the diets of high yielding dairy cattle was an important consideration. We showed that there were reductions in methane production from the partial grazing group compared with the cut-and-carry group, whilst milk yields were also maintained. This provides evidence in support of grazing as a methane abatement measure. It has been demonstrated that, when feeding occurs intensively once or twice a day, intensive feeding can accentuate changes in the concentration of rumen metabolites and change fermentation processes, thus increasing methane production – as may have been the case for the housed cut-and-carry and TMR groups (Annison and Lewis, 1959). However, it may also be the case that outdoor conditions may have diluted methane concentrations more rapidly, thus influencing measurements by the LMD, driven primarily by wind speed and direction (Chagunda et al., 2013, 2009). We therefore present preliminary evidence that increasing the proportion of grazed grass in high yielding dairy cattle diets may reduce methane production, but further work is required to confirm this observation.

We observed differences in the time spent ruminating between the treatment groups, and the TMR-fed group chewed more frequently and spent less time ruminating than the cut-and-carry group. Since both groups were permanently housed within the same shed and were balanced prior to commencing the study, these differences are unlikely to have been driven by housing or animal condition. Instead we propose that changes to chewing rate and rumination are both determined by differences in the composition, particle sizes and digestibility of TMR and grass. TMR is generally more readily digestible than grass and has a smaller particle size with larger surface area. Therefore, rumen microbes carry out digestion and generate methane at an increased rate when digesting TMR compared with grass (Annison and Lewis, 1959). As a result, the TMR-fed group spent more time carrying out other behaviours than the grass-fed group which invested more time in rumination. We did not gather behavioural information for the partial grazing group.

The recent rapid rise in global atmospheric methane concentrations may have been driven, at least in part, by the shift in cattle feeding practices around the world (Nisbet et al, 2016; Turner et al, 2016). In the year 2000, 48% (2.3 billion tons) of the biomass consumed by livestock was forage grass and this value represented a declining trend, away from grass and towards TMR (Herrero et al., 2013). We present data which suggest that such a shift in cattle diets may be associated with substantial increases in methane production. Recent assessments suggest that agricultural GHG emissions need to be reduced by ~1 GT CO_2eq annually in order to limit warming to 2 °C above pre-industrial levels by 2100 (Wollenberg et al., 2016). Our research shows that a reduced reliance on TMR for feeding high yielding dairy cattle may reduce GHG emissions from livestock in the future and could also maintain or improve farm profitability. Modifying feeding regimes by increasing the use of fresh grass could represent an economically sustainable methane abatement strategy: maintaining high milk yields and milk quality whilst reducing methane production or by accepting a moderate reduction in milk yields at a lower cost of production. We demonstrate that both mechanisms may be possible and could contribute to ambitious GHG reduction targets.

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Table 1. Mean ± standard error of milk yield, milk butterfat and protein contents, cattle liveweight and lactation number for the six weeks prior to commencing the study. Treatments were total mixed ration (TMR), cut and carry and partial grazing.

Treatment	Milk Yield (kg)	Butterfat (g kg^{-1})	Protein (g kg^{-1})	Weight (kg)	Lactation
Cut & Carry	37.5 ± 9.7	3.8 ± 1.0	3.1 ± 0.8	620 ± 160	3.5 ± 0.9
TMR	37.7 ± 9.7	3.8 ± 1.0	3.0 ± 0.8	615 ± 159	3.7 ± 0.9
Grazing	37.6 ± 9.7	3.4 ± 0.9	2.9 ± 0.8	620 ± 160	3.6 ± 0.9

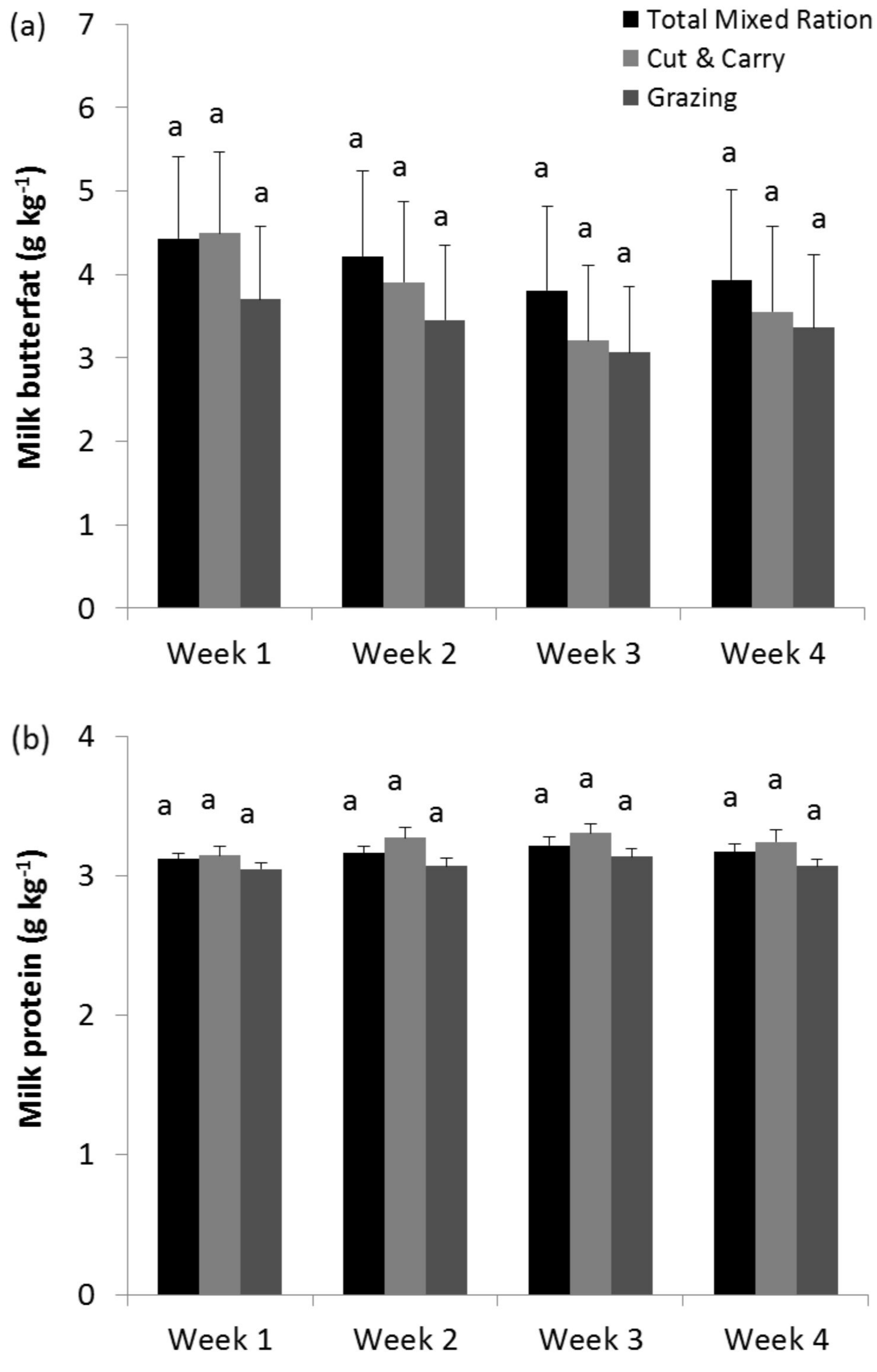
Table 2. Mean ± standard error of daily Total Mixed Ration (TMR) intakes for each treatment measured by fresh weight (FW) intake and dry matter (DM) intake. Values represent mean daily intake. The DM content of TMR and grass are also presented. Significantly different mean values are denoted by letters a and b.

	Dry Matter (%)		TMR intake (kg FW d^{-1})			TMR intake (kg DM d^{-1})		
Week	TMR	Grass	TMR	Cut & Carry	Grazing	TMR	Cut & Carry	Grazing
1	38.4 ± 1.1	18.7 ± 0.4	53.2 ± 3.6	36.3 ± 2.9	31.8 ± 2.3	22.2 ± 1.7	15.3 ± 1.2	13.2 ± 0.6
2	41.3 ± 3.8	22.9 ± 0.5	55.3 ± 5.2	38.9 ± 2.4	34.3 ± 4.0	23.2 ± 2.5	15.4 ± 0.9	14.6 ± 0.7
3	40.2 ± 1.9	14.6 ± 1.0	55.7 ± 3.4	42.3 ± 3.1	40.3 ± 2.9	23.0 ± 1.7	17.0 ± 1.3	16.4 ± 1.3
4	38.9 ± 4.8	17.2 ± 0.8	56.7 ± 2.7	40.2 ± 1.5	38.1 ± 3.0	20.6 ± 0.3	15.3 ± 0.6	13.0 ± 0.9
mean	39.7^{a} ± 0.7	18.4^{b} ± 1.7	55.2^{a} ± 0.7	39.4^{b} ± 1.3	36.1^{b} ± 1.9	22.3^{a} ± 0.6	15.8^{b} ± 0.4	14.3^{b} ± 0.8

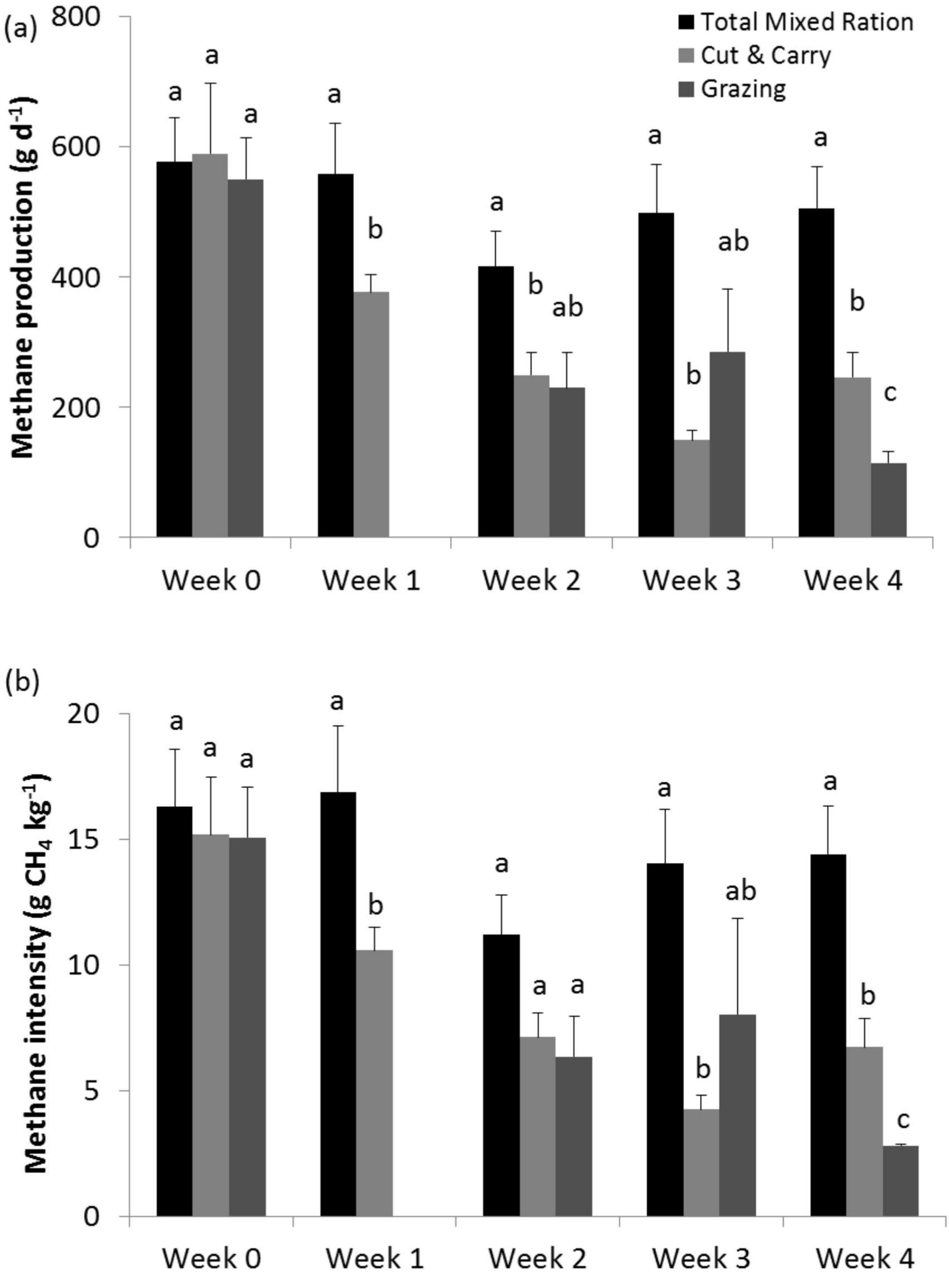
Figure 1. (a) Mean milk butterfat content per animal and (b) Mean milk protein content per animal for the three treatment groups during the four-week experiment. There were no significant differences between treatments, as denoted by the letter a. Bars represent standard error values.

Figure 2. (a) Mean daily methane production per animal and (b) mean methane intensity (methane produced per kg of milk) for the three treatment groups during the four-week experiment. Significantly different treatments are denoted by letters a, b and c. Methane was not measured from the partial grazing group in week 1 due to adverse weather conditions. Bars represent standard error values.

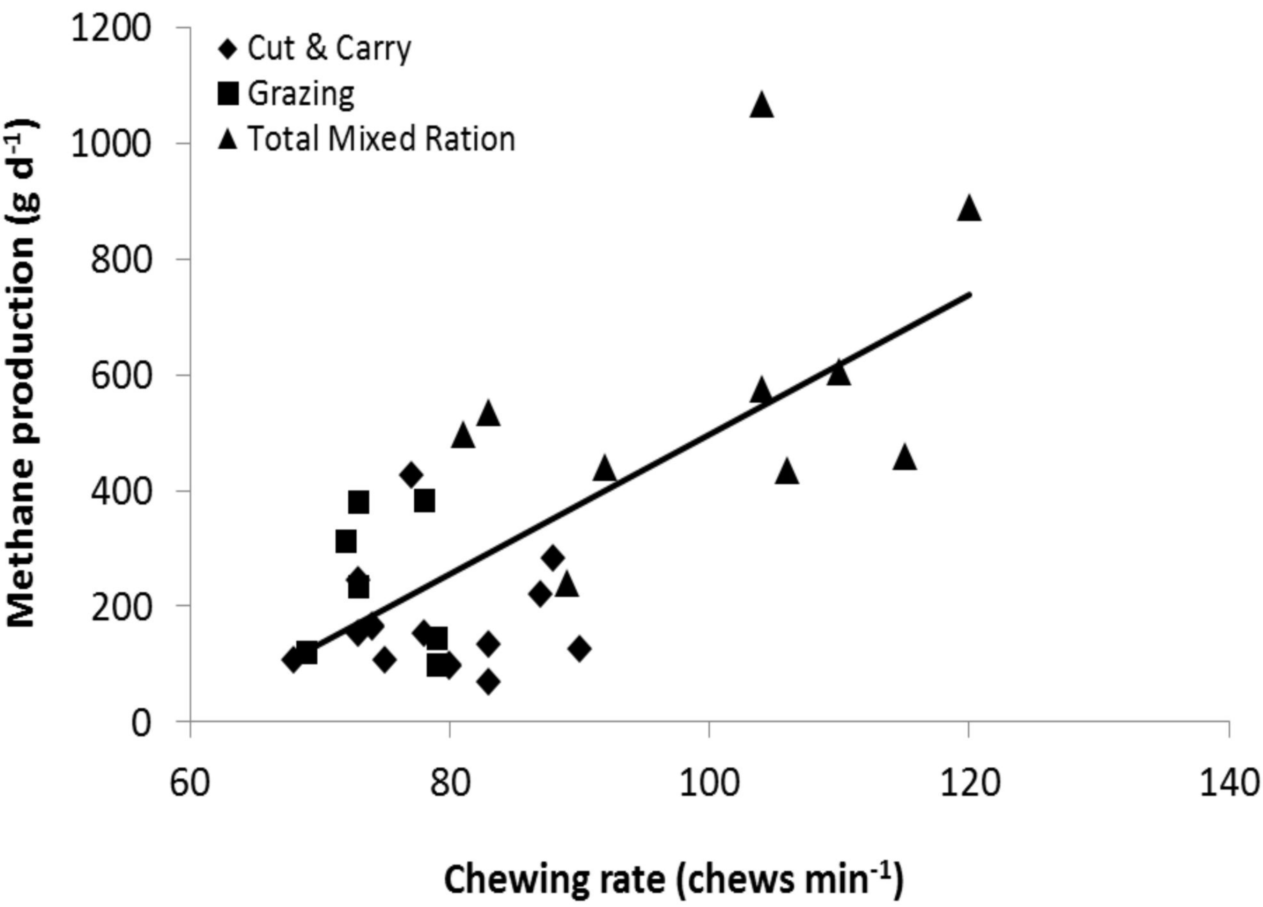
Figure 3. Linear relationship between the frequency of chews and methane production ($CH_4 = 12x - 738$, $r^2 = 0.5$, $p < 0.05$).



(a)
Total Mixed Ration
Cut & Carry
Grazing
Milk butterfat (g kg-1)
0
1
2
3
4
5
6
7
a
Week 1
Week 2
Week 3
Week 4
(b)
Milk protein (g kg-1)
0
1
2
3
4



(a)
Total Mixed Ration
Cut & Carry
Grazing
Methane production (g d^{-1})
800
600
400
200
0
a
a
a
a
b
a
b
ab
a
b
ab
a
b
c
Week 0
Week 1
Week 2
Week 3
Week 4
(b)
Methane intensity (g CH_4 kg^{-1})
20
15
10
5
0
a
a
a
a
b
a
a
a
a
b
ab
a
b
c
Week 0
Week 1
Week 2
Week 3
Week 4



Cut & Carry
Grazing
Total Mixed Ration
Methane production (g d-1)
Chewing rate (chews min-1)
0
200
400
600
800
1000
1200
60
80
100
120
140