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Original research article

Meta-analysis of calorimeter data to establish relationships between methane and carbon dioxide emissions or oxygen consumption for dairy cattle

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ABSTRACT

Recent developments suggest the use of other gases such as carbon dioxide (CO_2) to estimate methane (CH_4) emissions from livestock, yet little information is available on the relationship between these two gases for a wide range of animals. A large respiration calorimeter dataset with dairy cattle (n = 987 from 30 experiments) was used to investigate relationships between CH_4 and CO_2 production and oxygen (O_2) consumption and to assess whether the predictive power of these relationships could be improved by taking into account some dietary variables, including forage proportion, fibre and metabolisable energy concentrations. The animals were of various physiological states (young n = 60, dry cows n = 116 and lactating cows n = 811) and breeds (Holstein-Friesian cows n = 876, Jersey × Holstein-Friesian n = 47, Norwegian n = 50 and Norwegian × Holstein-Friesian n = 14). The animals were offered forage as a sole diet or a mixture of forage and concentrate (forage proportion ranging from 10 to 100%, dry matter basis). Data were analysed using a series of mixed models. There was a strong positive linear relationship between CH_4 and CO_2, and observations within an experiment were very predictable (adjusted R^2 = 0.93). There was no effect of breed on the relationship between CH_4 and CO_2. Using O_2 instead of CO_2 to predict CH_4 production also provided a very good fit to the observed empirical data, but the relationship was weaker (adjusted R^2 = 0.86). The inclusion of dietary variables to the observed CO_2 emissions, in particular forage proportion and fibre concentration, provided a marginal improvement to the prediction of CH_4. The observed variability in the CH_4:CO_2 ratio could only marginally be explained by animal physiological state (lactating vs. dry cows and young cattle) and dietary variables, and thus most likely reflected individual animal differences. The CH_4:CO_2 ratio can therefore be particularly useful to identify low CH_4 producing cows. These findings indicate that CO_2 production data can be used to accurately predict CH_4 emissions to generate large scale data for management and genetic evaluations for the dairy industry.

1. Introduction

Methane (CH_4) and carbon dioxide (CO_2) are important greenhouse gases (GHG), representing respectively 14 and 77% of the total anthropogenic GHG emissions estimated in 2004 (IPCC, 2007). Agricultural emissions of CH_4 account for approximately 43% of the total CH_4 from anthropogenic sources, mainly from enteric fermentation in livestock (25%) (Olivier et al., 2005). Over the past two decades, there has been a growing interest in developing predictive equations to estimate CH_4 emissions from ruminants, in order to improve the accuracy of GHG emission inventories (IPCC, 2006) and to identify viable strategies to reduce CH_4 emissions (Martin et al., 2010). A range of factors can affect enteric CH_4 production in cattle, with DM intake, metabolisable energy (ME) intake and digestible energy intake often found to be the best predictors (Yan et al., 2000; Ellis et al., 2007).

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Measurement of CH_4 production in cattle requires complex and often expensive equipment, which often limits both the number of tested animals and the length of the measurement period. As a result, a substantial level of variation is left unaccounted for by predictive models (Mills et al., 2003; Ellis et al., 2007). Hence, the use of tracers or proxy methods is becoming increasingly popular (Storm et al., 2012). Recent developments in measurement techniques to quantify gaseous exchanges for a large scale of livestock herd suggest the use of other gases such as naturally emitted CO_2 to estimate CH_4 emissions (Madsen et al., 2010; Bjerg et al., 2012). However, there is little information available on the relationship between CH_4 and CO_2 productions for a wide range of animals.

The majority of CH_4 produced in a cattle production system is from enteric fermentation, with only up to 15% produced by the manure (Hindrichsen et al., 2005). In contrast to CH_4, most (80%) of the CO_2 production comes from the metabolism of nutrients by the animal whereas only a small proportion (20%) originates from digestive fermentation (Hoernicke et al., 1965). Over the past three decades, a number of metabolism studies have been carried out on dairy cows using calorimetric chambers, thus providing very good estimates of total productions of CH_4 and CO_2 from animals of different breeds and live weights, subjected to a wide range of feeding regimes (Kirchgessner et al., 1991; Gordon et al., 1995; Yan et al., 2010). However, most of these studies have focused on factors affecting the production of CH_4, and few attempts have been made to relate it with the production of CO_2 or the consumption of oxygen (O_2).

Recently, several studies have reported a good correlation between CO_2 and CH_4 emissions at an individual animal level (Liu et al., 2012) and a whole barn level (Kinsman et al., 1995; Ngwabie et al., 2011; Bjerg et al., 2012). The dataset used in the present study was obtained from 30 feeding experiments using dairy cattle in calorimetric chambers. Unlike previous meta-analyses (e.g., Kirchgessner et al., 1991; Holter and Young, 1992), the data included in the present study represent a large number of different animals (393) at various physiological states (young cattle and dry and lactating cows), thus resulting in a wide range of CH_4 emissions (98 to 793 L/d). The objectives of the study were to use the gas measurements from these experiments to investigate the relationships between CH_4 and CO_2 productions, and to assess whether the predictive power of these relationships could be improved by taking into account some dietary variables, including diet forage proportion (FP), fibre and ME concentrations. A further objective was to investigate the relationships between CH_4 production and O_2 consumption, because O_2 consumption is related to CO_2 production and can also be used to estimate the energy expenditure of animals (Brouwer, 1965).

2. Material and methods

2.1. Animals and diets

Since 1992, a number of young cattle and dry and lactating dairy cows ($n = 987$) were subjected to gaseous exchange measurements in calorimetric chambers at the Agri-Food and Biosciences Institute. The animals used in the present study were of various physiological states (young $n = 60$, dry cows $n = 116$ and lactating cows $n = 811$) and breeds (Holstein-Friesian cows $n = 876$, Jersey × Holstein $n = 47$, Norwegian $n = 50$ and Norwegian × Holstein-Friesian $n = 14$). The animals were drawn from 30 feeding experiments and were offered forage alone as a sole diet ($n = 161$, i.e., 16% of all observations) or a mixture of forage and concentrate FP ranging from 10 to 100%, DM basis). A summary of the gas measurements and diet data obtained per animal is presented in Table 1.

Gaseous exchanges (CH_4 and CO_2 exhaled, O_2 inhaled) were measured using indirect open-circuit respiration calorimetric chambers. Prior to commencing energy metabolism measurements, all cows were offered the experimental diets for at least three weeks in group-housed pens in cubicle accommodation. Each animal was then subjected to a 3-to-4 day balance measurement with total faeces and urine outputs being collected. Immediately after completion of the balance measurements, each animal was transferred to respiration calorimeters. The animals remained in the chambers for 3 to 5 days, with measurement of gaseous exchange over the final 2 to 4 days. All equipment, procedures, analytical methods and calculations used in the calorimetric experiments were as reported by Gordon et al. (1995), and calibration of the chambers by Yan et al. (2000).

2.2. Statistical analyses

Preliminary analyses indicated that CH_4 and CO_2 productions, O_2 consumption, diet acid detergent fibre (ADF), neutral detergent fibre (NDF) and ME concentrations were normally distributed and that no transformation was required. In contrast, 16% of the animals used in the study were offered forage only diets. As a result, a factor FP was included in the analyses as a categorical variable with four categories: FP ≤ 25% ($n = 47$), 25% < FP ≤ 50% ($n = 437$), 50% < FP ≤ 75% ($n = 236$) and FP > 75% ($n = 267$).

The relationship between CH_4 and CO_2 (or O_2) was examined using the linear regression technique. Overall, 393 different cows were used across all experiments, and, depending on the experiment, each animal was used either once or up to six times per experiment when there were different treatments. As a result, data were analysed using a linear mixed effects model fit by REML, with CH_4 as the response variable, CO_2 or O_2 as a fixed effect, experiment and "cow within experiment" as random effects. A fixed factor 'physiological state' was also included in each model to differentiate between lactating cows ($n = 811$ from 27 experiments) and a second group of animals which included dry cows ($n = 116$ from five experiments) and young animals (30 heifers and 30 steers from one experiment). Preliminary analyses indicated that the best random structure was with a common slope and different intercepts for each experiment. The minimal model thus describes CH_4 production y_{ijk} from cow j within experiment i (kth value for cow j) using the equation:

$$y_{ijk} = a + bx_{ijk} + phys_g + expt_i + cow_{ij} + \varepsilon_{ijk},$$

where a = the overall constant, x_{ijk} = the kth value for CO_2 production from cow j within experiment i, b = the overall regression coefficient for CO_2 production across all experiments, $phys_g$ = the effect of the physiological state g (where g is the physiological state of unit ijk), $expt_i$ = the random effect of experiment i, cow_{ij} = the random effect of cow j within experiment i, ε_{ijk} = the residual error for unit ijk.

All random effects were assumed to be normally distributed: N $(0,\sigma^2)$, where σ^2 is the variance of each random effect.

Firstly, the relationship between CH_4 and CO_2 (or O_2) was examined (see "observed" values in Fig. 1). Secondly, a series of models were obtained by adding one or two dietary variables to CO_2 (or O_2), which included FP, diet ADF (kg/kg DM), NDF (kg/kg DM) and ME (MJ/kg DM). Lastly, the variability of the CH_4:CO_2 ratio (with both gases expressed in litres per day) was investigated, also using mixed models.

To assess the goodness of fit between the different models, the Akaike information criterion (AIC) was calculated for each model, with the lowest AIC representing the model with the best fit to the observed data. Differences in AIC were used to compare the strength of evidence between models, with differences greater than 10 units (ΔAIC > 10) indicating considerable more support