

Scotland's Rural College

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

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

4

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

6

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8

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14

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20 **ABSTRACT**

21 There have been reductions in grazing cattle and corresponding increases in mixed diets  
22 across many regions. Mixed diets consist of silage, grains, legumes and other herbaceous  
23 plants (termed total mixed ration, TMR). TMR has been associated with increased milk  
24 yields but has also been linked to increased enteric methane production. We measured milk  
25 yields and methane production from high yielding Holstein-Friesian cattle after substituting  
26 29–36% of a TMR diet with grass. Two feeding treatments were compared with a diet of  
27 TMR: grass grazed at pasture and grass cut in the field and delivered to housed cattle (termed  
28 cut and carry). Each feeding treatment was fed to 15 cattle and the experiment was conducted  
29 in South-west Scotland. Using a laser methane detector, we measured a two- and four-fold  
30 decline in enteric methane production for the cut and carry and grazing groups, respectively,  
31 when the animals consumed grass. TMR was consumed by both grass-fed groups overnight,  
32 so daily values were adjusted to include elevated methane production during this period. This  
33 revealed that methane production for the cut-and-carry and grazing groups were 17% and  
34 39% lower than for the TMR-fed group, respectively. Milk yields were maintained for all  
35 three groups and the efficiency of milk production per unit of methane was substantially  
36 greater for the two grass-fed groups. A shift away from exclusively feeding TMR by adding  
37 fresh grass to the diets of cattle could contribute to meeting emissions targets and could also  
38 represent an economically sustainable climate-change mitigation strategy.

39

40 **Keywords**

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

## 42 1. INTRODUCTION

43 Atmospheric methane concentrations have risen in the period between 2007 and 2013. The  
44 expansion of tropical wetlands during periods of high rainfall, the extraction and processing  
45 of fossil fuels, livestock farming and other meteorological factors likely to be the principal  
46 causes (Nisbet et al., 2016; Turner et al., 2016). These increases have been recorded on a  
47 global scale, but a rapid rise in livestock numbers and changes to feed and husbandry across  
48 southern and southeast Asia and India, Europe, North and South America, and savanna Africa  
49 has created hotspots of emissions (FAO, 2013; Robinson et al., 2014). Livestock farming,  
50 including feed production, land use change, enteric sources and manure decomposition  
51 produce approximately 7.1 gigatonnes of carbon dioxide equivalents (GT CO<sub>2</sub>eq) annually  
52 (FAO, 2013). Enteric fermentation by livestock produces 2.8 GT CO<sub>2</sub>eq of methane each  
53 year, with 77% being produced by cattle (FAO, 2013). This is a pressing issue because  
54 methane is the second most important contributor to anthropogenic climate change, with a  
55 radiative forcing of more than 25 times CO<sub>2</sub>eq (IPCC, 2013). However, the relatively short  
56 residence time of methane in the atmosphere (approximately 15 years) means that methane  
57 reduction strategies may offer the best opportunities to mitigate climate change in the short-  
58 term (IPCC, 2013).

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

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

73 Enteric methane is produced in the rumen by methanogenic microorganisms which  
74 utilize hydrogen and carbon dioxide to form methane. Methane is released as a by-product;  
75 approximately 97% by mouth and 3% from the rectum (Grainger et al., 2007; Muñoz, Yan,  
76 Wills, Murray, & Gordon, 2012). Methane production serves no contribution to animal  
77 productivity and instead leads to a loss in energy, ranging from 2 to 12% (Johnson &  
78 Johnson, 1995). Enteric methane is therefore a cost to both the farmer and environment. The  
79 magnitude of enteric methane production by livestock is influenced by breed, age, genotype,  
80 husbandry and diet (Havlík et al., 2014). Studies have shown that cattle consuming TMR  
81 increase methane production by 58% compared with those grazing grass (O'Neill et al.,  
82 2011). Increased enteric methane may have been caused by the increased availability of  
83 methane precursors, reduced feed particle sizes (and increased surface:area ratios) or  
84 increased total feed intakes. There has been recent interest in modifying high yielding  
85 livestock diets to reduce emissions of methane, either by reducing methane intensity (the  
86 amount of methane produced per unit of milk yield), by reducing total methane production or  
87 by increasing milk yields.

88 TMR has a higher cost of production than grass and there is emerging evidence that  
89 optimal profitability in the UK and elsewhere may be achieved by replacing a proportion of  
90 TMR with cheaper fresh grass and accepting a moderate milk yield loss (Lee and Roberts,  
91 2015). Studies have shown that high milk yields may be retained by incorporating some

92 fresh, immature grass into cattle diets if the grass is of high nutritive quality (Steinshamn &  
93 Thuen, 2008; Zebeli, Mansmann, Ametaj, Steingäß, & Drochner, 2010). Grass can be fed  
94 either through direct grazing at pasture or by cutting grass and delivering it to permanently  
95 housed cattle, known as ‘cut and carry’ or ‘zero grazing’ feeding regimes (Delaby & Peyraud,  
96 2009). Feed supplements including tannins (Woodward, Waghorn, Ulyatt, & Lassey, 2001)  
97 and macroalgae (Machado, Magnusson, Paul, De Nys, & Tomkins, 2014) can also reduce  
98 methane production. However, introducing fresh grass into the diets of high yielding dairy  
99 cattle may be the most readily achievable methane-mitigation strategy if farm profitability  
100 can be maintained.

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

109 **2. MATERIAL AND METHODS**

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

121

122 **2.1 Animals and experimental design**

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

131

132 → Table 1

133

## 134 2.2 Experimental treatments

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

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



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

169

170

### 171 **2.3 Methane production measurements**

172 Methane production was measured with a hand-held laser methane detector (LMD), model  
173 SA3C06A (Toyoto Gas Engineering, Japan). During methane measurements the LMD was  
174 held 1 m from the animal while they were feeding and immediately following milking, with  
175 the laser aimed at the animals' nostrils. Taking measurements of methane production  
176 immediately following milking has been shown to correlate strongly with total methane  
177 production by individual dairy cattle (Garnsworthy, Craigon, Hernandez-Medrano, &  
178 Saunders, 2012). The LMD has been designed to function normally in the temperature range

179 of 0 – 40° C and humidity range of 20 – 90%. A sampling duration of five minutes was used  
180 to capture the full eructation cycle. This method has been validated in previous studies  
181 (Chagunda et al., 2013; Chagunda, Ross, & Roberts, 2009).

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

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

194

## 195 **2.4 Feeding rate and rumination time**

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

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

208

## 209 **2.5 Feed intakes**

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

219

## 220 **2.6 Statistical analysis**

221 Linear regressions were used to test for relationships between methane production and milk  
222 yields over time within each treatment group, and to test for a relationship between methane  
223 production and feeding rate. T-tests were used to identify differences between the DM  
224 content of TMR and grass, and to test for differences in feed intakes between the treatment

225 groups. Analysis of variance (ANOVA) tests were performed to identify treatment effects for  
226 methane production, milk yields, milk composition, methane intensity (methane production  
227 per unit of milk), animal behaviour (the amount of time spent engaged in different  
228 behaviours) and feeding rates. These variables were included in separate models as the  
229 response variable with the three treatments (TMR, partial grazing and cut and carry) included  
230 in the models as the explanatory variables. Time was also included as a co-variate in these  
231 analyses. Each of the 15 cows were experimental replicates (N = 15). Separate analyses were  
232 also carried out for each study week to avoid temporal pseudo-replication and to assess  
233 changes to the magnitude and direction of the treatment effects during the study. Tukey's  
234 honest significant difference (HSD) tests were then used to describe individual treatment  
235 effects for each response variable. A Shapiro-Wilks test was conducted to test for normality  
236 in methane production across all of the animals (Crawley, 2013). All statistical analyses were  
237 carried out using R ([www.r-project.org](http://www.r-project.org), version 3.2.3).

## 238 3. RESULTS

### 239 3.1 Feed intake and milk yields

240 The mean DM content of TMR was approximately double the DM content of grass over the  
241 four weeks of the experiment ( $t = 11.5, p < 0.0001$ ; table 2). TMR intakes by FW for the cut and  
242 carry group ( $t = 8.9, p < 0.001$ ) and partial grazing group ( $t = 9.4, p < 0.001$ ) were lower than  
243 the group fed solely TMR, with the cut-and-carry group consuming moderately more TMR  
244 than the partial grazing group overnight, though the difference between the cut-and-carry and  
245 grazing groups was not significant ( $p > 0.05$ ). TMR intakes by DM showed the same patterns  
246 as FW, with both the cut-and-carry ( $t = 9.0, p < 0.001$ ) and partial grazing group ( $t = 8.1, p <$   
247  $0.001$ ) having lower TMR intakes than the TMR group, but again the two grass-fed groups  
248 were not significantly different from each other ( $p > 0.05$ ). The cut-and-carry group and the  
249 partial grazing group consumed means of  $6.5 \text{ kg DM d}^{-1}$  (30%) and  $8 \text{ kg DM d}^{-1}$  (36%) of their  
250 diet as grass, respectively. These values were approximately in line with the target of  $8 \text{ kg}$   
251  $\text{DM d}^{-1}$ .

252

253 → Table 2

254

255 Mean milk yields from all three treatment groups was  $37 \text{ kg d}^{-1}$  prior to commencing  
256 the treatments. Across all weekly sampling intervals there was no significant difference in  
257 milk yields between treatment groups (all  $p > 0.05$ ). Milk yields did not change over time and  
258 in the final week mean milk yields across all three treatment groups was also  $37 \text{ kg d}^{-1}$ .  
259 Although there were absolute treatment differences in mean milk butterfat across all weeks -  
260 for the TMR group mean butterfat was  $4.1 \text{ g kg}^{-1}$  compared with  $3.8 \text{ g kg}^{-1}$  and  $3.4 \text{ g kg}^{-1}$  for

261 the cut-and-carry and partial grazing groups, respectively - these differences were not  
262 significant (Figure 1a). Mean milk protein content across all weeks was 3.2, 3.3 and 3.1 for  
263 the TMR, cut-and-carry and partial grazing groups, respectively, but these differences were  
264 also not significant (Figure 1b).

265 → Figure 1

266

### 267 **3.2 Methane production**

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

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

284 with the cut-and-carry group and approximately four times the amount of methane compared  
285 with the partial grazing group.

286 Methane per unit of milk production followed a similar pattern to absolute methane  
287 production, with the amount of methane produced per unit of milk production declining for  
288 both grass-fed groups, whereas the methane intensity of the TMR group did not change over  
289 time (Figure 2b). There were no differences in methane intensity prior to commencing  
290 treatments ( $p > 0.05$ ) and at week 0 mean methane intensity was  $16 \text{ g CH}_4 \text{ kg}^{-1}$ . Methane  
291 intensity improved for the cut-and-carry group in week 1 but there were no differences  
292 between treatments in week 2. In the final week the partial grazing group had the lowest  
293 methane intensity, followed by the cut-and-carry group, whilst the TMR-fed group produced  
294 the most methane per unit of milk.

295

296 → Figure 2

297

### 298 3.3 Feeding rate and rumination time

299 Methane production was linearly related to the rate of chewing across all three treatments ( $p$   
300  $< 0.05$ , Figure 3). As the rate of chewing increased, methane production also increased across  
301 the range  $68 - 120 \text{ chews min}^{-1}$ . Chewing rates were greatest for the TMR-fed group, with a  
302 mean of  $100 \text{ chews min}^{-1}$ , and lower for both grass-fed groups, with a mean of  $78 \text{ chews min}^{-1}$ .  
303 The proportion of time spent ruminating also varied between groups, with the TMR-fed  
304 group spending a mean of 27% of their time ruminating compared with the mean of 42% for  
305 the cut-and-carry group ( $p < 0.05$ ).

306

307 → Figure 3

308



#### 309 4. DISCUSSION

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

322 The maintenance of high milk yields and reduced enteric methane production for both  
323 grass-fed groups resulted in improved methane production efficiencies for these two groups.  
324 In the final week of the experiment, methane intensity was lower for the cut-and-carry and  
325 partial grazing groups than the TMR-fed group. The range of values was broadly consistent  
326 with the range of values measured across several regions and feeding regimes ( $8 - 40 \text{ g CH}_4$   
327  $\text{kg}^{-1}$ ) (Appuhamy et al., 2016). It should be noted that TMR was consumed overnight by both  
328 of the grass-fed groups (64 – 71% of total DM intake). We adjusted our estimates of methane  
329 production for the grass-fed groups by including rates of methane production for the TMR  
330 group and applying it to 64% and 71% of the daily values for the partial grazing and cut-and-  
331 carry groups, respectively (according to DM intakes). This conservative calculation produced  
332 estimated daily methane production for the cut-and-carry group of  $431 \text{ g d}^{-1}$  and partial

333 grazing groups of 365 g d<sup>-1</sup>; 17% and 39% lower than methane produced by the TMR-fed  
334 group, respectively.

335 TMR is considerably more expensive to produce than grass (Delaby & Peyraud,  
336 2009), and so diets exclusively comprising TMR may be less efficient from an environmental  
337 and economic perspective in some cases. We show that milk yields can be maintained by  
338 replacing approximately 29 – 36% of the diet of high yielding dairy cattle with grass, over a  
339 four-week period, without a detectable change in milk quality. A previous study at this site  
340 has shown that when cattle are fed 25% or 50% of their diet as grass, the milk yields from  
341 grass-fed cattle may eventually decline over a longer time frame (16 weeks) when compared  
342 with TMR-fed cattle (Lee and Roberts, 2015). However, Lee and Roberts (2015) also  
343 demonstrated that 50% grass-fed cattle can be more profitable than those fed only TMR,  
344 depending on production costs and milk prices, due to savings from improved costs of  
345 production compared with moderate losses in milk sales. Further studies are needed to  
346 measure the longer-term effects of a modified diet on methane production. Care must be  
347 taken in the extrapolation of these results more broadly, since they were dependent on market  
348 conditions and grass nutritive quality. In particular, this study was conducted during a period  
349 when grass nutritive values will have been high in this region of South-west Scotland.  
350 Despite these caveats, the economic advantages of replacing a proportion of TMR with fresh  
351 grass, as well as an associated reduction in methane production, may mean that the costs of  
352 any longer-term reductions in milk yields may be outweighed by the benefits of improved  
353 farm profitability and reduced greenhouse gas emissions.

354 An alternative to increasing the proportion of grass to reduce methane production may  
355 be to adjust the composition of TMR. There is evidence that increasing TMR digestibility by  
356 reducing the proportion of fibre or non-structural carbohydrates, or increasing the proportion  
357 of fatty acids and proteins, may reduce methane production (Ellis et al., 2007; Moraes,

358 Strathe, Fadel, Casper, & Kebreab, 2014; Nielsen et al., 2013). In this study, fibre and  
359 carbohydrate concentrations were relatively high, but protein and fat concentrations were  
360 relatively low in the TMR formulation and these are components which could be manipulated  
361 to limit methane production. Feed supplements, such as tannins (Woodward et al., 2001), fats  
362 (Beauchemin & McGinn, 2006; McGinn, Beauchemin, Coates, & Colombatto, 2004), starchy  
363 cereal grains (McAllister & Cheng, 1996) and macroalgae (Machado et al., 2014) may also  
364 be introduced to reduce methane production. However, production costs and milk yields must  
365 be considered when making any changes to TMR composition and the introduction of many  
366 feed supplements is not practicable for many farmers. The introduction of a greater  
367 proportion of fresh grass into the diets of high yielding cattle may therefore be a more  
368 realistic methane abatement measure. However, future climate-driven changes to grass  
369 nutritive quality and productivity must also be taken into account when designing future  
370 feeding regimes (M. A. Lee, Davis, Chagunda, & Manning, 2017; M. Lee, Manning, Rist,  
371 Power, & Marsh, 2010).

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

383 evidence that increasing the proportion of grazed grass in high yielding dairy cattle diets may  
384 reduce methane production, but further work is required to confirm this observation.

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

397 The recent rapid rise in global atmospheric methane concentrations may have been  
398 driven, at least in part, by the shift in cattle feeding practices around the world (Nisbet et al,  
399 2016; Turner et al, 2016). In the year 2000, 48% (2.3 billion tons) of the biomass consumed  
400 by livestock was forage grass and this value represented a declining trend, away from grass  
401 and towards TMR (Herrero et al., 2013). We present data which suggest that such a shift in  
402 cattle diets may be associated with substantial increases in methane production. Recent  
403 assessments suggest that agricultural GHG emissions need to be reduced by ~1 GT CO<sub>2</sub>eq  
404 annually in order to limit warming to 2 °C above pre-industrial levels by 2100 (Wollenberg et  
405 al., 2016). Our research shows that a reduced reliance on TMR for feeding high yielding  
406 dairy cattle may reduce GHG emissions from livestock in the future and could also maintain  
407 or improve farm profitability. Modifying feeding regimes by increasing the use of fresh grass

408 could represent an economically sustainable methane abatement strategy: maintaining high  
409 milk yields and milk quality whilst reducing methane production or by accepting a moderate  
410 reduction in milk yields at a lower cost of production. We demonstrate that both mechanisms  
411 may be possible and could contribute to ambitious GHG reduction targets.

412

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539

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

543

Treatment	Milk Yield (kg)	Butterfat (g kg <sup>-1</sup> )	Protein (g kg <sup>-1</sup> )	Weight (kg)	Lactation
Cut & Carry	37.5 $\pm$ 9.7	3.8 $\pm$ 1.0	3.1 $\pm$ 0.8	620 $\pm$ 160	3.5 $\pm$ 0.9
TMR	37.7 $\pm$ 9.7	3.8 $\pm$ 1.0	3.0 $\pm$ 0.8	615 $\pm$ 159	3.7 $\pm$ 0.9
Grazing	37.6 $\pm$ 9.7	3.4 $\pm$ 0.9	2.9 $\pm$ 0.8	620 $\pm$ 160	3.6 $\pm$ 0.9

544

545

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

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

550

551

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

556

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

562

563 Figure 3. Linear relationship between the frequency of chews and methane production ( $\text{CH}_4$   
564  $= 12x - 738, r^2 = 0.5, p < 0.05$ ).

565

566





