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Fox, NJ; Smith, LA; Houdijk, JGM; Athanasiadou, S; Hutchings, MR

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1 **Ubiquitous parasites drive 33% increase in methane yield from livestock**

2

3 N.J. Fox^a, L.A. Smith^{a*}, J.G.M. Houdijk^a, S. Athanasiadou^a, M.R. Hutchings^a

4 ^aSRUC, Peter Wilson Building, King's Buildings, West Mains Rd, Edinburgh EH9 3JG

5 *Corresponding author: lesley.smith@sruc.ac.uk +44 (0)131 651 9352

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24 **Abstract**

25 Of anthropogenic methane emissions 40% can be attributed to agriculture, the majority of which
26 are from enteric fermentation in livestock. With international commitments to tackle drivers of
27 climate change, there is a need to lower global methane emissions from livestock production.
28 Gastrointestinal helminths (parasitic worms) are globally ubiquitous and represent one of the
29 most pervasive challenges to the health and productivity of grazing livestock. These parasites
30 influence a number of factors affecting methane emissions including feed efficiency, nutrient
31 use, and production traits. However, their effects on methane emissions are unknown. This is the
32 first study that empirically demonstrates disease-driven increases in methane (CH₄) yield in
33 livestock (grams of CH₄ per kg of dry matter intake). We do this by measuring methane
34 emissions (in respiration chambers), dry matter intake (DMI), and production parameters for
35 parasitised and parasite-free lambs. This study shows that parasite infections in lambs can lead to
36 a 33% increase in methane yield (g CH₄/kg DMI). This knowledge will facilitate more accurate
37 calculations of the true environmental costs of parasitism in livestock, and reveals the potential
38 benefits of mitigating emission through controlling parasite burdens.

39

40 Key words: methane, greenhouse gas, climate change, parasites, disease; lambs

41 **1. Introduction**

42 Strategies for minimising global greenhouse gas (GHG) emissions from livestock systems are
43 vital. Agriculture contributes an estimated 18% of GHG emissions (Steinfeld et al., 2006), with
44 approximately half of these emissions coming from meat and dairy (Garnett, 2009). Emissions
45 are a particular concern in small ruminant (sheep and goat) milk and meat production as 56% of
46 the global domestic ruminant population are small ruminants (Marino et al., 2016), and enteric
47 fermentation is responsible for the majority of emissions in these systems (Gerber et al., 2013).
48 Minimising GHG emissions from livestock systems will become increasingly important as
49 demand for livestock products grows; by 2050 the global sheep population is expected to
50 increase by 60%, from 1.7 billion in 2000 to about 2.7 billion by 2050 (Foresight, 2011). With
51 little chance of decreasing emissions through an overall reduction in the numbers of farmed
52 ruminants, other ways to mitigate ruminant methane emissions are required (Herrero et al., 2016;
53 Dangal et al., 2017).

54
55 The primary factors affecting ruminant enteric methane emissions are thought to be feed intake
56 levels, feed composition, and the microflora of the rumen (Lascano & Cárdenas, 2010).
57 Consequently, mitigation options currently fall into three broad categories: 1) animal breeding
58 for improved efficiency; 2) feed supplements and feed management; and 3) rumen control and
59 modifiers (Marino et al., 2016). However, a number of these strategies have high costs and/or
60 inconsistent effects (Marino et al., 2016) and reliable, affordable technologies for reducing
61 methane emissions in grazing livestock in a way that improves overall farm productivity and
62 efficiency remain elusive.

63

64 Gastrointestinal helminths are globally ubiquitous, offering the most pervasive challenge to all
65 grazing livestock worldwide and compromising animal health, welfare and production
66 efficiency. They have a substantial impact on the majority of the factors affecting methane
67 production, including feed intake levels, nutrient use, and rumen retention time (Houdijk et al.,
68 2016). Controlling gastrointestinal parasites could potentially reduce GHG emissions in grazing
69 livestock. However, their effects on methane emissions are currently unknown.

70

71 In addition to revealing the mitigation potential of reducing parasitism, understanding the impact
72 of parasitism on methane production is also vital in calculating the true extent of GHG emissions
73 from livestock. Many studies have attempted to calculate the GHG emissions from livestock
74 systems, often with the aim of quantifying how changes in efficiency will impact on methane
75 production (Kipling et al., 2016; Özkan et al., 2016). Emissions estimates are generally
76 calculated based on livestock numbers, time in the production system, and basic national
77 multipliers. However, such calculations ignore the potential impacts of common infections.
78 Efforts have been made to explore the impacts of parasitism on production efficiency and time
79 on pasture, and the consequent implications for emissions (Kenyon et al., 2013). However this
80 approach assumes that methane yield remains constant regardless of infection status, and that
81 parasitism has no additional effect beyond the higher overall feed intake due to decreased
82 production efficiency and increased time to slaughter.

83

84 By quantifying how parasitism affects methane emissions per unit of feed intake, we can obtain a
85 more complete understanding of the environmental costs of parasitism and the potential benefits
86 of mitigating emission through controlling parasite burden. Here, we address this aim by

87 evaluating methane emissions per unit of feed intake in parasitised and non-parasitised finishing
88 lambs, using respiration chambers.

89

90

91 **2. Materials and methods**

92 **The protocol was conducted under Home Office licence (PPL 60/4489) and was approved**
93 **by SRUC's Animal Experiment Committee (AE ED 24-2015).**

94

95 *2.1 Animals and experimental design*

96 A total of 72 parasite naïve lambs (Suffolk x Mule), 12-15 weeks old were selected from a
97 commercial sheep flock. All animals were expected to be parasite naïve at the start of the trial,
98 as they were reared indoors and only fed commercial pelleted feed. Their parasite free status was
99 confirmed using faecal egg counts. The animals were divided into three treatment groups,
100 balanced for live weight (mean body weight at day 0 = 36.62kg ±0.35 S.E.) and sex (mixed
101 pens). These treatments were: *Ad lib* fed control ; restricted-fed control ; and parasitised .

102

103 There were a total of eight replicates for each treatment, with each replicate comprised of one
104 pen of three lambs. There were three lambs in each pen to ensure adequate eructation for
105 methane detection. The lambs were housed in indoor pens in these groups of three for the
106 duration of the trial. The trial lasted for 39 days and animals were returned to stock at the end of
107 the trial.

108

109

110 2.2 Parasite challenge

111 The animals in the parasitised treatment were trickle challenged with 7,000 infective
112 *Teladorsagia circumcincta* larvae suspended in 10ml of water, three times a week from days 0 to
113 35 (five weeks). *T. circumcincta* is an abomasal nematode which represents a substantial
114 parasitic challenge to sheep, and is often linked with parasitic gastroenteritis in lambs (Coop et
115 al., 1982). The trickle infection was used to represent the challenge encountered by grazing
116 lambs, and was expected to result in subclinical infection consistent with rates of natural
117 infection on moderately parasitised pasture (Coop et al., 1982). The *ad lib* control, and
118 restricted-fed control treatments were sham infected with 10ml of water, following the same
119 protocol as the parasitised treatment. Parasite levels were monitored through weekly faecal
120 sampling for faecal egg counts (FEC), using the modified flotation method with a sensitivity of 1
121 egg per gram of faeces (epg)(Christie & Jackson, 1982). To give an indication of gut damage by
122 *T.circumcincta*, pepsinogen levels were measured from blood samples taken at three points in the
123 trial. Blood samples were collected from all animals at day 0 (pre-challenge), day 36 (peak
124 challenge, prior to being placed in the respiration chambers), and day 39 (after removal from the
125 respiration chambers).

126

127 2.3 Feeding

128 The *ad-lib* control and parasitised treatments were fed *ad-lib* access to pelleted grass. The
129 restricted fed treatments were fed 80% of the intake of their *ad lib* fed counterparts, relative to
130 body weight. Parasite induced anorexia was expected in the parasitised treatment, hence the
131 restricted-fed control group enabled the assessment of the impact of parasitism *per se* versus that
132 of anorexia associated with parasitism. All lambs were fed their rations once a day.

133

134 *2.4 Measurements*

135

136 *2.4.1 Methane*

137 From days 43 to 46 lambs were housed in indirect open-circuit respiration chambers (No
138 Pollution Industrial Systems Ltd., UK). The trial was conducted over four rounds, using six
139 respiration chambers, with treatments balanced across each round so that each treatment was
140 tested in two respiration chambers per round. The area of each chamber is 25.4m² with penning
141 for three lambs. Temperature and humidity were set at 15 ± 1°C and 60 ± 5% respectively, and
142 air was removed from the chambers by exhaust fans set at 50litres/s. Methane concentration was
143 recorded for the air in each chamber once every six minutes, using infrared absorption
144 spectroscopy. Animals remained in the chambers for three full days (days 43 to 46), the first 24
145 hours were the adaptation period, and measurements taken during the final 48 hours (days 44-46)
146 were used to quantify methane production. Total feed intake in the chambers was measured
147 daily, and methane yield (g CH₄/kg DMI) was calculated by dividing daily methane production
148 by the daily DMI.

149

150 *2.4.2 Digestibility*

151 The collection of faeces directly from the rectum of all lambs was carried out over three
152 consecutive days (days 30 to 32), pooled per lamb, and stored at -20°C prior to digestibility
153 analysis. Acid insoluble ash (AIA) was used as an internal, indigestible marker to assess the
154 apparent total tract digestive matter (DM). Faecal and feed AIA were analysed using the 2N HCl

155 procedure (Van Keulen & Young, 1977). During feeding, feed samples were collected daily and
156 pooled for analysis.

157

158 *2.4.3 Feed intake and weight gain*

159 Pelleted feed intake was measured three times a week, to calculate the restricted-feeding
160 allowances. Feed intake was also measured daily in each respiration chamber for calculation of
161 methane yield (gCH₄/kg DMI). All lambs were weighed weekly.

162

163 *2.5 Statistical analysis*

164 Data were analysed using ANOVA, with round as the block term. For statistics pertaining to
165 body weight, day 0 body weight was included as a covariate. Daily intake values are presented
166 per animal, by dividing the total pen intake by three. All statistical analyses were performed in
167 GENSTAT 16

168 **3. Results**

169 3.1 Development of the parasite challenge

170 Lamb FEC increased over time for the parasitised treatment, indicating that parasite infections
171 were achieved in the groups dosed with *T. circumcincta*, whilst the control and restricted-fed
172 control treatments remained parasite free for the duration of the trial (Fig. 1a). Pepsinogen levels
173 were significantly higher in the parasitised group at the two sample points in the final week of
174 the trial ($P<0.001$) (Fig. 1b). These increased levels of blood pepsinogen confirmed abomasal
175 damage in the parasitised animals compared to the controls. The FEC and pepsinogen results
176 indicate that the parasitised treatment group did harbour helminth infection when in the
177 respiration chambers, whilst the *ad lib* and restricted fed control groups did not. No clinical
178 signs of parasitism were observed in any groups throughout the experiment.

179

180 3.2 Lamb performance

181 Table 1 shows the variation in performance, feed intake, and digestibility, across the three
182 treatment groups. The DMI of the parasitised group was significantly lower than the *ad lib*
183 group ($P<0.001$), indicative of parasite induced anorexia with their feed intake being an average
184 of approximately 80% of the *ad lib* control group over the study period. Maximum anorexia
185 was found in the final week of the study, where average daily DMI per animal in the parasitised
186 group was approximately 70% of the *ad lib* control group. The highest level of inappetance
187 coincided with the time of highest FEC. Average body weight gain was 174 g/day in control *ad*
188 *lib* fed individuals, whilst the average body weight gain for *ad lib* fed parasitised individuals was
189 7 g/day.

190

191 3.3 Methane output and yield

192 Methane output was significantly higher in the *ad lib* fed control group ($P < 0.001$), than in the
193 other two treatments (Fig. 2). Whilst methane emissions remained relatively steady over time in
194 the two *ad lib* fed treatments (*ad lib* control and parasitised), in the restricted fed group the
195 emissions rose steadily shortly after feeding time, before reaching a peak and declining again.

196

197 Although total methane emissions were highest in the *ad lib* fed control group, Fig. 3 reveals that
198 methane yield ($\text{g CH}_4/\text{kg DMI}$) was significantly higher in the parasitised group. Methane yield
199 was 33% higher in the parasitised lambs compared to the *ad lib* control group. Whilst there was
200 a significant difference in methane yield between the parasitised treatment group and both
201 control treatment groups ($P < 0.001$), there was no significant difference in methane yield
202 between the *ad lib* fed control group and the restricted-fed control group despite a significant
203 difference in feed intake (Fig. 3).

204 **4. Discussion**

205

206 This study aimed to quantify the impact of parasitism on methane emissions in lambs. Our
207 results show that methane yield was 33% higher in the parasitised lambs relative to the *ad lib*
208 control group. This is the first study to demonstrate that infectious disease can increase methane
209 yield (g CH₄/kg DMI).

210

211 The total quantity of methane produced per day was highest in the *ad lib* control group (Fig. 2).
212 This is because the primary driver of methane production (g CH₄/day) is dry-matter intake
213 (DMI), with a strong positive correlation between methane emissions and DMI (Buddle et al.,
214 2011). The *ad lib* control group had a significantly higher level of DMI (P<0.001), providing a
215 higher total supply of substrate for methane production in the rumen. Whilst in the respiration
216 chambers the parasitised lambs consumed 70% of the feed quantity consumed by the *ad lib*
217 control group. This reduced intake was associated with 20% less methane production in the
218 parasitised animals. Snap shot measurements of methane output would therefore show parasitism
219 being associated with a positive environmental impact. However, the methane yield (g CH₄/kg
220 DMI) was 33% higher in the parasitised animals compared to the ad-lib control group. The
221 parasitised lambs also had significantly lower weight gain compared to the controls, and would
222 require a higher overall feed intake over their lifetime to reach target weight. Whilst worldwide
223 there is a mixture of sheep management practices i.e. intensively and extensively reared lambs
224 and a variety of different nutritional environments, parasite induced anorexia is a phenomena
225 which occurs over all systems where livestock are at risk from gastrointestinal parasites
226 (Kyriazakis *et al.* 1998; Sutherland & Scott, 2010). Thus the combination of increased methane

227 yield, and higher feed intake per kg product demonstrated in this study has substantial
228 implications for the impacts of parasitism on emissions from meat production.
229

230 Low feed intake can be associated with increased methane yield, however, the methane yield
231 from the parasitised animals was higher than would be expected based solely on their lower
232 DMI (Hammond et al., 2013). Additionally, despite a significant difference in DMI between the
233 *ad lib* and restricted fed control groups, there was no significant difference in methane yield
234 between these groups (Table 1 and Fig. 3). These findings suggest that parasitism has an impact
235 on methane yield beyond that expected from changes in DMI alone. The extent of bacterial
236 fermentation is influenced by myriad elements of gastrointestinal physiology and digesta kinetics
237 (Moraes et al., 2014; Stergiadis et al., 2016). Gastrointestinal nematode infection in small
238 ruminants can lead to substantial changes in the digestive tract including increased cell turnover,
239 changes in permeability, changes in pH, altered secretory activities (e.g. mucous production),
240 and inhibited gastric acid production (Li et al., 2016; Louie et al., 2007). Some of these parasite
241 induced changes in the gastrointestinal tract will disrupt the intricate interactions between hosts
242 and their gut microbiome, as the large array of products secreted by gastrointestinal nematodes
243 impact on growth and metabolism of resident microbial communities (Zaiss & Harris, 2016).
244 However, we are only now beginning to understand the complexity of microbiota, and the effects
245 of parasitism on interactions between hosts and their gastrointestinal bacteria remain largely
246 unexplored (Buddle et al., 2011; Zaiss & Harris, 2016). Thus the effects of parasitism on
247 microbial survival, proliferation, spatial organisation, and ultimately rate of methanogenesis, are
248 yet to be understood. Whilst our results identify a novel phenomenon, they do not reveal the
249 mechanism.

250

251 In this study, weight gain was significantly lower in the parasitised group compared to that in
252 other groups. This highlights the substantial impact of parasitism on productivity, with
253 parasitised hosts needing to stay in the system much longer to reach slaughter weight. Attempts
254 have previously been made to quantify the impacts of parasitism on emissions through exploring
255 the increased time on pasture, and increased DMI required to reach slaughter weight. Without
256 accounting for the effects of parasitism on emissions per kg DMI such studies will likely
257 underestimate the full influence of parasitism on methane production. The parasite driven
258 increase in methane yield demonstrated in this study, combined with the knowledge that
259 parasitism decreases production efficiency and increases time to achieve production targets
260 (Houdijk et al., 2016; Kenyon et al., 2013), demonstrates that parasitism has the potential to have
261 substantial impacts on livestock methane emissions. In addition to emissions increasing with
262 parasitism is the concern that parasite intensity is projected to increase under climate change
263 (Fox et al., 2011, 2012, 2015).

264

265 The potential impact that parasitism has on livestock emissions makes it an attractive target for
266 mitigation. Parasite control practices (i.e. rearing indoors, clean grazing and *refugia*-based
267 control strategies), which break the parasite lifecycle, provide an opportunity to sustainably
268 reduce GHG emissions as it is cost effective, practical, and improves overall production
269 efficiency. As the increase in ovine meat production is expected to be highest in developing
270 countries (O'Mara, 2011), with restricted access to improved feeds, feed supplements and
271 efficiency gains through genetic selection, parasite control offers a viable and accessible way of
272 reducing emissions.

273

274 This study shows that parasite infections in lambs can lead to a 33% increase in methane yield.

275 Combined with impacts of parasitism on production efficiency, and the subsequent increased

276 time on pasture, there is potential for parasitism to have an extensive impact on GHG emissions.

277 There are international commitments to reduce GHG emissions, and an informed understanding

278 of how production-limiting diseases affect GHG production is vital in developing public policies

279 and combating climate change. As we improve our understanding of how parasitism affects

280 livestock methane emissions we begin to elucidate the true environmental costs of parasitism,

281 and reveal the potential benefits of mitigating emission through controlling infectious disease.

282

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289

290 **Declarations of interest**

291 None

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- 370

371 **Figure legends**

372

373 **Figure 1. Indirect measures of parasitism across all treatment groups.**

374 A) Mean faecal egg counts (FEC) (eggs/g faeces) by trial week (\pm SE), and B) mean pepsinogen
375 levels (\pm SE) at three time points, for all three treatment groups of lambs - Ad lib control (*ad lib*
376 fed), restricted fed control (fed 80% of feed intake of *ad lib* control, to account for parasite
377 induced anorexia), and parasitised lambs (also *ad lib* fed) .

378

379

380 **Figure 2. Daily mean methane output**

381 Mean methane output in A) grams per hour (\pm SE), and B) grams per day (\pm SE), for Ad lib
382 control (*ad lib* fed), restricted fed control (fed 80% of feed intake of *ad lib* control, to account for
383 parasite induced anorexia), and parasitised lambs (also *ad lib* fed), averaged across individuals.

384

385

386 **Figure 3. Mean Methane yield**

387 Mean methane yield (grams of methane per kg of dry matter intake) (\pm SE) for Ad lib control (*ad*
388 *lib* fed), restricted fed control (fed 80% of feed intake of *ad lib* control, to account for parasite
389 induced anorexia), and parasitised lambs (also *ad lib* fed).

390

391

392 **Table 1. Performance, feed intake and digestibility**

393 The mean body weight parameters, levels of feed intake, and digestibility values for *ad lib*
 394 control lambs, restricted fed control lambs, and parasitised lambs, averaged across individuals.

395 Values in rows with different letter superscripts differed significantly ($P < 0.05$).

	Treatments			Standard error	P-value
	<i>Ad lib</i> control	Restricted fed control	Parasitised		
Final BW (kg)	42.6 ^a	37.1 ^b	38.2 ^b	0.8	<0.001
BW gain (g/day) per animal	174 ^a	71 ^b	7 ^c	12.8	<0.001
Daily DMI over trial, per animal (g/day)	1783 ^a	1302 ^b	1396 ^c	28.3	<0.001
Daily DMI per kg BW over trial (g/kg BW/day)	44.6 ^a	34.4 ^b	37.0 ^c	0.98	<0.001
Digestibility Dry Matter (DM, %)	55.4	58.2	58.4	0.01	0.09

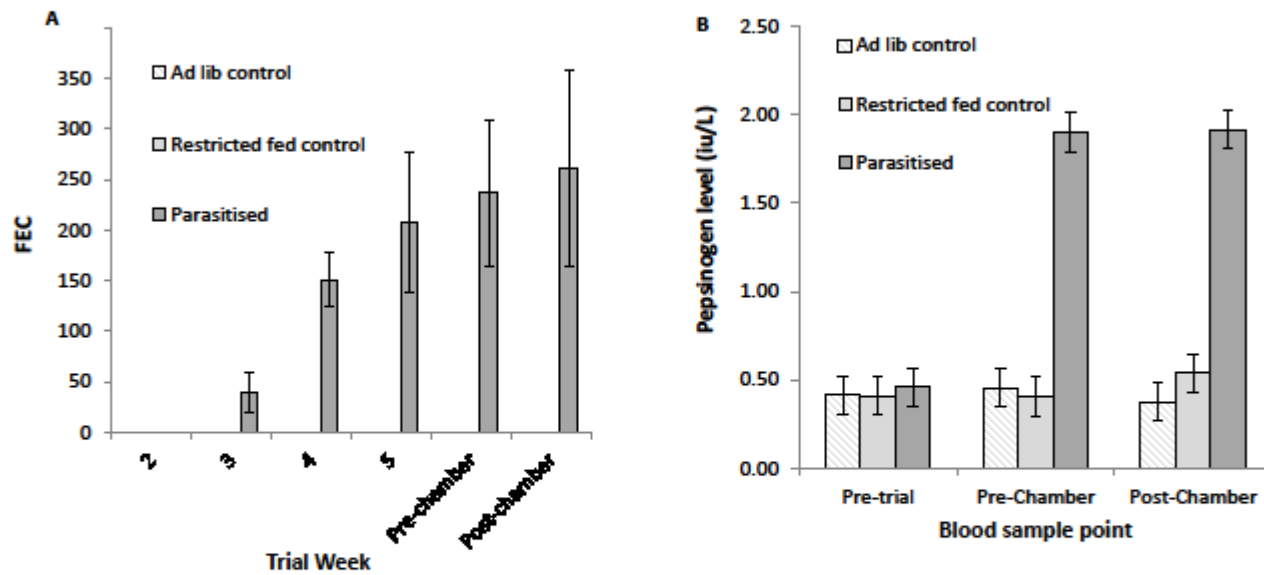


Figure 1.

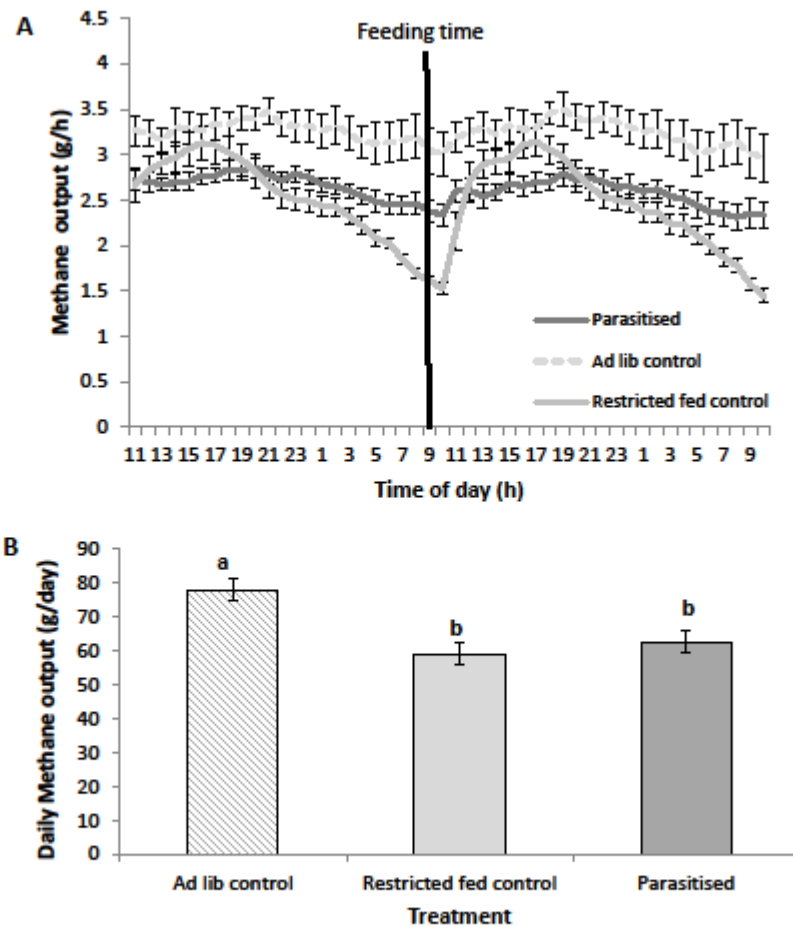


Figure 2.

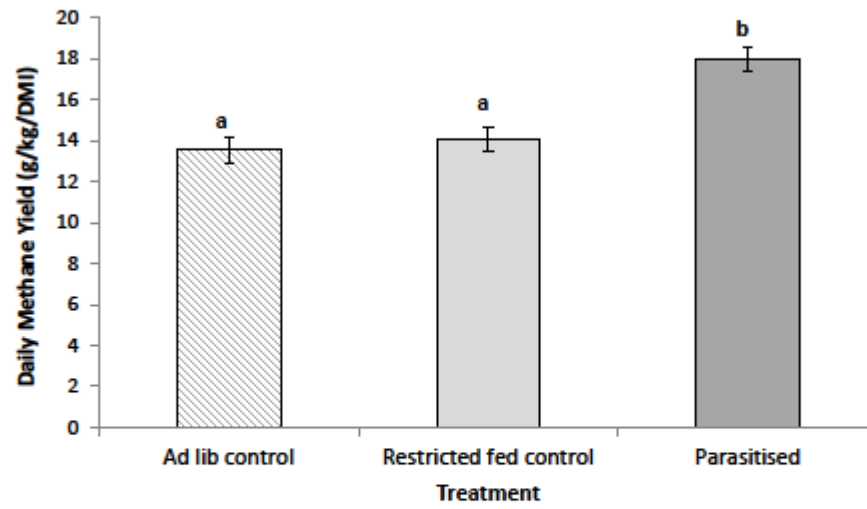


Figure 3.