Animal Nutrition 1 (2015) 329–338

Contents lists available at ScienceDirect

Animal Nutrition

journal homepage: http://www.keaipublishing.com/en/journals/aninu/

Original research article

A mathematical model to describe the diurnal pattern of enteric methane emissions from non-lactating dairy cows post-feeding

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
9 November 2015
Accepted 12 November 2015
Available online 28 November 2015

Keywords:
Methane
Logistic–exponential model
Methanogen
Rumen

ABSTRACT

Enteric methane emission is not only a source of energy loss in ruminants, but also a potent contributor to greenhouse gas production. To identify the nature and timing of interventions to reduce methane emissions requires knowledge of temporal kinetics of methane emissions during animal husbandry. Accordingly, a mathematical model was developed to investigate the pattern of enteric methane emissions after feeding in dairy cows. The model facilitated estimation of total enteric methane emissions (V, g) produced by the residual substrate (V_1, g) and newly ingested feed (V_2, g). The model was fitted to the 10 h methane emission patterns after morning feeding of 16 non-lactating dairy cows with various body weights (BW), and the obtained parameters were used to predict the kinetics of 24 h methane emission for each animal. The rate of methane emission (g/h) reached a maximum within 1 to 2 h after feeding, followed by a gradual post-prandial decline to a basal value before the next feeding. The model satisfactorily fitted curves for each cow according to the criterion of goodness-of-fit, and provided biological descriptions for fluctuations in methane emissions based on basal V_1 and feeding V_2 in response to the changes in BW and dry matter intake (DMI) of different dairy cows. The basal V_1 and feeding V_2 are probably maintained by slow- and readily-degradable substrates, respectively. The former contributed at least 0.6 of methane production. In summary, the model provides a means to separate basal V_1 and feeding V_2 within V, and can be used to predict 24 h emission from a single feeding period.

1. Introduction

The rumen is an important organ for degradation of feeds to produce volatile fatty acids (VFA), ammonia, and methane and for the production of microbial cells. Methane emissions represent an energy loss of 2 to 12% of gross energy intake (Johnson and Johnson, 1995). High enteric methane emissions not only indicate an inefficiency of energy utilization by the animal, but also are a potent source of greenhouse gases that trap heat in the atmosphere. Over recent decades, a number of mathematical models have been developed to estimate the amount of daily enteric methane production in ruminants, based on either mechanistic or regression equations (Bannink et al., 2011; Benchaar et al., 1998; Ellis et al., 2009). However, few studies have been conducted using models to investigate the diurnal pattern of enteric methane emissions from ruminants. Such information may be important as various strategies are considered to reduce methane production by ruminants.

Methane is produced through the activity and growth of methanogens in the rumen, and the diurnal pattern of enteric methane emissions is dependent on both the amount of feed ingested and the feeding pattern (IPCC, 2006; Johnson and Johnson,

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Peer review under responsibility of Chinese Association of Animal Science and Veterinary Medicine.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.aninu.2015.11.009

1995; Martin et al., 2010). Enteric methane emissions increase after feeding, reach a maximum and then gradually decrease to the pre-feeding (basal) level (van Zijderveld et al., 2010, 2011). The aim of the present study was to develop a model to describe the temporal pattern of enteric methane emissions and thus identify the contribution of the various processes to total methane emission. Empirical data from non-lactating dairy cows were individually fitted to a mathematical model, and the corresponding parameters were used to predict daily methane emission in non-lactating cows. In particular, the proportional responses in basal and feeding methane emissions to variations in dry matter intake (DMI) and body weight (BW) were explored.

2. Materials and methods

2.1. The model

The parameters for the model development are summarized in Table 1. Methane is emitted during the metabolism of methanogens that use hydrogen as an energy source, and this hydrogen is produced mainly during fermentation of degradable substrate by microorganisms in the rumen (Wang et al., 2013a). Methane emission rate ($\mathrm{d}V/\mathrm{d}t$, g/h) is assumed to be proportional to methanogen mass (M_r, g), activity of methanogens and degradable substrate (S_r, g) in the rumen, and is expressed as:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \alpha\beta_M M_r S_r, \quad (1)$$

where α is a proportionality constant [/(h·g)], β_M is the activity of methanogens linking the methane production and methanogen mass (g/g).

The substrate in the rumen was separated into two components: newly ingested and the residue, representing potential nutrient sources from the current and previous feeding, respectively. The total enteric methane produced associated with these feed fractions was a combination of that produced from use of residual (basal) substrate (V_1) and newly ingested (V_2) feed in the rumen. Many studies indicate that the methanogens grow only slowly, and the population does not increase much within a 12 h time window (Khelaifia et al., 2013; Sakai et al., 2009). Indeed, it was reported that the population of methanogens had the density of 4×10^8 to 8×10^8/g of rumen content and remained constant post-prandially (Leedle and Greening, 1988). Therefore, the current model assumes that changes in methane emissions are a response to substrate supply and activity of the methanogens, while methanogen mass (M_r) was assumed fixed for an individual animal on a particular ration. The rate of enteric methane emission, thus, can be expressed as follows:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\mathrm{d}V_1}{\mathrm{d}t} + \frac{\mathrm{d}V_2}{\mathrm{d}t}, \quad (2)$$

$$\frac{\mathrm{d}V_1}{\mathrm{d}t} = \alpha_1\beta_{M1} M_r S_{rr}, \quad (2a)$$

$$\frac{\mathrm{d}V_2}{\mathrm{d}t} = \alpha_2\beta_{M2} M_r S_{Ir}, \quad (2b)$$

where α_1 and α_2 are proportionality constants [/(h·g)] for basal V_1 and feeding V_2, respectively; β_{M1} is the activity of methanogens to generate basal V_1; S_{rr} is the amount of degradable substrate in the residue of rumen before feeding (g); β_{M2} is the activity of methanogens to generate feeding V_2; S_{Ir} is the amount of degradable substrate in the rumen from the newly ingested feed (g).

Both S_{rr} and S_{Ir} are impacted by the ruminal passage rate (k_p) (Dijkstra et al., 1992), and will be zero as '$t \to +\infty$'. As a result, the rate of methane emission will theoretically be zero at '$t \to +\infty$' based on Eq. (1). However, in the livestock husbandry, both S_{rr} and S_{Ir} will not be zero under normal feeding regimes. In practice, a proportion of new feed ingested will become a part of S_{rr} in the next feeding, and contribute to the portion lost by passage rate. So, we assumed that the replacement (by feeding) and outflow of S_{rr} were in approximate balance under any specific feeding regime, so that the S_{rr} could be given a fixed value.

The activity of methanogens is positively correlated to hydrogen produced (Janssen, 2010). The hydrogen itself is positively correlated to the amount of degradable substrate in the rumen (Leedle

Table 1
Explanation of the selected terms during the development of the model.

Term	Unit	Explanation
V	g	Volume of enteric methane emission
V_1	g	Volume of enteric methane emission generated by the residual substrate in the rumen
V_2	g	Volume of enteric methane emission generated by the newly ingested feed
$\mathrm{d}V/\mathrm{d}t$	g/h	Rate of enteric methane emission
$\mathrm{d}V_1/\mathrm{d}t$	g/h	Rate of enteric methane emission for basal V_1
$\mathrm{d}V_2/\mathrm{d}t$	g/h	Rate of enteric methane emission for feeding V_2
α	/(h·g)	Proportionality constant
α_1	/(h·g)	Proportionality constant for basal V_1
α_2	/(h·g)	Proportionality constant for feeding V_2
β_M	–	Activity of methanogens
β_{M1}	–	Activity of methanogens to generate basal V_1
β_{M2}	–	Activity of methanogens to generate feeding V_2
S_r	g	Degradable Substrate in the rumen
S_{rr}	g	Degradable substrate in the residue in the rumen before feeding
S_{Ir}	g	Degradable substrate in the rumen from the newly ingested feed
S_I	g	Degradable substrate from newly ingested feed
S_{Ie}	g	Degradable substrate from newly ingested feed which outflow from rumen
M_r	g	Methanogens in the rumen
k_p	/h	Ruminal passage rates
S_T	g	Potential degradable substrate in the newly ingested feed
VF_2	g	Final asymptotic accumulated enteric methane emissions for feeding V_2
γ	g/h	Shape parameter
d	–	Shape parameter
a	g	Shape parameter