ENTERIC METHANE EMISSIONS FROM DAIRY AND BEEF CATTLE: A META-ANALYSIS

by

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Abstract

This study reviewed state-of-the-art cattle enteric methane (CH_4) emissions with three reported measuring units: g/head/d, g/kg DMI (dry matter intake), and %GEI (gross energy intake). Cattle emissions studies included in this meta-analysis were reported from 1995 to 2013. Fifty-five published studies were analyzed with specific objectives: (1) to gain basic information regarding magnitudes and distributions of enteric CH_4 emission rates with various units, regions, cattle types and feed situations; (2) to identify and evaluate effects of influence factors or diet mitigation techniques on enteric CH_4 emissions; and (3) to evaluate Intergovernmental Panel on Climate Change (IPCC) approaches to estimate enteric CH_4 emissions.

Emissions data (n=165) with the unit of g/head/d had large variances and non-normal distribution, and were not homogeneous across the studies. Emissions data (n=134) with the unit of g/kg DMI were not homogeneous across the studies, while emissions data (n=76) with the unit of %GEI had small variances and normal distribution, and were homogeneous across the studies. Therefore, data with the unit of %GEI may be better for meta-analysis compared to data with the units of g/head/d and g/kg DMI; however, the number of data with the unit of %GEI was small relative to the number of data with the units of g/head/d and g/kg DMI.

Enteric CH_4 emissions with the unit of g/head/d are significantly influenced by geographic region, cattle classification, sub-classification, humidity, temperature, body weight, and feed intake. Emissions and feed intake had a strong positive linear relationship with R^2 of 0.75 (n=148). Emissions with the unit of g/kg DMI are significantly affected by humidity, body weight, and feed intake. The relationship between emissions and feed intake is positive. Emissions with the unit of %GEI are significantly associated with humidity, production stage, and body weight.

IPCC Tier 1 and Tier 2 estimated emissions were approximate to most of the measured enteric CH_4 emissions; however, the residuals were not normally distributed. Based on results from PRD method and paired t-tests, IPCC Tier 1 overestimated emissions in Asian studies, underestimated emissions in European studies for beef cattle, and underestimated emissions in Oceanian studies for dairy cattle. IPCC Tier 2 underestimated emissions in Asian studies for beef cattle. The underestimated emissions of IPCC Tier 2 in Asian studies might result from no consideration of effects from production stage and body weight.

Table of Contents

Abstract I

Table of Contents iii

List of Figures v

List of Tables vii

Acknowledgements ix

Chapter 1 - INTRODUCTION 1

1.1 INTRODUCTION 1

1.2 OBJECTIVES 2

Chapter 2 - LITERATURE REVIEW 4

2.1 MEASUREMENT OF ENTERIC METHANE EMISSIONS FROM CATTLE 4

2.1.1. Methane Concentration 4

2.1.2. Methane Sampling 6

2.2 EMISSION MODELS OF ENTERIC METHANE FROM CATTLE 9

2.2.1 Mechanistic Models 9

2.2.2 Empirical (Statistical) Models 11

2.2.3 Mechanistic Models VS Empirical (Statistical) Models 14

2.2.4 Intergovernmental Panel on Climate Change Approaches (2006) 15

2.3 MITIGATION STRATEGIES OF ENTERIC METHANE EMISSIONS FROM CATTLE17

2.3.1 Concentrates within the Diet 17

2.3.2 Forage Quality 18

2.3.3 Dietary Additives 18

2.3.4 Plant Secondary Compounds 19

2.4 META-ANALYSIS 21

2.4.1 A Brief History and Application of Meta-Analysis 21

2.4.2 Designing Meta-Analysis 22

2.4.3 Meta-Analysis in Systematic Review of Livestock Methane Emissions 25

Chapter 3 - METHODS 27

3.1 Literature Search 27

3.2 Data Extraction 28

3.3 Data analysis.. 31
3.3.1 Aim 1: Statistics of Enteric CH_4 Emission Rates 31
3.3.2 Aim 2: Effects of Variables on Enteric CH_4 Emissions Rates 32
3.3.3 Aim 3: Evaluation of the Intergovernmental Panel on Climate Change Approaches..... 32
Chapter 4 - RESULTS AND DISCUSSION 34
4.1 Aim 1: Statistics of Enteric CH_4 Emission Rates.. 34
4.1.1 Statistics of Enteric CH_4 Emission Rates with Various Units.. 34
4.1.2 Statistics of Enteric CH_4 Emission Rates from Various Geographic Regions................ 36
4.1.3 Statistics of Enteric CH_4 Emission Rates from Dairy and Beef Cattle 40
4.1.4 Statistics of Enteric CH_4 Emission Rates from Various Feed Situations........................ 42
4.1.5 Comparison variations in means of enteric CH_4 emission rates between various regions, cattle types, and feed situations 43
4.2 Aim 2: Effects of Variables on Enteric CH_4 Emissions Rates 44
4.2.1 Overall Analysis of Variables' Effects on Enteric CH_4 Emissions Across the Studies .. 44
4.2.2 Analysis of Significant Variables on Enteric CH_4 Emissions 45
4.2.3 Analysis of Variables of Sub-classification and Production Stage on Enteric CH_4 Emissions.. 56
4.2.4 Analysis of Diet mitigation Strategies on Enteric CH_4 Emissions................................. 63
4.3 Aim 3: Evaluation of the Intergovernmental Panel on Climate Change Approaches........... 69
4.3.1 Overall Comparison of Measured Emissions and IPCC (2006) Estimated Emissions ... 69
4.3.2 Comparison of Measured Emissions and IPCC (2006) Estimated Emissions on study-level and on region-level 74
4.3.3 Causes of ineffectiveness of IPCC Tier 1 and Tier 2 87
Chapter 5 - CONCLUSIONS 88
5.1 Aim 1: Statistics of Enteric CH_4 Emission Rates.. 88
5.2 Aim 2: Effects of Variables on Enteric CH_4 Emission Rates... 88
5.3 Aim 3: Evaluation of the Intergovernmental Panel on Climate Change Approaches........... 90
5.4 Research Implications and Future Work 91
References 116

List of Figures

Figure 4-1 Box plot for enteric CH_4 emission rates with three units 35
Figure 4-2 Box plot for enteric CH_4 emission with various regions when the unit is g/head/d .. 36
Figure 4-3 Box plot for enteric CH_4 emissions with various regions when the unit is g/kg DMI38
Figure 4-4 Box plot for enteric CH_4 emissions with various regions when the unit is % GEI.... 39
Figure 4-5 Box plot for enteric CH_4 emissions from dairy and beef cattle 41
Figure 4-6 Relationship between enteric CH_4 emissions and temperature when the unit is g/head/d 46
Figure 4-7 Relationship between enteric CH_4 emissions and humidity when the unit is g/head/d 47
Figure 4-8 Relationship between enteric CH4 emissions and cattle body weights when the unit is g/head/d 48
Figure 4-9 Relationship between enteric CH4 emissions and feed intakes when the unit is g/head/d 49
Figure 4-10 Relationship between enteric CH_4 emissions and humidity when the unit is g/kg DMI 50
Figure 4-11 Relationship between enteric CH4 emissions and cattle body weights when the unit is g/kg DMI 51
Figure 4-12 Relationship between enteric CH4 emissions and feed intakes when the unit is g/kg DMI 52
Figure 4-13 Relationship between enteric CH_4 emissions and humidity when the unit is %GEI53
Figure 4-14 Relationship between enteric CH_4 emissions and cattle body weights when the unit is %GEI 54
Figure 4-15 Box plot of differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the total cattle data pool 69
Figure 4-16 Box plot of differences between measured emissions and IPCC (2006) estimated emissions based on the beef cattle data pool 71
Figure 4-17 Box plot of differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the dairy cattle data pool 72

Figure 4-18 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 1 estimated emissions based on the total cattle data pool across the studies 75
Figure 4-19 Forest plot of the differences between measured enteric CH_4 emissions and IPCC (2006) Tier 2 estimated emissions for all types of cattle across the studies 77
Figure 4-20 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 1 estimated emissions for beef cattle by regions (kg/head/day).................................... 79
Figure 4-21 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 2 estimated emissions for beef cattle by regions (% GEI) 81
Figure 4-22 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 1 estimated emissions for dairy cattle by regions (kg/head/day) 83
Figure 4-23 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 2 estimated emissions for dairy cattle by region (% GEI)................................. 85

List of Tables

Table 2-1 Empirical (statistical) models used to predict enteric CH_4 emission from cattle........ 12

Table 2-2 Checklist for meta-analysis (Russo, 2007).. 24

Table 2-3 Qualities of meta-analysis application in livestock methane emissions...................... 26

Table 3-1 Literature search... 27

Table 3-2 Data extraction protocol.. 29

Table 4-1 Statistics of enteric CH_4 emission rates with three different units 34

Table 4-2 Normality test for CH_4 emission rates with various units.. 35

Table 4-3 Homogeneity test for CH_4 emissions with various units between studies 36

Table 4-4 Statistics of enteric CH_4 emission rates with various types of cattle........................... 41

Table 4-5 Statistics of enteric CH_4 emission rates with various feed situation............................ 42

Table 4-6 RSDs of means of enteric CH_4 emission rates between various regions, cattle types, and feed situations... 43

Table 4-7 Results of overall analysis of variables' effects on enteric CH_4 emissions from all types of cattle 44

Table 4-8 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for all cattle at various regions when the unit is g/head/d.. 45

Table 4-9 Regression models between enteric CH_4 emissions and significant numeric variables 56

Table 4-10 Analysis results of effects from sub-classification and production stage on enteric CH_4 emissions when the unit is g/head/d... 57

Table 4-11 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for sub-classifications of dairy when the unit is g/head/d.. 58

Table 4-12 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for dairy at production stages when the unit is g/head/d.. 59

Table 4-13 Results of effects from sub-classification and production stage on enteric CH_4 emissions when the unit is g/kg DMI 60

Table 4-14 Results of effects from sub-classification and production stage on enteric CH_4 emissions when the unit is %GEI 61

Table 4-15 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for beef at production stages when the unit is %GEI 62
Table 4-16 Effects from variables of sub-classification and production stage on enteric CH_4 emissions 62
Table 4-17 Effectiveness of various concentrate proportions on enteric CH_4 emission reduction 63
Table 4-18 Regression models between relative reduction percentages in enteric CH_4 emissions and concentration proportions within the diet 64
Table 4-19 Effectiveness of various chemicals on enteric CH_4 emission reduction 65
Table 4-20 Overall effectiveness analysis of feed additive or plant secondary compound mitigation 68
Table 4-21 Normality test for differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on total cattle data pool 70
Table 4-22 Normality test for differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the beef cattle data pool 71
Table 4-23 Normality test for the differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the dairy cattle data pool 73
Table 4-24 Summary of different IPCC estimated approaches for all types of cattle on region-level 78
Table 4-25 Summary of different IPCC estimated approaches for beef cattle on the region-level 82
Table 4-26 Summary of IPCC estimated approaches for dairy cattle on region level 86

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Chapter 1 - AINTRODUCTION

1.1 INTRODUCTION

CH_4 (methane) is a greenhouse gas (GHG) which absorbs heat, consequently creating the issue of global warming (U.S.EPA, 2013). According to the 2014 U.S. (United States) inventory report of GHGs, total emission of CH_4 was 564.4 Tg CO_2-eq (8.7% of total GHGs), while total emission of CO_2 was 5,376.9 TgCO_2-eq (82.7% of total GHGs). CH_4 was emitted in smaller quantities compared to CO_2; however, CH_4 emission is significant because it has high global warming potential (GWP) and long atmospheric lifetime.

Significant sources of CH_4 include enteric fermentation in domestic livestock, livestock manure management and storage, rice cultivation and agricultural soil management. Among significant CH_4 sources, enteric fermentation in farm animals is the largest emission source and represents 25% of total emissions from the agricultural sector (U.S.EPA, 2013). Of all farm animal types, beef and dairy cattle are the largest emitters of CH_4 and one of the main factors contributing to the GHG increase since 1990 (U.S.EPA, 2013).

Enteric CH_4 is a result of microbial fermentation in the gut. In ruminants, the majority (95%) of CH_4 is released with livestock breathing, while a smaller proportion is produced and expelled from the hindgut (Takenaka, 2008). Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories was revised in 1996, so a lot of research paid attention to CH_4 emission reduction as it pertains to global warming. Even before 1996, animal scientists viewed CH_4 as energy loss and interest in decreasing CH_4 emission primarily focused on increasing energetic efficiency. Therefore, many studies have investigated results of enteric CH_4 emission, specifically enteric CH_4 emission estimation and mitigation strategies;

however, in general, a research topic for individual study is narrow and it is difficult to discern relationship between various regions, cattle types, and etc.

In addition, Intergovernmental Panel on Climate Change (IPCC, 2006) has developed guidelines for estimating and reporting emissions of GHGs. IPCC Tier 1 and Tier 2 are the methodology to estimate enteric CH_4 emissions. Tier 1 methodology is the simplest calculation that utilizes default emission factor (EF) (kg CH_4/ head/year) value in order to estimate enteric CH_4 production. IPCC Tier 1 is characterized by region-specific research and cattle category Tier 2 methodology calculates CH_4 production based on gross energy intake (GEI) of the animal and default CH_4 conversion factor (Ym, % GEI). Default Ym values proposed by IPCC (2006) are 6.5 $\pm$1 for beef and dairy cattle and 3$\pm$1 for feedlot cattle. The methodologies are relatively crude. EFs or Ym, to a large extent, are based on expert judgment of the IPCC Expert Group. Therefore, the effectiveness of IPCC estimation and factors influencing the effectiveness are concerned.

Meta-analysis is a quantitative statistical analysis of a large collection of results from various individual studies in order to answer study questions, such as pattern identifications, sources of disagreement among study results, or others relationships. Study results of enteric CH_4 emission from cattle provide opportunity for meta-analysis.

1.2 OBJECTIVES

Objectives of this thesis attempt to present a systematic review of state-of-the-art cattle enteric CH_4 emissions and corresponding mitigation strategies. Meta-analysis is proposed to obtain the following research aims：

(1) To obtain basic information regarding magnitudes and distributions of enteric CH_4 emission rates from previous studies through meta-analysis by various units, regions, cattle types, and feed situations.

(2) To identify and evaluate the effects of influence factors or mitigation techniques on enteric CH_4 emissions. Influence factors include environmental variables, cattle characteristics, feed situation, and feed intake. Mitigation techniques include concentrates' effects, dietary additives, and plant secondary compounds. This section allows for a wider-range of conclusions which integrate study variables, and the results of this section provide relevant information for future research on order to improve and expand current knowledge about enteric CH_4 emissions. In addition, results of this section also could become a resource and offer guidelines for farmers or environmental engineers in order to reduce enteric CH_4 emissions.

(3) To evaluate Intergovernmental Panel on Climate Change (IPCC) approaches to predict enteric CH_4 emissions based on measured data from studies by different cattle types, geographic regions, and overall. Results highlight the effectiveness and ineffectiveness (e.g., overestimation or underestimation) of IPCC approaches to various cattle types, different geographic regions and overall. Results of IPCC ineffectiveness can also provide suggestions to update emission factors of IPCC.

Chapter 2 - LITERATURE REVIEW

2.1 MEASUREMENT OF ENTERIC METHANE EMISSIONS FROM CATTLE

2.1.1. Methane Concentration

Several techniques have been used to determine CH_4 concentration, including gas chromatography, mass spectroscopy, infrared analyzers, and tunable laser diode absorption spectroscopy (Johnson et al., 1995) .

Gas chromatograph (GC) equipped with thermal conductivity or a flame ionization detector is one of the widely used techniques to measure CH_4 concentration. The principle is based on individual partitioning characteristics of various gases in the sample between a mobile phase (an inert gas such as Helium) and a stationary solid phase packed in a column. The CH_4 concentration can be determined by comparing the peak height and retention time of the sample to standards of known concentration. This technique is highly accurate and precise. Relative error is 1.1%, and detection limits can be below 200 ppb (parts per billion) (Van der Laan et al., 2009).

Mass spectrometers may also be used to measure CH_4 concentration. These instruments have very rapid response times and can simultaneously detect many gases (McLean et al., 1987). They exhibit accurate and stable linear responses over a wide range of concentrations. The relative error is less than 1%; however, mass spectrometers are expensive and the cost often exceeds that of other analyzers.

An infrared analyzer or infrared (IR) photo acoustic spectrometer-trace gas analyzer measures CH_4 in the range of 0-100ppm (parts per million) in a steady gas stream. The principle of this technique, as described by Yamulki (1999), includes a gas sample contained in a sealed cell and irradiated with chopped IR light of a selected wavelength. The wavelength, specifically absorbed by the gas to be studied, is selected using filters. Energy absorbed by the gas increases in its temperature and pressure. Chopped IR light causes a series of pressure pulses in the cell, which are detected by microphones. Voltage generated by the microphones is proportional to gas concentration in the cell. Laboratory inter-comparison between the IR analyzer and GC measurements of CH_4 standards show good agreement (R^2>0.9993) (Yamulki et al., 1999). Advantages of this technique are portability and in-line measurement; however, this kind of instruments is very expensive and sensitive to gas humidity (Xiong et al., 2008).

Tunable laser diode absorption spectroscopy may also be used to measure CH_4 concentration. It is based on absorption of an IR laser beam as it travels along a path through the gas sample. Sensitivity of the tunable diode laser depends on the path according to length and the strength of the absorption line, with highest detection sensitivities for gas having strong absorption lines in the spectral region emitted by the laser (Kan et al., 2005). Typical laser emission line widths are small compared to typical absorption line widths, and a high spectral resolution could be achieved in resolving individual absorption lines at atmospheric and low pressures, without interference from other gases; however, the tunable laser diode is an expensive technique and the expense may limit its usefulness.

2.1.2. Methane Sampling

Enclosure techniques and tracer methods are two common kinds of enteric CH_4 sampling.

2.1.2.1 Enclosure Techniques

Enclosure techniques of enteric CH_4 emission from cattle, or respiration calorimeter techniques, include whole animal chambers, ventilated hoods or head boxes, and face masks.

Whole animal chamber systems are elaborate, highly computerized systems in order to control the environment inside the chamber (Chaokaur, 2011; Powers et al., 2008). The principle of whole animal chamber systems, such as open-circuit indirect-respiration techniques, is that in-flowing air is circulated around the animal's head, mouth, and nose and the out-flowing air is collected (Grainger et al. , 2007). CH_4 emission is determined by measuring total air flow through the system and the concentration difference between in-flowing and out-flowing air. Miller and Koes (1988) presented various types of chambers and correlating design. A primary advantage of chambers is the ability to accurately measure cattle emissions, including ruminal and hindgut fermentation. A disadvantage of this technique is cost related to the expenses associated with chamber construction and maintenance, the restriction of animal movement, and high labor input for animal training.

Ventilated hoods or headboxes can also be used to quantify CH_4 emission using the same principles (Chaokaur, 2011; Suzuki et al., 2007). This technique involves the use of an air-tight box which surrounds the animal's head. The box is big enough to allow the animal to move its head in an unrestricted manner and allows access to feed and water. A sleeve or drape is placed around the neck of the animal to minimize air leakage. The primary advantage of this technique is relatively lower cost compared to a whole animal chamber. However, the use of a hood requires a restrained and trained animal and this technique is unable to measure all hindgut CH_4.

Ventilated hoods or headboxes, compared with whole chamber systems, underestimate CH_4 by approximately 5 % (Takenaka, 2008).

Face masks may also be used to quantify CH_4 production (Liang et al., 1989). The principle behind the use of a face mask is the same as that of the chamber and hood. The disadvantages of this method are numerous because it requires subject cooperation and eliminates the animal's ability to eat and drink, consequently eliminating the ability to obtain meaningful CH_4 emission measurements because of normal daily variation in emissions. Short-term measurements should be avoided as much as possible. Compared to chamber methods, the face mask also underestimates CH_4 at least about 5% (Takenaka, 2008).

2.1.2.2 Tracer Techniques

ERUCT (Emissions from Ruminants Using a Calibrated Tracer) technique is another method commonly used to estimate CH_4 emission. ERUCT technique includes isotopic and non-isotopic tracer techniques (Johnson et al., 1995). Isotopic tracer techniques generally require simple experimental designs and relatively straightforward calculations, at least for lower number pools (Johnson et al., 1995). Isotopic methods involve the use of (3H-) CH_4 or (14C-) CH_4 on ruminally cannulated animals (J France et al., 1993; Murray et al., 1975). Using the continuous infusion technique, infusion lines deliver labeled gas to the ventral part of rumen and gas sampling occurs in the dorsal rumen. After determining specific activity of the radio-labeled CH_4 gas, total CH_4 production can be calculated. In addition, CH_4 production can be measured from a single dose of injection of tracer (J France et al., 1993). France et al. (1993) described models for up to three or more CH_4 pools. Because of low solubility of CH_4 gas, the primary limitation of this technique is difficulty in preparing the infusion solution when isotopic tracers are used.

Non-isotopic tracer techniques are also available for measurement of CH_4 production. Johnson et al. (1994, 2000) described a technique using sulfur hexafluoride (SF_6), an inert gas tracer, placed in the rumen. The release rate of the gas from a permeation tube is known before its insertion into the rumen. Emissions from groups of animals in a room or groups in pastures are possible through the release of the tracer into the room or pasture area.

For individual animal measurement, a calibrated source of SF_6 is placed in the rumen prior to an experiment. The source of SF_6 is a permeation tube, and the rate of release of SF_6 is controlled. CH_4 and SF_6 concentrations are determined by gas chromatography. CH_4 emission rate is calculated as follows: $Q_{CH4} = Q_{SF6} \times [CH_4]/[SF_6]$; where Q_{CH4} is the emission rate of CH_4 in liters/hour, Q_{SF6} is the known release rate of SF_6 from the permeation tube, and $[CH_4]$ and $[SF_6]$ are measured concentrations in the canister. Grainger (2007) reported that CH_4 emission values from the SF_6 tracer technique were approximately 2.7% lower than those measured by the chamber through experiments.

This technique does not require the animal to be restrained or enclosed. Samples do not need to be taken directly from the animal's rumen or throat because the tracer accounts for dilution changes associated with head or air movement. However, SF_6 is a GHG, with a GWP of 23,900 times that of CO_2 and an atmospheric lifetime of 3,200 years. SF_6 residue in meat and milk from farm animals is another issue. This tracer technique underestimates the CH_4.

2.2 EMISSION MODELS OF ENTERIC METHANE FROM CATTLE

Mathematical model has been developed to estimate enteric CH_4 emission. These models are based on equations involving dry matter intake (DMI), intake of carbohydrates, digestibility and intake of dietary energy, animal size, milk components and digestibility of dietary components. They are typically classified into two groups: (1) dynamic mechanistic models that attempt to simulate CH_4 emission based on a mathematical description of ruminal fermentation biochemistry, and (2) empirical (statistical) models that directly relate intake nutrients to CH_4 output (Kebreab et al., 2008).

2.2.1 Mechanistic Models

Mechanistic models are complex which are based on ruminal fermentation biochemistry (James France et al., 2008; Thornley et al., 2007) . Reaction equations are shown the below:

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ (main pathway)

$4\ HCO_2H \rightarrow CH_4 + 3CO_2 + 2H_2O$ (15-20%)

$4\ CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$ (minor pathway)

$4\ CH_3CO_2H \rightarrow CH_4 + CO_2$ (minor pathway)

Several dynamic mechanistic models of CH_4 production have attempted to consider the most important feature of ruminal digestion and fermentation that influences CH_4 produced by the animal. Mathematical models representing fermentation processes require rumen microbial consortia, digestion kinetics production, and metabolism of volatile fatty acid (VFA) and CH_4 production. The two typical mechanistic models, COWPOLL and MOLLY, estimate CH_4 production in the rumen based on H_2 balance and sources (i.e., acetate and butyrate formation) and ruminal H_2 sinks (i.e., propionate formation, biohydrogenation) (Mills et al., 2001).

2.2.1.1 COWPOLL Model

COWPOLL model is a dynamic mechanistic model that simulates digestion, absorption and outflow of nutrients in the rumen (Dijkstra et al., 1992). The model contains 17 state variables representing N, carbohydrate (NDF, starch and sugar), lipid and VFA pools. Chemical composition of the diet is presented as starch (soluble and insoluble), NDF (degradable and undegradable), crude protein (soluble and insoluble), water soluble carbohydrate, ether extract, VFA (acetate, propionate, butyrate and valerate), ammonia, ethanol and lactate. Because VFA molar proportions are important determinants of CH_4 formation, COWPOLL uses a VFA stoichiometry developed by Bannink et al. (2006), based on data collected from digestion trials with dairy cows. This model utilizes three microbial pools (amylolytic, cellulolytic and protozoa). Enteric CH_4 is produced in the rumen when excess H_2 is used by methanogens to reduce CO_2 to CH_4 (Moss et al., 2000).

2.2.1.2 MOLLY Model

MOLLY is another dynamic mechanistic model based on rumen digestion and metabolism of lactating dairy cows (Baldwin, 1995). The model was constructed under the assumption of continuous feeding, using Michaelis-Menten or mass reaction kinetics. The model is comprised of 12 state variables. Chemical composition of the diet is presented as starch, cellulose, hemicellulose, lignin, soluble carbohydrate, acetate, propionate, butyrate, crude protein (soluble and insoluble), non-protein nitrogen, urea, ash (soluble and insoluble), lipid, organic acid, lactate, pectin and fat. After microbial attachment and substrate hydrolysis, the rumen model uses stoichiometric coefficients to convert starch, soluble carbohydrate and amino acids into VFA. VFA stoichiometry is based on the equation developed by Murphy et al. (1982). Besides stoichiometric differences from COWPOLL, MOLLY uses one microbial pool (protozoa), whereas COWPOLL uses three pools (amylolytic, cellulolytic and protozoa).

2.2.2 Empirical (Statistical) Models

Empirical (statistical) model is essentially a direct description of observational and experimental data. It utilizes existing data to describe the relationship of observation between one or two variables. In the enteric CH_4 emissions field, the models directly relate animal and/or dietary factors to CH_4 output. Common equations used to predict CH_4 emission from cattle are summarized in Table 2-1.

Table 2-1 Empirical (statistical) models used to predict enteric CH_4 emission from cattle

Equations	Reference	Relationship	variables
CH_4 (kg/head/yr)= the default EF value based on regional-specific and cattle types	*IPCC(2006) Tier 1*	/	/
CH_4 (MJ/d) = Ym(%GEI) × GEI (MJ/d)	*IPCC(2006) Tier 2*	Linear	single
CH_4 (kg/d) = 5.93 + 0.92 × DMI (kg/d)	*Mills et al., 2003*		
CH_4 (MJ/d) = 8.25 + 0.07 × MEI (MJ/d)	*Mills et al., 2003*		
CH_4 (kg /d) = a-(a+b) $e^{(-c\ DMI(kg/d))}$	*Mills et al., 2003*	Non-linear	
CH_4 (MJ/d) = −2.07 + 2.636 × DMI (kg/d) − 0.105 × DMI^2(kg/d)	*Axelsson, 1949*		
CH_4 (MJ/d) = 5.447 + 0.469 × (energy digestibility at maintenance intake, % of GE) + multiple of maintenance × [9.930 − 0.21 × (energy digestibility at maintenance intake, % of GE)/100 × GEI, MJ/d]	*Blaxter and Clapperton, 1965*	Linear	multiple
CH_4 (MJ/d) = 0.341 + 0.511 × NFC (kg/d) + 1.74 × HC (kg/d) + 2.652 × CEL (kg/d)	*Moe and Tyrrell (1979)*		
CH_4 (kg/d) = 1.06 +10.27xforage proportion+ 0.87 × DMI (kg/d)	*Mills et al., 2003*		
CH_4, MJ/d = 2.72 + 0.0937 × MEI (MJ/ d) + 4.31 × CEL (kg d^{-1}) − 6.49 × HC (kgd^{-1}) -7.44 × Fat (kg/d).	*Ellis et al., 2009*		
CH_4, MJ/d = 10.8 × [1-$e^{-[-0.034x(NFC/NDF)+0.228]x\ DMI,\ kg/d}$]	*Ellis et al., 2009*	Non-linear	

Note : a = Theoretical maximum CH_4 output (kg /d), b = Minimum CH_4 output (kg/ d), c = Shape parameter calculated as [0.0011 x starch (g/ kg DM)/acid detergent fiber (ADF) (g/ kg DM)] + 0.0045, CEL = Cellulose, DMI = Dry matter intake, GE = Gross energy, GEI = Gross energy intake, HC = Hemicellulose, MEI = Metabolizable energy intake, NDF = Diet neutral detergent fiber concentration, NFC = Diet non-fiber carbohydrate concentration [100 – (crude protein (%) – fat (%) - NDF (%), - ash (%))], Ym = CH_4 conversion factor (6.5±1% for dairy cow and grazing beef cattle, 3±1% for feedlot cattle).

2.2.2.2 Simple Regression Equations

Simple regression equations have been developed based on DMI, Gross energy intake (GEI) or metabolizable energy intake (MEI), in order to estimate CH_4 emissions. IPCC Tier 2 (2006), Axelsson's equation, and Mill's equations are common simple regression equations used to estimate CH_4 emission from cattle (Table 2-1). Simple regression equations can also be classified into two categories: linear relationship and non-linear relationship. According to Miller's report, correlation analysis results for observed CH_4 production from dairy cattle showed that DMI predicted CH_4 production with an R^2 of 0.60 and MEI with an R^2 of 0.55 for the linear relationship, and DMI with an R^2 of 0.97 for a non-linear relationship. This research demonstrated that simple regression equations can accurately predict CH_4 emissions for dairy cattle and that the non-linear relationship is better than the linear relationship. However, Ellis et al. (2007) pointed out that correlations of DMI and MEI with CH_4 are lower for beef database. R^2 is 0.437 with DMI parameter and R^2 is 0.362 with MEI. The reason for lower correlation in beef cattle is unclear. Nkrumah et al. (2006) showed that beef cow feedlot DMI is highly correlated with CH_4 production, while Basarab et al.(2005) demonstrated that various classes of beef animals, divided by animal type, physiological status, gender, weight, growth rate, activity level and age, produce differing amounts of CH_4.

2.2.2.3 Multiple Regression Equations

Multiple regression equations have considered multiple combinations of variables, such as MEI, DMI and measures of dietary chemical composition, to predict CH_4 emissions, expressed as MJ/d or kg/d. The relationship between CH_4 production and dietary variables expressed as percentage of dry matter (DM) would have attracted attention in the animal science research field. They could indicate the influence of the variable if DMI remained constant, similar to the forage:

concentrate ratio. In general, equations such as Blaxter and Clapperton's equation, Moe and Tyrrell's equation, some of Mills' linear and non-linear multiple regression equations and Ellis's equations, are multiple regression equations. They are the most complicated approaches among empirical models. Calculation of CH_4 production should be based on detailed dietary and animal information, thus limiting their applications.

2.2.3 Mechanistic Models vs Empirical (Statistical) Models

Many empirical models, also known as statistical models, have been fairly successful in predicting CH_4 production. In addition, prediction capacity of empirical models is unconstrained by physical laws (energy conservation or laws of thermodynamics), biological information, or knowledge of system structure. They usually require a curve-fitting practice. If the developed models accurately fit the data, the equations are useful under particular conditions for the generated data. Although empirical models can provide a practical tool, they have difficulty in predicting CH_4 production outside the range of developed values. Their inability to incorporate biological components combined with the need for mechanistic explanations have forced researchers to seek models that integrate underling rumen fermentation biochemistry and microbial consortia.

Mechanistic models employ a scientific reductionism approach based on H_2 balance. For example, H_2 produced from fermentation of carbohydrates to VFA or amino acid to VFA (e.g., H_2 input), H_2 used for biosynthesis of microbial cell components and bio-hydrogenation of unsaturated fatty acids, and CH_4 production are estimated from H_2 balance. In addition, the models apply the rate concept of standard mathematics: state formalism (e.g., rate of CH_4 emission process= state VFA in rumen and state of microbial consortia). The state formalism of investigated, system is defined at time t by q state variables (x1,x2, x3,…,xq) that represent properties or attributes of the system (e.g. quantity of VFA, H_2, microbial consortia, organ or tissue mass). Therefore, mechanistic models explicitly incorporate time. Differential equations are built based on the law of mass conservation, and have the capacity of accurate prediction. They also incorporate biological components and can explain the mechanism. However, complexity of the developed model increases with the number of organizational level, thereby limiting their applications.

According to aforementioned discussions, mechanistic models can provide high accurate prediction, but they require excessive information of detailed dietary, microbe and animal information as model inputs. Most differential equations have no solution. However, empirical models, deduced from practice and application without considering strict energy conservation or thermodynamics laws, are simple and therefore have strong practical capacity. For air quality research, the objective of this study was to understand enteric CH_4 emission rates, CH_4 environmental effects, and responding emission mitigation strategies, so empirical models give improved results.

2.2.4 Intergovernmental Panel on Climate Change Approaches (2006)

Intergovernmental Panel on Climate Change Approaches (IPCC, 2006), which recommends equations for estimating enteric CH_4, may have the largest predictive capacity among empirical (statistical) model approaches. Depending on the quality of the established database, the IPCC operates at three levels (Tiers 1, 2, 3) to estimate CH_4 emissions. Tier 1 methodology is the simplest calculation that utilizes default emission factor (EF) (kg CH_4/ head/year) value in order to estimate enteric CH_4 production. IPCC Tier 1 is characterized by region-specific research and cattle category as detailed in Appendix C. For example, the default EF value proposed for North American dairy cattle is 128 kg CH_4/ head/ year and other cattle is 53 kg CH_4 /head/ year, while the default EF value for Oceania is 90kg CH_4 / head/ year and other cattle is 60 kg CH_4 /head/ year (IPCC 2006). Tier 2 methodology calculates CH_4 production based on Gross Energy Intake (GEI) of the animal and default CH_4 conversion factor (Ym, % GEI) as detailed in Appendix D. Default Ym values proposed by IPCC (2006) are 6.5 ± 1 for beef and dairy cattle and 3 ± 1 for feedlot cattle. Tier 1 methodology also provided more special default EF values for other cattle (see Table 10A.1 in IPCC 2006). Tier 3 methodology is a complex approach in which calculation of CH_4 production is based on a sophisticated model that considers detailed dietary, ruminal passage rate, fluid volume, pH, and VFA stoichiometry.

2.3 MITIGATION STRATEGIES OF ENTERIC METHANE EMISSIONS FROM CATTLE

Options of enteric CH_4 emission mitigation for enteric fermentation encompass a wide range of activities, including animal manipulation (e.g., animal breeding and management systems), diet manipulation (e.g., forage quality, plant breeding, dietary supplements and plant secondary compounds), and rumen manipulation (e.g., biological control, vaccination and chemical defaunation). Current mitigation strategies primarily focus on diet manipulation: concentrates within diet (e.g., starch-based concentrates or fiber-based concentrations), forage type and quality (e.g., DMI, forage-to-concentrate ratio), dietary additive (e.g., oils, dicarboxylic acids), and plant secondary compounds (e.g., tannin, saponins, and fat).

2.3.1 Concentrates within the Diet

Several studies have been conducted concerning CH_4 emission variations against the proportions of concentrate within the diet. Yan et al. (2000) reported a negative relationship between CH_4 emission and the proportion of concentrate. Lovett et al. (2005) found that enteric CH_4 production was decreased with increased fiber-based concentrate. A positive response to a high level of starch-based concentrate on CH_4 reduction was also reported by Beauchemin et al. (2005). The principle of CH_4 reduction is based on the changing composition of VFAs (volatile fatty acids) production in the rumen, where less acetate and more propionate inhibits methanogenic activities by decreasing the pH and reducing the protozoa population. However, changing proportions of concentrate can cause health problems such as acidosis.

2.3.2 Forage Quality

Forage quality refers to fiber content, soluble carbohydrates, C_4 /C_3 grasses, or even less-mature pastures. Altering the forage quality can reduce CH_4 production (Ulyatt et al., 2002; Beauchemin et al., 2008). Moe et al. (1979) reported greater CH_4 production with cellulose forage compared to hemicellulose. Cellulose produces more CH_4 because the speed of cellulose fermentation is slower than that of hemicellulose fermentation and non-structural carbohydrates fermentation (McAllister et al., 1996). Consequently, one mitigation strategies is to add grain to forage diets in order to increase starch and reduce fiber intake (McAllister and Newbold, 2008). Another strategy of forage quality is to increase voluntary intake and reduces retention time in the rumen, thereby promoting energetically more efficient post-ruminal digestion and reducing the proportion of dietary energy converted to CH_4 (Blaxter and Clapperton, 1965). CH_4 production with legume is also lower compared to CH_4 production with grass, partly because of the lower fibre content, the faster rate of passage, and in some cases, the presence of condensed tannins (CTs) (Beauchemin et al., 2008). Changing forage quality can reduce CH_4 emission; but, their results have not been tested under field conditions. In addition, most strategies lead to increased DM intake per animal, resulting in no net change or net increase in CH_4 production. Similarly, the addition of more grain to the diet causes increased N_2O and transport emissions during grain production processes.

2.3.3 Dietary Additives

Dietary additives have potential to profitably reduce CH_4 emissions from intensive ruminant production systems. Yeast cultures of Saccharomyces cerevisiae potentially stimulate acetogenic microbes in the rumen, consuming H_2 to form acetate (Chaucheyras et al., 1995), and reducing CH_4 production. However, results appear to be strain dependent (Newbold et al., 1996) and variable in their impact on CH_4 production in the rumen (McGinn et al., 2004). Enzymes in the form of celluloses and hemicelluloses added to diets of ruminants, improved ruminal fiber digestion and productivity (Beauchemin et al., 2003). These enzymes are available at reasonable cost and in large quantities because they are widely used in food processing, textile, and paper industries. Dicarboxylic acids, such as fumarate, malate, and acrylate, are precursors to propionate reduction in the rumen and can act as an alternative H_2 sink, thus restricting methanogenesis. McAllister and Newbold (2008) reviewed studies and demonstrated that 0%–75% reductions in CH_4 could be achieved by feeding fumaric acid. However, dicarboxylic acids are prohibitively expensive as an abatement strategy because high doses are required. Nitrate can also replace CO_2 as an electron acceptor, forming ammonia as an alternative H_2 sink in the rumen (McAllister and Newbold, 2008). However, nitrates have potential toxic effects on ruminants when relatively large quantities of nitrates are introduced directly into the rumen without a period of adaptation (Eckard, 1990).

2.3.4 Plant Secondary Compounds

CH_4 emission can be reduced by plant secondary compounds, such as condensed tannins (CT), plant saponins, and fat. CT can reduce CH_4 production through a direct toxic effect on methanogens, but high CT concentrations can reduce voluntary feed intake and digestibility (Grainger et al., 2009). Plant saponins can reduce CH_4 because of their anti-protozoa properties (Holtshausen et al., 2009). Although plant saponin extracts are available, their cost is currently prohibitive for routine use in ruminant production systems. Fat has negative effects on enteric CH_4 emissions, but is dependent on its composition. Martin et al. (2010) reported that medium chain fatty acids are more effective (e.g., coconut oil, 7.3% less CH_4 per percentage added fat) than linoleic acid (e.g., soybean and sunflower, approximately 4.1% less CH_4 per percentage added fat), linolenic acid (e.g., linseed, approximately 4.8% less CH_4 per percentage added fat), monounsaturated fatty acids such as oleic acid (e.g., rapeseed, 2.5% less CH_4 per percentage added fat), and saturated fats (e.g., tallow, 3.5% less CH_4 per percentage added fat). Five possible mechanisms can reduce enteric CH_4 emissions of lipid supplementation: reducing fiber digestion (mainly long-chain fatty acids), lowering DMI, suppressing methanogens (mainly medium-chain fatty acids), suppressing rumen protozoa, and bio-hydrogenation to a limited extent (McGinn et al., 2004). A number of high-oil by-products are already being used to reduce CH_4 emissions at cost-effective prices.

2.4 META-ANALYSIS

Meta-analysis refers to methods that focus on summarizing, contrasting and combining/aggregating results from various studies to answer study questions, including identification of consistent patterns among study results, sources of disagreement among those results, or other interesting relationships in the context of multiple studies (Rothman et al., 2008). The simplest form can only identify a common measure of effect size. A weighted average may be the output of meta-analysis. The weighting may be related to sample sizes within individual studies. Other differences exist between the studies, but the general aim of meta-analysis is to more powerfully estimate the true “effect size” compared with a smaller “effect size” in a single study with a given single set of assumptions and conditions (Wilson, 2001). Meta-analyses are often essential elements of a systematic review procedure (Collaboration, 2009).

2.4.1 A Brief History and Application of Meta-Analysis

As early as the twelfth century in China, Zhu Xi (朱熹，1130-1200), a famous philosopher, composed his philosophical theory by summarizing a series of related literatures. He named his research methodology “Theory of Systematic Rule” (Van Norden, 2011), which could be considered meta-analysis. In the Western world, a historical case of meta-analysis may be traced to a paper published in 1904 by the British statistician Karl Pearson (Nordmanna et al., 2012). In 1940, the publication of Extra-sensory perception, edited by Duke University psychologists J.D. Pratt, et al. (Bösch, 2004), was another milestone because meta-analysis was identified as a theory and toolbox of statistical techniques for all conceptually identical experiments concerning a particular research issue conducted by independent researchers in “extra-sensory perception”. In 1976, Gene Glass used the term ‘meta-analysis’ to refer to ‘the statistical analysis of a large collection of analysis results from individual studies and the term of meta-analysis has been adopted since then (Cochran et al., 1953). Meta-analysis was primary applied in social research in the early days (Armitage et al., 2008). Since 1987, meta-analysis has been used in gastroenterology literature and expanded to most conditions in clinical trials (Watkins et al., 2009). In the early 1990s, meta-analysis was introduced in ecology and evolutionary biology (JARVINEN, 1991). Later on, other disciplines adopted meta-analysis in their literatures (Petticrew, 2001).

2.4.2 Designing Meta-Analysis

Comparing traditional narrative reviews, meta-analysis can be quantitative and be qualitative. It can reveal biases and weaknesses of existing studies to discern the direction and magnitude of effects across the studies (Wilson, 2001). However, the primary advantage of meta-analysis is in its design, including identification or assessment of an area, where effect of the treatment or exposure is uncertain and where a relatively homogenous body of literature exists and selection of correct and suitable statistical models, such as effects model, random effects model, quality effects model and meta-regression, in order to obtain comparable effect size (e.g., standardized mean difference, correlation coefficient, odds-ratio).

Meta-analysis design determines the validity of its results. An international group of clinical epidemiologists, clinicians, and statisticians have been working on the quality of meta-analyses in the last few decades and several standardized approaches such as QUOROM (the Quality of Reporting of Meta-analyses), MOOSE (the Meta-analysis of Observational Studies in Epidemiology), and PRISMA (Preferred Reporting Items of Systematic reviews and Meta-analyses) were developed and updated. QUOROM statement, which was published in 1999, provided guidelines for conducting meta-analyses. Six major areas of the original 18 items formed the basis of QUOROM reporting. Evaluation of reporting was organized into headings and subheadings regarding searches, selection, validity assessment, data abstraction, study characteristics, and quantitative data synthesis (Moher et al., 1999). MOOSE, formed in 2000, contained specifications for reporting meta-analyses, including background, search strategies, methods, results, discussions, and conclusions (Stroup et al., 2000). QUOROM's statement was updated to address several conceptual, practical advances in the science of systematic reviews, and was renamed PRISMA in 2009. It is comprised of 27 items. Evaluation of reporting was modified into protocol and registration, eligibility criteria, information sources, search, study selection, data collection process, data items, risk of bias in individual studies, summary measures, synthesis of results, risk of bias across the studies and additional analyses (Liberati et al., 2009).

According to QUOROM, MOOSE or PRISMA, six key areas should be emphasized during the meta-analysis design process: development of the study question, comprehensive literature search, data extraction, evaluation of results, evaluation for publication bias, and applicability of results. A checklist to evaluate validity of a meta-analysis is listed in Table 2-2. The six key areas require additional details which are included in appendix A.

Table 2-2 Checklist for meta-analysis (Russo, 2007)

Section in Methods	Item	Checklist Item
Study question	1	Objectives clearly stated
Literature search	2	Comprehensive literature search conducted
	3	Searched information sources listed
	4	Terms used for electronic literature search provided
	5	Reasonable limitations placed on search (i.e., English language)
	6	Manual search conducted through references of articles, abstracts
	7	Attempts made at collecting unpublished data
Data abstraction	8	Structured data abstraction form used
	9	Number of authors(>2)who abstracted data given
	10	Disagreements listed between authors and how they were resolved
	11	Characteristics of studies listed(i.e., sample size)
	12	Inclusion and exclusion criteria provided for studies
	13	Number of excluded studies and reasons for exclusion included
Evaluation of results	14	Studies were combinable
	15	Appropriate statistical methods used to combine results
	16	Results displayed
	17	Sensitivity analysis conducted
Evaluation for publication bias	18	Publication bias addressed through evaluation methods such as funnel plot or sensitivity analysis
Applicability of results	19	Results were generalizable

(Mark W. Russo, 2007)

2.4.3 Meta-Analysis in Systematic Review of Livestock Methane Emissions

Livestock scientists and practitioners recognized the value of meta-analysis to address the marked increase in literature and meta-analysis was extended to livestock studies as early as 1991 (Oetzel, 1991); however, the meta-analysis method has expanded to estimate and evaluate CH_4 emissions from livestock in the last few years (Eugène et al., 2008; Z. P. Liu, W., and Liu H. , 2013; Machmüller et al., 2006). Lean (2009) published a review paper concerning the approach of meta-analysis in livestock studies with topics focused on animal health and reproduction. In livestock CH_4 emission studies, approximately 30 publications use meta-analysis, but no paper reviews or summarizes the approach of meta-analysis in this field of study.

Table 2-3 summarizes the meta-analysis application in livestock CH_4 emissions, using Table 2-2 as checklist. Table 2-3 demonstrates that early application of meta-analysis in livestock CH_4 emissions was incomplete. The reports included only 5-6 items and most of them did not check the heterogeneity among the data across the studies, structured data abstraction form, or address publication bias. After 2010, meta-analysis quality has improved and reports have included most checklist items; however, some sections still need improvement, such as language bias.

Table 2-3 Qualities of meta-analysis application in livestock methane emissions

source	*Check items*																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
(Z. Liu et al., 2014; Z. P. Liu, W., and Liu H. , 2013)	√	√	√	/	×	√	√	√	√	√	×	√	×	/	√	√	×	×	/
(Ranga Niroshan Appuhamy et al., 2013)	√	√	√	√	×	√	√	√	×	×	√	√	√	√	√	√	√	√	√
(Amlan Kumar Patra, 2013)	√	√	√	×	×	√	×	√	×	×	√	√	√	/	√	√	√	×	√
(Poppy et al., 2012)	√	√	√	√	×	√	√	√	×	×	√	√	√	√	√	√	√	√	√
(Jayanegara et al., 2012)	√	√	√	√	×	√	√	√	×	×	√	√	×	√	√	√	√	×	/
(Grainger et al., 2011)	√	×	×	×	×	×	×	√	×	×	√	×	×	√	/	√	×	×	/
(Moate et al., 2011)	√	×	×	×	×	×	√	×	×	×	√	×	×	/	/	√	×	×	/
(Archimède et al., 2011)	√	×	√	√	×	√	×	√	×	×	√	√	×	√	/	√	×	×	/
(Amlan K Patra, 2010)	√	√	×	×	×	×	×	√	×	×	√	√	×	√	/	√	×	×	/
(Eugène et al., 2008)	√	×	×	×	×	×	×	√	×	×	√	√	×	/	/	√	√	×	/
(Duffield et al., 2008)	√	√	√	√	√	√	√	√	×	×	√	√	√	√	/	√	√	√	/
(Machmüller et al., 2006)	√	×	×	×	×	×	√	×	×	×	√	×	√	/	/	√	×	×	√

Note: " √ " =report in the paper, "×" =no report in the paper, "/"= cannot be judged by author

Chapter 3 - METHODS

3.1 Literature Search

Multiple methods were undertaken to identify potentially eligible studies to be included in the meta-analysis. First, studies were identified in four electronic bibliographic databases: AGRICOLA (Agricultural Online Access), CAB Abstracts, Web of Science, and Google Scholar. Search terms included: cattle, beef/dairy, GHG, and CH_4 emission. An iterative process was used to refine the search strategy by testing several search terms and incorporating new search terms as new relevant studies were identified. One hundred ninety-one papers published in the years from 1995 to 2013 were retrieved. Studies reporting measurements of enteric CH_4 emissions from cattle were included and 55 papers reported measurements of enteric CH_4 emissions. Inclusion was not restricted by study size, and all included studies were in English. Table 3-1 presents the literature for this study.

Table 3-1 Literature search

Geographic region	No. of studies	Author, year
North America	19	Beauchemin et al., 2005; Beauchemin et al., 2006; Beauchemin et al., 2006; Beauchemin et al., 2009; Beauchemin et al., 2007; Boadi & Wittenberg, 2002; Boadi, Wittenberg, et al., 2002; Boadi et al., 2004; Brown et al., 2011; Chung et al., 2011; Grainger et al., 2008; Grainger et al., 2009; Hales et al., 2012; Hollmann et al., 2010; Holtshausen et al., 2009; McGinn et al., 2006; McGinn et al., 2009; Powers et al., 2008; Sun et al., 2008
South America	5	Berra et al., 2008; de Oliveira et al., 2007; Demarchi et al., 2004; Dini et al., 2012; Hulshof et al., 2012
Europe	18	(Foley et al., 2009; Hart et al., 2009; Hindrichsen et al., 2005; Jordan et al., 2006; Külling et al., 2002; D Lovett et al., 2003; DK Lovett et al., 2005; Martin et al., 2008; Mc Geough et al., 2010;

		McCartney et al., 2013; Münger et al., 2006; Muñoz et al., 2012; Ngwabie et al., 2011; Patel et al., 2011; Van Zijderveld, Fonken, et al., 2011; Van Zijderveld, Gerrits, et al., 2011; Willén, 2011; Yan et al., 2000)
Asia	3	(Chaokaur, 2011; Ding et al., 2010; Kasuya et al., 2010)
Oceania	10	(Grainger et al., 2007; Grainger, Williams, Clarke, et al., 2010; Grainger, Williams, Eckard, et al., 2010; Hegarty et al., 2007; Kurihara et al., 1999; Moate et al., 2011; Moate et al., 2013; Pinares-Patiño et al., 2008; Ulyatt et al., 2002; Vlaming et al., 2007)

3.2 Data Extraction

Three levels were developed to extract data from individual studies: study level, comparison level, and measure and effect size level.

Study level: Three items were used to code information at the study level in order to identify basic information about each study: author names, year of publication, and study title.

Comparison level: Five clusters and 12 items were used to code information at the comparison level. The first cluster was comprised of environmental variables, including geographic region, temperature, and humidity. The second cluster consisted of variables regarding cattle characteristics such as cattle classification, sub-classification, production stage, and body weight. The third cluster was feed situation, the fourth cluster was feed intake, and the fifth cluster was mitigation strategies (i.e., types of mitigation, qualitative characteristics, and quantitative characteristics).

Measure and effect size level: Eight items were used to code information concerning the measure and effect sizes within a study. Two items of CH_4 measurement concentration method and CH_4 sampling method identified CH_4 measurement techniques. Six items were used to describe three types of units of CH_4 emissions and their corresponding SD (standard deviation).

More specific information is included in the tree structure diagram in Appendix B. Data extraction protocol is presented in Table 3-2.

Table 3-2 Data extraction protocol

	Categories of data	Extracted values
Information on the study level		
1	Names of authors	Input the text
2	Year of publication	Input numeric values
3	Title of the study	Input the text
Information on the comparison level		
4	Geographic region	Select from North America, Europe, Asia, Oceania, South America
5	Temperature (℃)	Input numeric values
6	Humidity (%)	Input numeric values
7	Cattle classification	Select from dairy and beef
8	Sub-classification of dairy	Select from Holstein, Friesian, Jersey, Simmental, Swedish Red, Swiss brown, Friesian×Jersey, Holstei×Friesian, Jersey×Holstein
	Sub-classification of beef	Select from heifer, steer, bull, and Nelore
9	Production Stage of dairy cattle	Select from non-pregnant, dry, and lactating (early lactating, mid lactating, and late-lactation)
	Stage of beef production	Select yearling, young, growing, fattening, and finishing
10	Body weight	Input numeric values
11	Feed Situation	Select from stall feed and pasture/range
12	Feed intake	Input numeric values
13	Diet mitigation strategies	Select from concentrates within diet, forage quality, diet additives, and plant secondary compounds
14	Qualitative characteristics	Input the text(chemicals or compositions)
15	Quantitative characteristics	Input numeric values

Information on the measuring effect size level		
16	Enteric CH_4 sampling	Select from head box, hood, mask, chambers and SF_6
17	CH_4 concentration measurement method	Select from gas chromatograph, MS and infrared analyzer
18	CH_4 emission with the unit of g/head/d	Input numeric values
19	SD of CH_4 emission with the unit of g/head/d	Input numeric values
20	CH_4 emission with the unit of g/Kg DMI	Input numeric values
21	SD of CH_4 emission with the unit of g/Kg DMI	Input numeric values
22	CH_4 emission with the unit of % GEI	Input numeric values
23	SD of CH_4 emission with the unit of % GEI	Input numeric values

3.3 Data analysis

3.3.1 Aim 1: Statistics of Enteric CH_4 Emission Rates

Three types were used for units-of-measure. The first type was g/head/d, but various units, such as L/head/d, kg/head/year, or kg/AU/year, were used in the literature. In order to perform statistical analysis and compare the emissions between studies, the units of L/head/d, kg/head/year, and kg/AU/year data were converted to g/head/d. When unit conversion was not possible due to lack of key information, original emission data was excluded from statistical analysis. The second type was g/kg DMI, and the third type was %GEI.

Data across the studies were analyzed using UNIVARIATE procedures of SAS (SAS for Windows, Version 9.3, SAS Institute, Cary, NC). Variables (factors), such as different units, different geographic regions, different types of cattle, and feed situations, on enteric CH_4 emissions were analyzed. Kolmogorov-Smirnov was selected to test the normal distribution when the data points were more than 50, and Shapiro-Wilk or Anderson-Darling was used to test the normal distribution when the data points were less than 50. Brown-Forsythe was selected to test the homogeneity of enteric CH_4 emissions across the studies. Some studies provided emission data under different settings; therefore, in these cases more than one data point was used from one study. Study (or each publication) was treated as a random effect. Box plots were proposed to represent moments (including skewness and kurtosis), quantiles or percentiles (such as the median), and extreme values of the enteric CH_4 emissions from various geographic regions, cattle category, from different feed situations, and overall.

3.3.2 Aim 2: Effects of Variables on Enteric CH_4 Emissions Rates

Data across the studies were analyzed statistically by ANOVA using MIXED procedures of SAS (SAS for Windows, Version 9.3, SAS Institute, Cary, NC). These variables (factors) were treated as fixed effects in the analyses: geographic region, temperature, humidity, cattle classification, sub-classification, production stage, body weight, feed situation, feed intake, and mitigation strategy. Each study (or publication) was treated as a random variable. Effects of variables at comparison level on emission rates were examined using Tukey's test. Significant effects were declared at $P < 0.05$. For diet mitigation strategies, relative reduction percentages (RRPs) between measured emissions from control groups and measured emissions after mitigation techniques were adopted as the metric for meta-analysis and they were calculated using the following equation:

RRP = (control emission-mitigation emission)/(control emission)X100%

3.3.3 Aim 3: Evaluation of the Intergovernmental Panel on Climate Change Approaches

1) Overall Comparison of Measured Emissions and Estimated Emissions Using IPCC (2006)

Enteric CH_4 emissions from cattle were estimated using IPCC Tier 1 and Tier 2 approaches. Differences (predicting residuals/estimating residuals) between measured emissions and IPCC estimated emissions were calculated, and analyzed using the UNIVARIATE procedures of SAS (SAS for Windows, Version 9.3, SAS Institute, Cary, NC). Box figures were also plotted to show moments (including skewness and kurtosis), quantiles or percentiles (such as the median), and extreme values of the enteric CH_4 emissions based on the beef cattle data pool, the dairy cattle data pool, and the total cattle data pool. Kolmogorov-Smirnov and

Anderson-Darling were selected to test the estimated strength of IPCC. If the differences do not have a normal distribution, IPCC is not perfect and some emission factors need to be revise.

2) Comparison of Measured Emissions and Estimated Emissions in Subgroups Using IPCC (2006)

Measured emissions were divided into subgroups according to geographic region and cattle classification. Measured emissions in subgroups were compared with the corresponding IPCC estimated values. Two methods were developed to compare the data. The first method was the paired t-test in which the same type of cattle represented one group data in each study. Paired t-tests were performed to compare the measured emissions with the corresponding IPCC estimated values based on each study and each subgroup. Significant differences were declared at $P < 0.05$. The second method was PRD (percentage relative differences) (Z. Liu et al., 2013). For CH_4 emissions, PRD between the measured values and IPCC estimated values were adopted as the metric for meta-analysis and were calculated using the following equation:

PRD = [(measured values – IPCC values)/ (measured values + IPCC values)] X100%

Each study and each region represents 1 data point. PRD on study-level was average metrics with standard deviation in each study. A random-effect model was used to calculate PRD on region-level (average metrics with 95% confidence intervals) to determine the direction and significance of the differences between measured values and IPCC values in each different geographic regional subgroup. If the interval of PRD did not include 0, it suggested the ineffective estimation of IPCC approaches (e.g., when the PRD interval was above 0, IPCC underestimated, and when the PRD interval was below 0, IPCC overestimated); if the interval of PRD included 0, it indicated the effectiveness of IPCC approaches; In addition, forest plots were used to graphically represent study-level effect size and aggregate information.

Chapter 4 - RESULTS AND DISCUSSION

4.1 Aim 1: Statistics of Enteric CH_4 Emission Rates

4.1.1 Statistics of Enteric CH_4 Emission Rates with Various Units

Ranges, means, relative standard deviation (RSD), medians, and skewness of CH_4 emission rates are presented in Table 4-1 and Figure 4-1[1] with three units in which three differences are exhibited. First, RSD with the unit of g/head/d is the largest among the three units, while RSD with the unit of g/kg DMI is very close to RSD with the unit of %GEI. The value of RSD with the unit of g/head/d (54.62%) is two times larger than that with the unit of g/kg DMI (24.97%) and with the unit of % GEI (23.57%). Second, enteric CH_4 emission rates with the unit of g/head/d show a positively skewed distribution with corresponding skewness value of 0.5019, while those with the units of g/kg DMI and % GEI exhibit negatively skewed distribution with respective skewness value of -0.1530 and -0.3961. Third, the difference between median and mean is largest among the three units when the unit is g/head/d. Relative error between median and mean is 12.1% when the unit is g/head/d, while relative error is 1.4% when the unit is g/kg DMI and 5.4 when the unit is %GEI.

Table 4-1 Statistics of enteric CH_4 emission rates with three different units

Unit	N	range	Mean	RSD (%)	Median	Skewness
g/head/d	165	39.10 to 657.00	245.62±134.15	54.62	216.00	0.5019
g/kg DMI	134	7.75 to 36.30	20.54±5.13	24.97	20.83	-0.1530
% GEI	76	3.70 to 7.10	6.45±1.52	23.57	6.10	-0.3961

RSD: relative standard deviation. N: number of data points from the studies

[1] The data of moments (including skewness and kurtosis), means, medians, and extreme values are attached in Appendix E

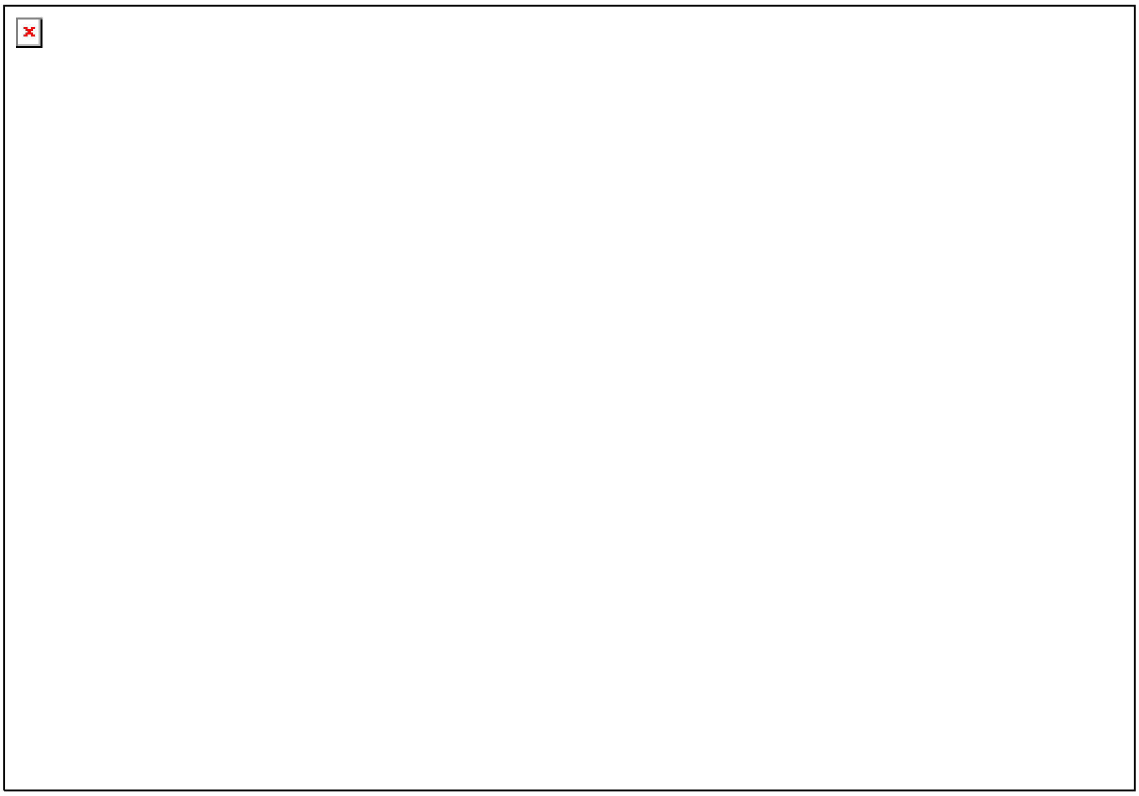


Figure 4-1 Box plot for enteric CH_4 emission rates with three units

Normal distribution was tested and results are shown in Table 4-2. CH_4 emission rates from various studies had a normal distribution (p>0.05) with Kolmogorov-Smirnov's test when the units were g/kg DMI and %GEI, while CH_4 emission rates did not have a normal distribution (P<0.01) when the unit was g/head/d. In addition, according to Figure 4-1, distribution of CH_4 emission rates is bimodal when the unit is g/head/d.

Table 4-2 Normality test for CH_4 emission rates with various units

	g/head/d		g/kg DMI		% GEI	
	Test	P-value	Test	P-value	Test	P-value
Kolmogorov-Smirnov	0.10	0.01	0.057	***0.15***	0.11	***0.057***

Homogeneity was tested with Brown and Forsythe, as shown in Table 4-3. Only data with the unit of % GEI were homogenous across the studies, while data with the other two units were heterogeneous. According to results from the normality test and homogeneity test, data with the unit of %GEI may be the best for meta-analysis across the studies and the data with the unit of g/head/d may be the poorest.

Table 4-3 Homogeneity test for CH_4 emissions with various units between studies

Unit	g/head/d		g/Kg DMI		% GEI	
	F value	P value	F value	P value	F value	P value
Brown and Forsythe	5.51	0.0001	4.31	0.0001	1.86	***0.090***

4.1.2 Statistics of Enteric CH_4 Emission Rates from Various Geographic Regions

Figure 4-2, 4-3, and 4-4[2] present the means, medians, and SDs of enteric CH_4 emission rates from various geographic regions when the unit is g/head/d, g/kg DMI, or % GEI respectively.

Figure 4-2 Box plot for enteric CH_4 emission with various regions when the unit is g/head/d

[2] The data of moments (including skewness and kurtosis), means, medians, and extreme values are attached in Appendix E

Figure 4-2 illustrates large variations in enteric CH_4 emission rates between geographic regions, and RSD of the means of CH_4 emission rates between geographic regions is shown to be 40.26%. According to the means of enteric CH_4 emission rates, regions arranged from maximum emission to minimum emission are Oceania (336.16 g/head/d), Europe (302.32 g/head/d), North America (181.34 g/head/d), South America (164.78 g/head/d), and Asia (132.73 g/head/d. RSDs of enteric CH_4 emission rates within regions are South America (63.89%), North America (59.73%), Asia (46.45%), Oceania (39.38%), and Europe (36.51%). In addition, two relatively reverse relationships were observed: discrepancies between means and medians in areas such as in Asia (21.76 g/head/d), North America (16.36 g/head/d), and South America (22.65 g/head/d) in which small enteric CH_4 emission rates (i.e., 132.73±61.64 g/head/d in Asia, 181.34±108.32 in North America, and 164.78±105.28 g/head/d) are larger than those in areas such as Oceania (4.61g/head/d) and Europe (1.68 g/head/d) with relatively large enteric CH_4 emission rates (i.e., 336.16±132.38 g/head/d in Oceania and 302.32±110.38 g/head/d in Europe); RSDs of enteric CH_4 emission rates within areas of Asia (46.44%), North America (59.73%), and South America (63.89%) with small enteric CH_4 emission rates are larger than RSDs in Oceania (39.37%) and Europe (36.51%) with relatively large enteric CH_4 emission rates.

Figure 4-3 Box plot for enteric CH_4 emissions with various regions when the unit is g/kg DMI

In Figure 4-3, variations in emission rates between various areas are illustrated, but RSD of means of CH_4 emission rates between areas is only 12.70% when the unit is g/kg DMI, which is much smaller than RSD of means of CH_4 emission rates with the unit of g/head/d (40.26%). Areas arranged from maximum emission to minimum emission are Europe (22.96 g/kg DMI), Oceania (20.24 g/kg DMI), Asia (19.90 g/kg DMI), North America (18.83 g/kg DMI), and South America (16.08 g/kg DMI). RSDs of CH_4 emission rates within areas are South America (29.35%), North America (29.31%), Europe (23.14%), Oceania (21.73%), and Asia (16.15%). The two relatively reverse relationships when the unit is g/kg DMI are similar to those when the unit is g/head/d except in Europe. Discrepancies between means and medians of enteric CH_4 emission rates in the areas (e.g. 2.06 g/kg DMI in South America and 1.93 g/kg DMI in North America) with small enteric CH_4 emission rates (e.g., 16.80±4.72g/kg DMI in South America and 18.83±5.51 g/kg DMI in North America) are larger than those in areas (e.g. 0.26 g/kg DMI in Asia and 0.54 g/kg DMI in Oceania) with relatively large enteric CH_4 emission rates (e.g.

19.90±3.21 g/kg DMI in Asia and 20.24±4.39 g/kg DMI in Oceania). In addition, RSDs of enteric CH_4 emission rates within areas (e.g., 29.35% in South America and 29.31% in North America) with small enteric CH_4 emission rates are larger than those within areas(e.g., 116.15% in Asia and 21.72 %) in Oceania with relatively large enteric CH_4 emission rates

Figure 4-4 Box plot for enteric CH_4 emissions with various regions when the unit is % GEI

In Figure 4-4, variations in emission rates between areas are small, and RSD of means of enteric CH_4 emission rates between areas is only 8.69%. Discrepancies between means and medians have similar rules with those with the unit of g/head/d and g/kg DMI except in Asia: large values in areas of relatively small enteric CH_4 emission rates and small values in areas of relatively large CH_4 emission rates: the discrepancies between means and medians of enteric CH_4 emission rates in the areas (e.g. 0.61 %GEI in Oceania and 0.47 %GEI in North America) with small enteric CH_4 emission rates (e.g., 5.49±1.52 %GEI in Oceania and 6.23±1.57 %GEI in North America) are larger than those in areas (e.g. 0.07 %GEI in South America and 0.28 %GEI in Europe) with relatively large enteric CH_4 emission rates (e.g. 6.33±0.404 %GEI in

South America and 7.02 $\pm$0.1.77 %GEI in Europe). In addition, the RSDs of enteric CH_4 emission rates within areas also have very similar rules with those with the unit of g/head/d and g/kg DMI: the RSDs of enteric CH_4 emission rates within areas (e.g., 27.69% in Oceania and 25.25% in North America)) with small enteric CH_4 emission rates are larger than those within areas (e.g., 6.38% in South America, 21.47% in Asia and 25.30 % in Europe) with relatively large enteric CH_4 emission rates

4.1.3 Statistics of Enteric CH_4 Emission Rates from Dairy and Beef Cattle

The means, medians, and RSDs of enteric CH_4 emission rates from dairy and beef cattle are represented in Figure 4-5[3] and Table 4-4, in which three significant results are presented. First, enteric CH_4 emission rates from dairy cattle (325.83$\pm$118.95) are larger than those from beef cattle (149.38$\pm$75.19) when the unit is g/head/d, while enteric CH_4 emission rates between dairy cattle and beef cattle are very close when the units are g/kg DMI (20.96$\pm$4.01 for dairy cattle, and 20.05$\pm$6.20 for beef cattle) and % GEI (6.02$\pm$1.14 for dairy cattle, and 6.63$\pm$1.69 for beef cattle). Second, RSDs of emission rates are larger when the unit is g/head/d (36.51% for dairy cattle, and 50.27% for beef cattle) as compared to those when the units are g/kg DMI (19.13% for dairy cattle, and 30.92% for beef cattle) and % GEI (18.93% for dairy cattle, and 25.49% for beef cattle). Third, RSDs of emission rates within beef cattle (50.27% with the unit of g/head/d, 30.92 % with the unit of g/kg DMI, and 25.49 % with the unit of %GEI) are larger than those within dairy cattle (36.51% with the unit of g/head/d, 19.13 % with the unit of g/kg DMI, and 18.93 % with the unit of %GEI). In addition, RSDs of enteric CH_4 emission rates

[3] The data of moments (including skewness and kurtosis), means, medians, and extreme values are attached in Appendix E

between different types of cattle are 52.51% with the unit of g/head/d, 6.52% with the unit of g/kg DMI, and 3.13% with the unit of %GEI.

Table 4-4 Statistics of enteric CH_4 emission rates with various types of cattle

Unit	N	Cattle classification	range	Mean	RSD (%)	Median
g/head/d	90	dairy	94.10 to 657.00	325.83±118.95	36.51	330.50
	75	beef	39.11 to 322.00	149.38±75.19	50.27	135.39
g/kg DMI	72	dairy	12.3 to 36.3	20.96±4.01	19.13	20.60
	62	beef	7.75 to 35.60	20.05±6.20	30.92	21.05
% GEI	21	dairy	3.7 to 9.0	6.02±1.14	18.93	6.10
	55	beef	2.47 to 9.90	6.63±1.69	25.49	6.90

RSD: relative standard deviation. N: number of the data points from the studies

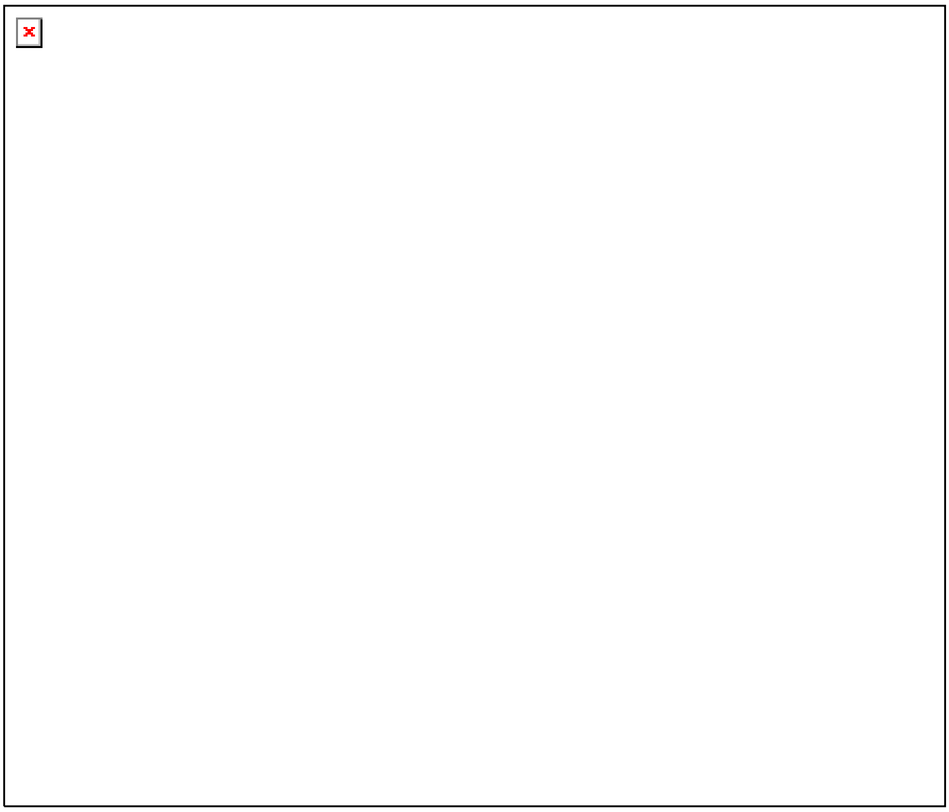


Figure 4-5 Box plot for enteric CH_4 emissions from dairy and beef cattle

4.1.4 Statistics of Enteric CH_4 Emission Rates from Various Feed Situations

The means, medians, and RSDs of enteric CH_4 emission rates from various feed situations are presented in Table 4-5 in which small variations in enteric CH_4 emission rates between feed situations are observed. For RSDs of CH_4 emission rates, two differences are evident. The first difference is that RSDs of CH_4 emission rates with pasture/range feed are larger than those with stall feed. As shown in Table 4-5, RSD with pasture/range feed (54.00%) is larger than RSD with stall feed (49.58%) when the unit is g/head/d, RSD with pasture/range feed (27.20%) is also larger than RSD with stall feed (23.38%) when the unit is g/kg DMI, and RSD with pasture/range feed (31.23%) is larger than the RSD with stall feed (16.51%) when the unit is %GEI. The second is that RSDs of enteric CH_4 emission rates between feed situations when the unit is g/head/d (52.51%) are larger compared to RSD when the units are g/kg DMI (6.52%) and %GEI (3.13%).

Table 4-5 Statistics of enteric CH_4 emission rates with various feed situation

Feed situation	N	range	Mean	RSD (%)	Median	Skewness
Pasture/range	78	39.11 to 543.00	235.63±127.26	54.00	243.67	0.2506
Stall feed	36	53.40 to 604.00	293.10±145.33	49.58	300.20	0.0578
Note: the unit of CH_4 emission rates is g/head/d						
Pasture/range	70	7.75 to 35.60	20.11±5.47	27.20	20.15	-0.0796
Stall feed	31	9.14 to 36.30	20.61±4.82	23.38	20.50	0.6032
Note: the unit of CH_4 emission rates is g/kg DMI						
Pasture/range	36	2.47 to 9.72	6.34±1.98	31.23	6.75	-0.4635
Stall feed	16	4.40 to 7.93	6.36±1.05	16.51	6.40	-0.3538
Note: the unit of CH_4 emission rates is % GEI						

4.1.5 Comparison variations in means of enteric CH_4 emission rates between various regions, cattle types, and feed situations

Table 4-6 summarizes RSDs (relative standard deviations) of means of enteric CH_4 emission rates between various regions, cattle types, and feed situations. When the unit is g/head/d, RSDs of means of enteric CH_4 emission rates are 40.26% between different regions, 52.51% between different cattle types, and 15.37% between different feed situations. RSD-values with the unit of g/head/d indicate the differences in means of enteric CH_4 emission rates between different regions and cattle types are larger compared to those between different feed situations. When the unit is g/kg DMI, RSDs of means of enteric CH_4 emission rates are 12.70% between different regions, 6.52% between different cattle types, and 0.22% between different feed situations. RSD values with the unit of g/kg DMI manifest that differences of enteric CH_4 emission rates between regions are large relative to those between cattle types and feed situations. When the unit is %GEI, the RSDs of enteric CH_4 emission rates are 8.69% between different regions, 3.13% between different cattle types, and 1.74% between different feed situations. Therefore, the variations of the means of enteric Ch_4 emissions in different regions are large relative to those in different feed situations; and the variations in different cattle types are larger than those in different regions and feed situations when the unit is g/head/d, and the variations in different cattle types are between those in different regions and in different feed situations.

Table 4-6 RSDs of means of enteric CH_4 emission rates between various regions, cattle types, and feed situations

	Geographic regions	Cattle types	Feed situations
g/head/d	40.26%	52.51%	15.37%
g/kg DMI	12.70%	6.52%	0.22%
% GEI	8.69%	3.13%	1.74%

4.2 Aim 2: Effects of Variables on Enteric CH_4 Emissions Rates

4.2.1 Overall Analysis of Variables' Effects on Enteric CH_4 Emissions Across the Studies

Table 4-7 provides results of variables' effects on enteric CH_4 emission rates with three units except variables of sub-classification, production stage, and diet mitigation strategy. Variables of sub-classification and production stage are analyzed in section 4.2.3, and the variable of diet mitigation strategy is analyzed in section 4.2.4.

Table 4-7 Results of overall analysis of variables' effects on enteric CH_4 emissions from all types of cattle

variables		P values of causes of variation		
		g/head/d	**g/kg DMI**	**% GEI**
Environmental variables	Geographic region	***0.0064***	0.3716	0.9357
	Temperature (℃)	***<0.0001***	0.2534	0.2630
	Humidity (%)	***0.0202***	***0.0017***	***0.0059***
Cluster of cattle characteristics	Cattle classification	***0.0001***	0.6750	0.2151
	Body weight	***<0.0001***	***<0.0001***	***0.0011***
Feed Situation	Feed situation	0.4730	0.5751	0.7334
Feed intake	Feed intake	***0.0038***	***0.0112***	0.2558

When the unit is g/head/d, p values of the effects from geographic regions, temperature, humidity, cattle classification, body weight, and feed intake are 0.0064, 0.0001, 0.0202, 0.0001, 0.0001, and 0.0038, respectively, showing that these variables significantly affect enteric CH_4 emission rates. P value of effects from feed situation is 0.4730, indicating that data across the studies do not provide sufficient evidence of feed situation effects. When the unit is g/kg DMI, variables of humidity (p=0.0017), body weight (p<0.0001), and feed intake (p=0.0112) have significant effects on enteric CH_4 emission rates, while data across the studies do not provide sufficient evidence of other variables' effects. When the unit is %GEI, variables of humidity

(P=0.0059) and body weight (p=0.0011) significantly affect enteric CH_4 emission rates, and data across the studies do not provide sufficient evidence of other variables' effects.

4.2.2 Analysis of Significant Variables on Enteric CH_4 Emissions

1) g/head/d

Geographic region effects

Differences in enteric CH_4 emission least-squares means caused by different temperatures were significant (p=0.0064). Table 4-8 shows results of multiple pairwise comparisons of least-squares means of enteric CH_4 emission rates between geographic regions. Least-squares means of enteric CH_4 emission rates in Asian, North American, and South American studies present significant differences from least-squares means of enteric CH_4 emission rates in European and Oceanian studies, while least-squares means of enteric CH_4 emission rates do not present significant differences between Asian, North American, and South American studies or between European and Oceanian studies.

Table 4-8 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for all cattle at various regions when the unit is g/head/d

i/j	Asia	Europe	North America	Oceania	South America
Asia	--	**0.0398**	0.3770	**0.0134**	0.7515
Europe	--	--	**0.0296**	0.3738	**0.0402**
North America	--	--	--	**0.0067**	0.5331
Oceania	--	--	--	--	**0.0116**
South America	--	--	--	--	--

Temperature effects

Differences in enteric CH_4 emission least-squares means caused by different temperatures were significant ($p<0.0001$). The relationship between enteric CH_4 emission rates and temperature is a positive association. Linear regression was performed. The fit plot is presented in Figure 4-6 and the linear regression equation is shown below:

$$aa = (135.15 \pm 43.17) + (7.64 \pm 2.57) * p$$

Where: aa is enteric CH_4 emission rates with the unit of g/head/d, p is the variable of air temperature with the unit of ℃. The slope of linear relationship is 7.64±2.57 ℃/ (g/head/d) and R^2 is 0.158.

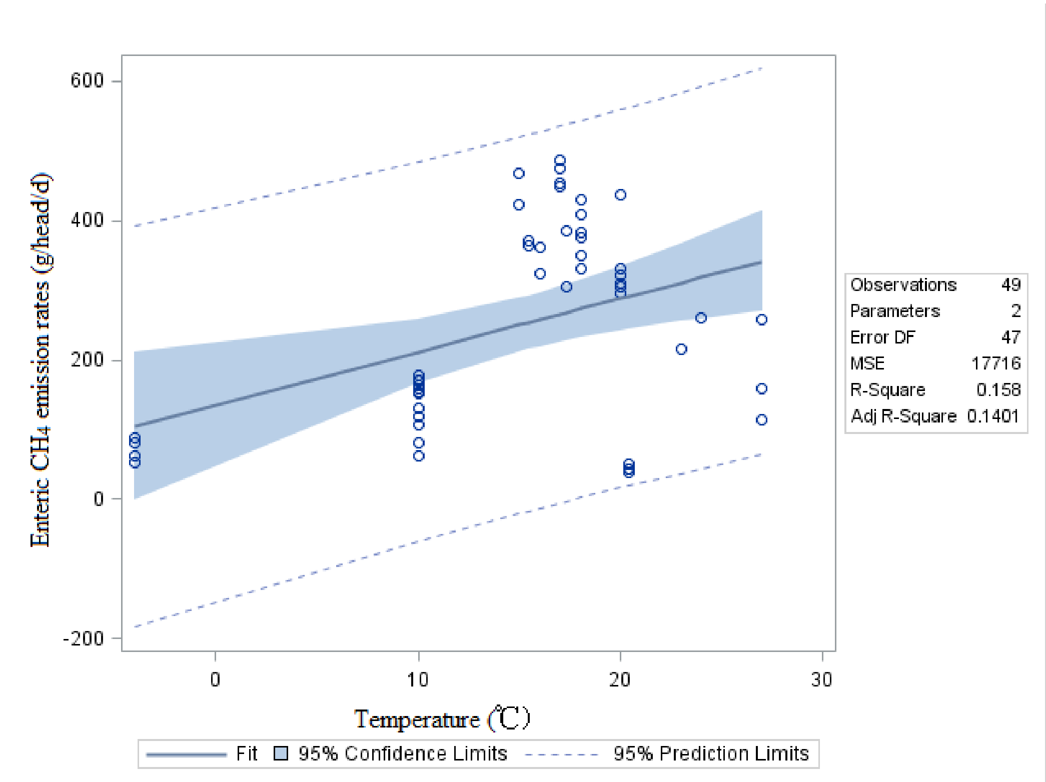


Figure 4-6 Relationship between enteric CH_4 emissions and temperature when the unit is g/head/d

Humidity effects

Differences in enteric CH_4 emission least-squares means caused by varying humidity were significant (p=0.0202). The relationship between CH_4 emissions and humidity is a negative association. The linear regression fit plot is presented in Figure 4-7 and the linear regression equation is shown below:

$$aa = (1188.35 \pm 161.87) + (-14.71 \pm 2.65)*q$$

Where: aa is enteric CH_4 emission rates with the unit of g/head/d, q is the variable of humidity with the unit of %. The slope is -14.71±2.65 %Humidity/(g/head/d) and R^2 is 0.5244.

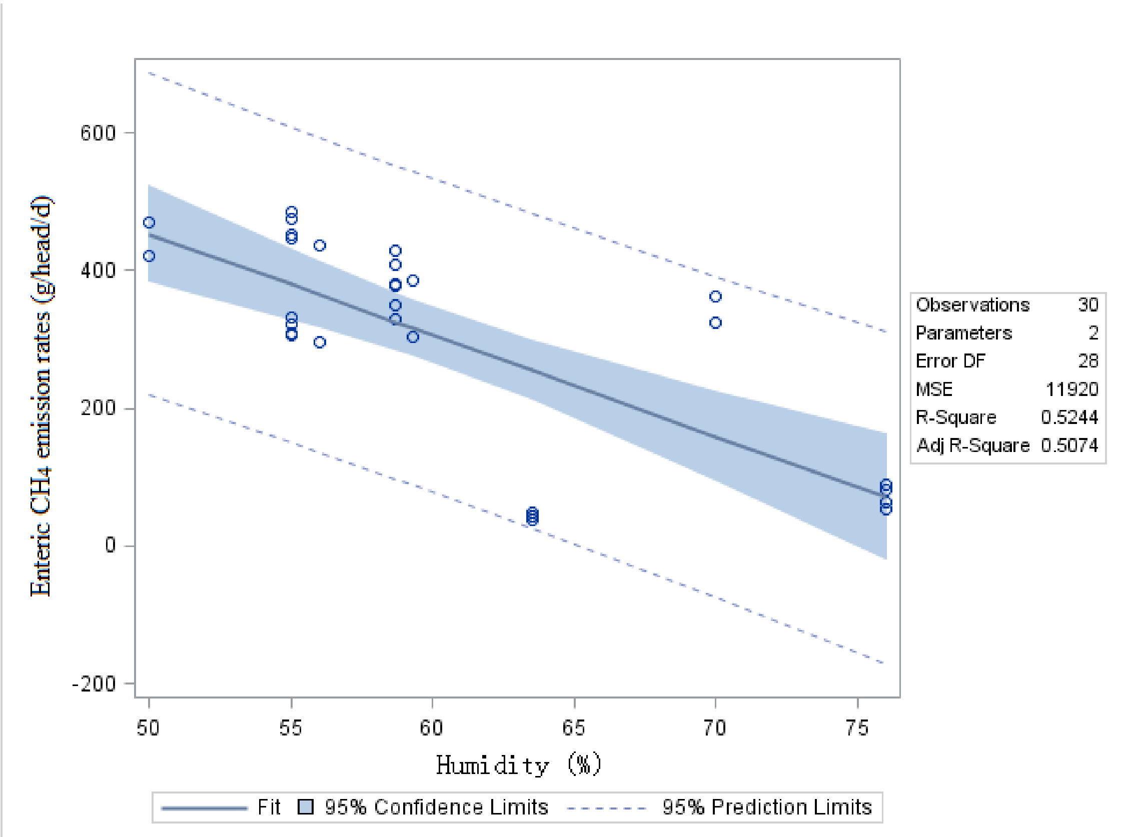


Figure 4-7 Relationship between enteric CH_4 emissions and humidity when the unit is g/head/d

Cattle classification effects

Differences in enteric CH_4 emission least-squares means between dairy and beef were significant ($p<0.0001$), and least-squares means with a 95% confident interval were estimated at 325.83±118.95g/head/d and 149.38±75.19g/head/d for beef and dairy, respectively.

Body weight effects

Differences of enteric CH_4 emission least-squares means caused by various body weights were significant ($p<0.0001$). The relationship between enteric CH_4 emissions and body weights is a positive association. The linear regression fit plot is presented in Figure 4-8 and the linear regression equation is shown below:

$$aa = (-9.38 \pm 25.65)+(0.55 \pm 0.05208)*n$$

Where: aa is enteric CH_4 emission rates with the unit of g/head/d, n is cattle's body weight (BW) with the unit of kg. The slope is 0.55±0.05208 kg BW/(g/head/d) and R^2 is 0.3678.

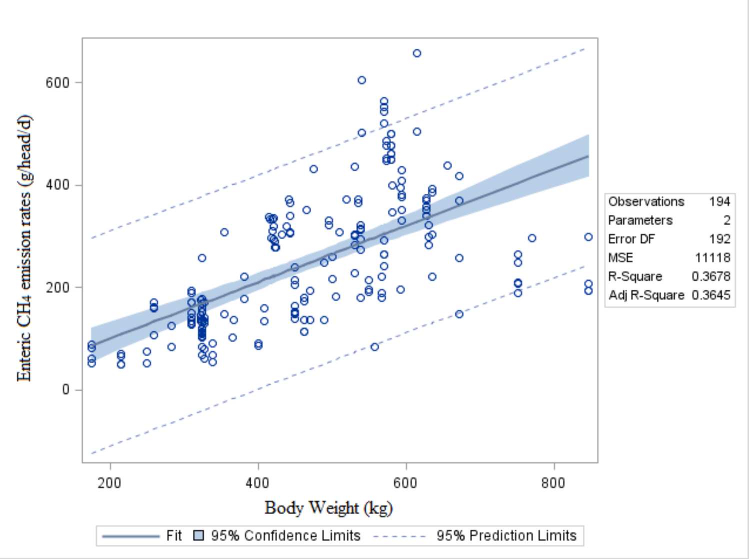


Figure 4-8 Relationship between enteric CH4 emissions and cattle body weights when the unit is g/head/d

Feed intake effects

Differences of enteric CH_4 emission least-squares means caused by feed intake were significant ($p<0.0001$). The relationship between enteric CH_4 emissions and feed intake is a positive association. The linear regression fit plot is presented in Figure 4-9 and the linear regression equation is shown below:

$$aa = (-2.04 \pm 13.67) + (20.59 \pm 0.98) * t$$

Where: aa is enteric CH_4 emission rates with the unit of g/head/d, t is feed intake (FI) with the unit of kg/d. The slope is 20.59±0.9852 kg FI /(g/head/d) and R^2 is 0.7496.

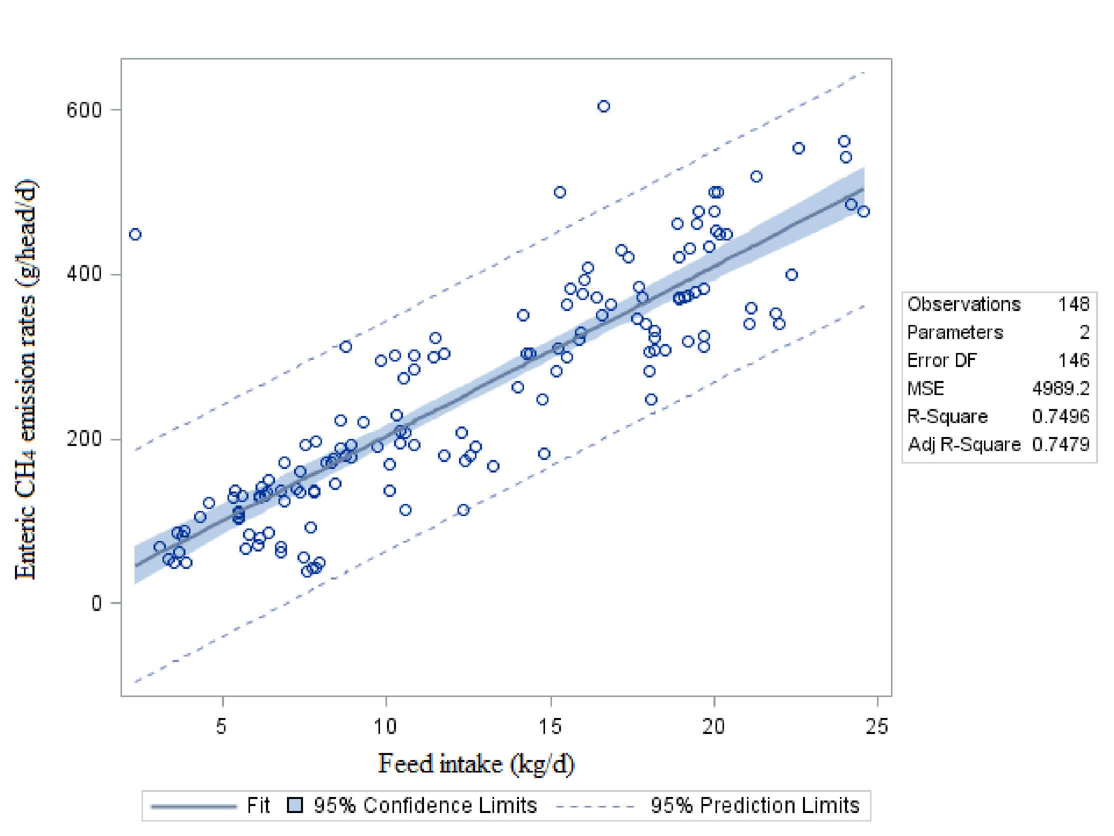


Figure 4-9 Relationship between enteric CH4 emissions and feed intakes when the unit is g/head/d

2) g/kg DMI

Humidity effects

Differences of enteric CH_4 emission least-squares means caused by various humidity were significant (p=0.0017). The linear regression fit plot is presented in Figure 4-10 and the linear regression equation is shown below:

$$u = (26.85 \pm 8.40) + (-0.12 \pm 0.13) * q$$

Where: u is enteric CH_4 emission rates with the unit of g/kg DMI, q is the variable of humidity with the unit of %. The slope is -0.12 ± 0.13 % humidity/(g/head/d) and R^2 is 0.0322.

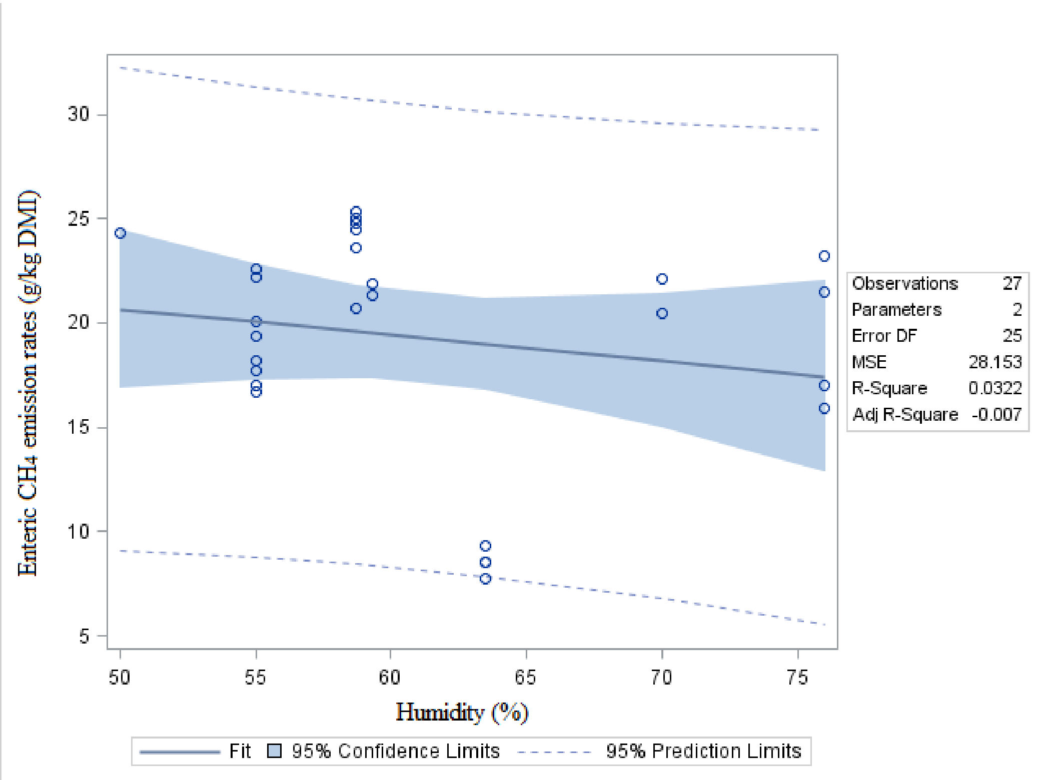


Figure 4-10 Relationship between enteric CH_4 emissions and humidity when the unit is g/kg DMI

Body weight effects

Differences of enteric CH_4 emission least-squares means caused by various body weights were significant ($p<0.0001$). However, discerning whether positive association relationship or negative association relationship exists between enteric CH_4 emissions and body weights is difficult. The linear regression fit plot is presented in Figure 4-11 and the linear regression equation is shown below:

$$u = (17.84 \pm 1.27) + (0.0054 \pm 0.0026)*n$$

Where: u is enteric CH_4 emission rates with the unit of g/kg DMI, n is cattle's body weight (BW) with the unit of kg. The slope is 0.0054±0.0026 (kg BW)/(g/kg DMI) and R^2 is ***0.0273***.

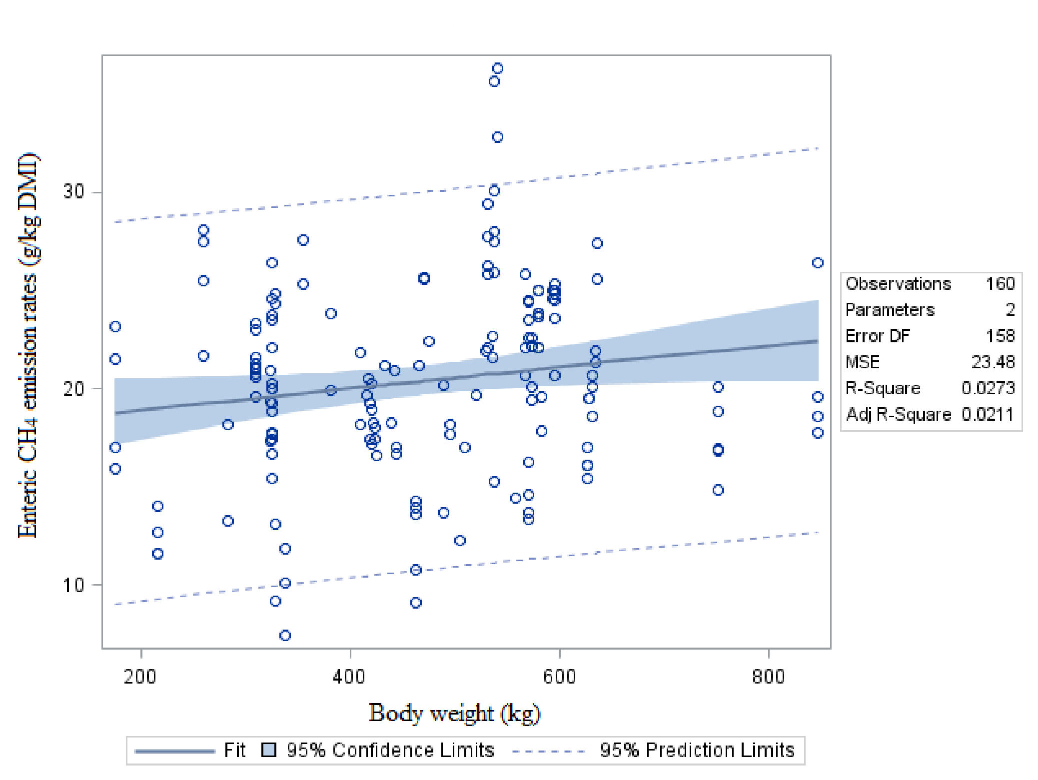


Figure 4-11 Relationship between enteric CH_4 emissions and cattle body weights when the unit is g/kg DMI

Feed intake effects

Differences of enteric CH_4 emission least-squares means caused by feed intakes were significant ($p<0.0001$). However, discerning whether positive association relationship or negative association relationship exists between enteric CH_4 emissions and body weights is also difficult. The linear regression fit plot is presented in Figure 4-12 and the linear regression equation is shown below:

$$u=（18.60\pm0.99）+(0.11\pm0.07)*t$$

Where: u is enteric CH_4 emission rates with the unit of g/kg DMI, t is feed intake (FI) with the unit of kg/d. The slope is 0.11 ± 0.07 (kg FI)/(g/kg DMI) and R^2 is 0.0155.

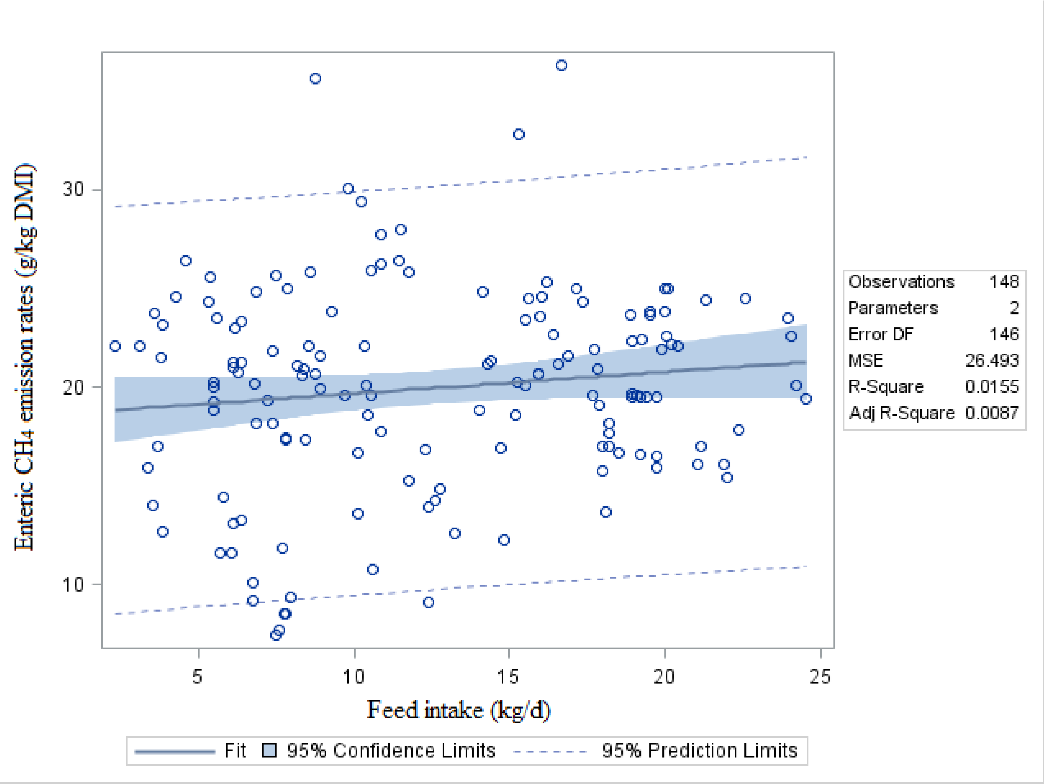


Figure 4-12 Relationship between enteric CH_4 emissions and feed intakes when the unit is g/kg DMI

3) %GEI

Humidity effects

Differences of enteric CH_4 emission least-squares means caused by varying humidity were significant ($p=0.0059$). The relationship between enteric CH_4 emissions and humidity is a positive association. The linear regression fit plot is presented in Figure 4-13 and the linear regression equation is shown below:

$$v = (-13.43 \pm 4.67) + (0.26 \pm 0.07)*q$$

Where: v is enteric CH_4 emission rates with the unit of %GEI, q is the variable of humidity with the unit of %. The slope is 0.26±0.07 %humidity/(g/kg DMI) and R^2 is 0.654.

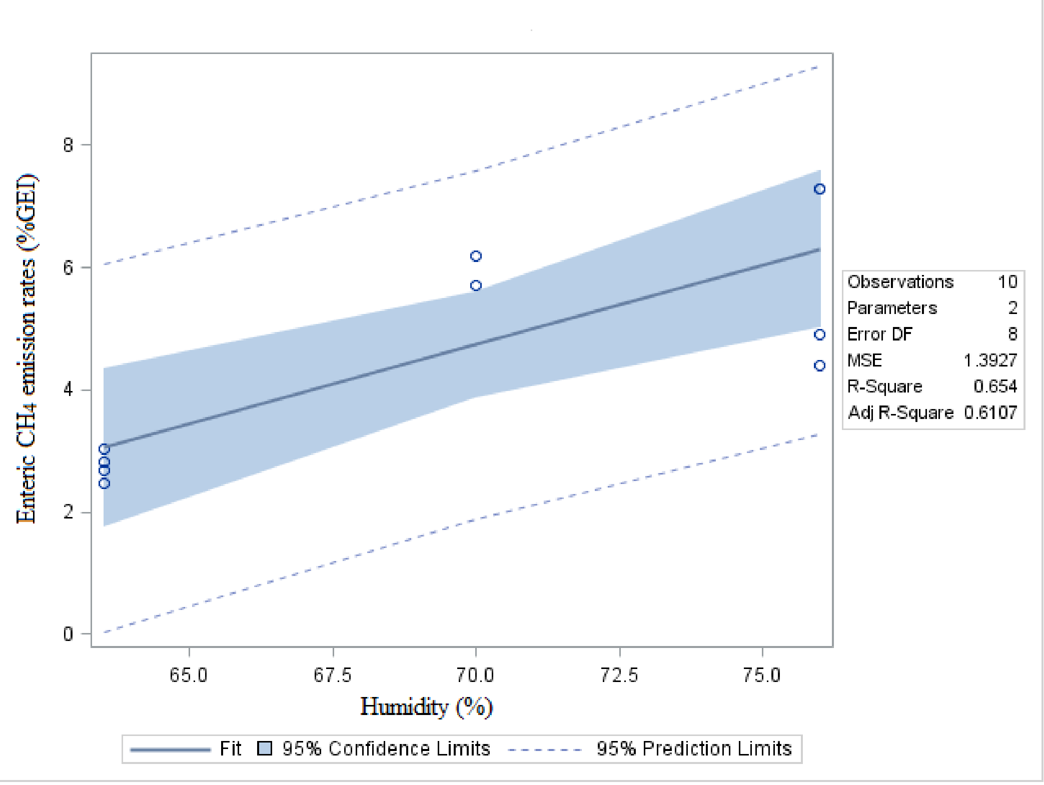


Figure 4-13 Relationship between enteric CH_4 emissions and humidity when the unit is %GEI

Body weight effects

Differences of enteric CH_4 emission least-squares means caused by various body weights were significant (p=0.0011). The linear regression fit plot is presented in Figure 4-14 and the linear regression equation is shown below:

$$v = (5.36 \pm 0.64) + (0.0034 \pm 0.0016)*n$$

Where: v is enteric CH_4 emission rates with the unit of %GEI, n is cattle's body weight (BW) with the unit of kg. The slope is 0.0034±0.0016 (kg BW)/ (g/kg DMI) and R^2 is 0.0623.

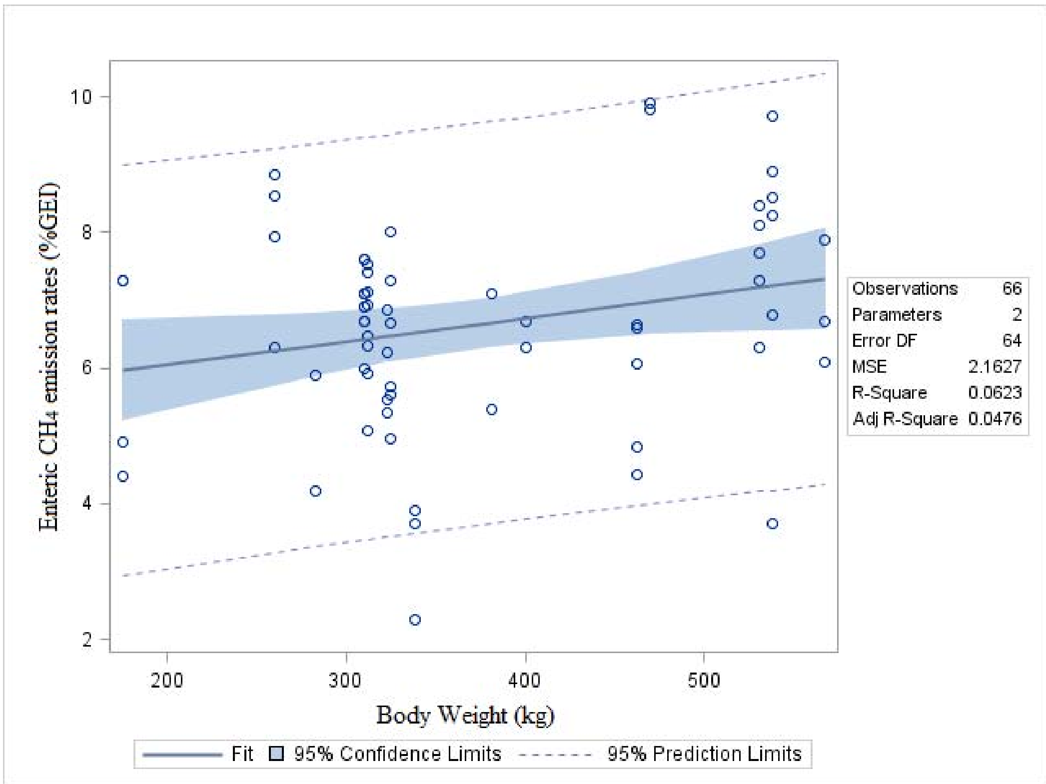


Figure 4-14 Relationship between enteric CH_4 emissions and cattle body weights when the unit is %GEI

4) Comparison of effects from numeric variables on enteric CH_4 emissions with three units

Table 4-9 summarizes the effects from numeric variables of temperature, humidity, body weight, and feed intake on enteric CH_4 emissions. In Table 4-9, the relationship between enteric CH_4 emissions and temperature is positive (slope=7.64±2.57), but the linear regression model is not fitted well when the unit is g/head/d (R^2=0.158, n=49). Relationships between enteric CH_4 emissions and humidity are negative when the units are g/head/d (slope=-14.71±2.65), and g/kg DMI (slope=-0.12±0.13), but the relationship is positive when the unit is % GEI (slope=0.26± 0.07). Linear regression models were fitted well when the units are g/head/d (R^2=0.5244, n=30) and %GEI (R^2=0.654, n=10), but the linear regression model is not fitted well when the unit is g/kg DMI (R^2=0.0322, n=27). Discerning what relationship between humidity and enteric CH_4 emissions is difficult. Relationship between enteric CH_4 emissions and body weight are positive with all three units. Linear regression models are all not fitted well with all three units, especially when the units are g/kg DMI (slope=0.0054±0.0026, R^2=0.0273, n=160) and the % GEI (slope=0.0034±0.0016, R^2=0.0623, n=66). Relationships between enteric CH_4 emissions and feed intake are positive when the units are g/head/d (slope=20.59±0.98) and g/kg DMI (slope=0.11±0.07). The linear regression model is fitted well when the unit is g/head/d (R^2=0.7496, n=148), but linear regression model is not fitted well when the unit is g/kg DMI (R^2=0.155, n=148). What relationship between feed intake and enteric CH_4 emissions with the unit of g/kg DMI need further investigation.

Table 4-9 Regression models between enteric CH_4 emissions and significant numeric variables

Regression model between enteric CH_4 emissions and Temperature				
units	association	equations	R^2	n
g/head/d	Positive	CH_4= (135.15±43.17) + (7.64±2.57)* Temperature	0.158	49
Regression models between enteric CH_4 emissions and Humidity				
units	association	equations	R^2	n
g/head/d	negative	CH_4= (1188.35±161.87) + (-14.71±2.65)* Humidity	0.524	30
g/kg DMI	negative	CH_4= (26.85±8.40) + (-0.12±0.13)* Humidity	0.0322	27
% GEI	positive	CH_4= (-13.43±4.67) + (0.26±0.07)* Humidity	0.654	10
Regression models between enteric CH_4 emissions and body weight				
units	association	equations	R^2	n
g/head/d	positive	CH_4= (-9.38±25.65) + (0.55±0.052)* BW	0.368	194
g/kg DMI	positive	CH_4= (17.84±1.27) + (0.0054±0.0026)* BW	0.0273	160
% GEI	positive	CH_4= (5.36±0.64) + (0.0034±0.0016)* BW	0.0623	66
Regression models between enteric CH_4 emissions and feed intake				
units	association	equations	R^2	n
g/head/d	positive	CH_4= (-2.04±13.67) + (20.59±0.98)* FI	0.750	148
g/kg DMI	positive	CH_4= (18.60±0.99) + (0.11±0.07)* FI	0.0155	148

4.2.3 Analysis of Variables of Sub-classification and Production Stage on Enteric CH_4 Emissions

1) g/head/d

Effects from two variables of sub-classification and production stage on enteric CH_4 emission rates from beef and dairy were analyzed. Results are provided in Table 4-10. For beef cattle, the p value of effects from different production stages is below 0.001, showing that the production stage significantly affects enteric CH_4 emission rates. The p value of effects from the sub-classification is 0.7674, meaning that data across the studies does not provide evidence that various sub-classifications have different enteric CH_4 emission rates. For dairy cattle, p values of the effects from different sub-classifications and production stages are below 0.05, meaning that both variables significantly affect enteric CH_4 emission rates.

Table 4-10 Analysis results of effects from sub-classification and production stage on enteric CH_4 emissions when the unit is g/head/d

	P values of causes of variation	
variables	**Beef**	**Dairy**
Sub-classification	0.767	***0.0439***
Production Stage	0.144	***<0.0001***

Sub-classification effects

Multiple pairwise comparisons of least-squares means of enteric CH_4 emissions between different sub-classifications of dairy were analyzed. Table 4-11 shows results of multiple pairwise comparisons. According to p values in Table 4-11, three sub-groups are divided. The first sub-group is comprised of Friesians, Friesian × Jersey, Holstein, and Holstein-Friesian. The second sub-group is comprised of Jersey, and the third sub-group is comprised of Swedish Red and Swedish Brown. The least-squares means of enteric CH_4 emissions have significant differences between sub-groups, but do not provide evidence of the differences within groups.

Table 4-11 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for sub-classifications of dairy when the unit is g/head/d

i/j	Friesians	Friesian × Jersey	Holstein	Holstein-Friesian	Jersey	Swedish Red	Swedish Brown
Friesians	--	0.8220	0.5191	0.2968	0.2799	***0.0398***	0.4998
Friesian × Jersey	0.8220	--	0.4447	0.4529	0.1729	0.0649	0.6743
Holstein	0.5191	0.4447	--	0.3788	0.0005	***0.0018***	0.0989
Holstein-Friesian	0.2968	0.4529	0.3788	--	0.1469	0.0900	0.7801
Jersey	0.2799	0.1729	***0.0005***	0.1469	--	***0.0004***	***0.0238***
Swedish Red	***0.0398***	0.0649	***0.0018***	0.0900	***0.0004***	--	0.0906
Swedish Brown	0.4998	0.6743	0.0989	0.7801	***0.0238***	0.0906	--

Production stage effects

Table 4-12 show results of multiple pairwise comparisons of least-squares means of enteric CH_4 emission rates at various production stages from dairy cattle. The least-squares means of enteric CH_4 emission rates at the stage of dry are significantly different from those at the lactating, early lactating, and mid-lactating stages. However, data across the studies does not provide evidence of significant differences between crossed, fattening, finishing, growing, and yearling stages for beef cattle, and between lactating, early lactating, mid-lactating, late-lactating, and non-pregnant and non- lactating stages for dairy cattle.

Table 4-12 Pr> ∣ t ∣ H0: LSMEAN (i) = LSMEAN (j) for dairy at production stages when the unit is g/head/d

i/j	Dry	early- lactating	Mid-lactating	late-lactating	lactating	non-pregnant non-lactating
Dry	--	***0.0285***	***0.0148***	0.3019	**<*.0001***	0.8409
early- lactating	***0.0285***	--	0.5863	0.9678	0.4143	0.2488
Mid-lactating	***0.0148***	0.5863	--	0.6857	0.114	0.1279
late-lactating	0.3019	0.9678	0.6857	--	0.766	0.3696
lactating	**<*.0001***	0.4143	0.114	0.7261	--	0.3696
non-pregnant non-lactating	0.8409	0.2488	0.1279	0.3702	0.3696	--

2) g/kg DMI

The least-squares means of enteric CH_4 emissions did not show significant differences between dairy and beef (p=0.6750). However, effects of cattle characteristic variables such as sub-classification and production stage on enteric CH_4 emission rates from beef and dairy were further analyzed. Results are presented in Table 4-13. For beef cattle, P value of effects from variables of sub-classification and production stage is 0.2413 and 0.8018, indicating that the variables of sub-classification and production stage do not show significant effects. For dairy cattle, p values of variables of sub-classification and production stage are 0.9440 and 0.0576, respectively, demonstrating that those variables do not show significant effects on enteric CH_4 emission rates.

Table 4-13 Results of effects from sub-classification and production stage on enteric CH_4 emissions when the unit is g/kg DMI

	P values of causes of variation	
variables	**Beef**	**Dairy**
Sub-classification	0.2413	0.9440
Production Stage	0.8018	0.0576

3) %GEI

Enteric CH_4 emission least-squares means did not show significant differences between dairy and beef (p=0.2151). However, the effects of cattle characteristics variables such as sub-classification and production stage on enteric CH_4 emission rates from beef and dairy were further analyzed. Results are presented in Table 4-14. For beef cattle, the p value of effects from various production stages is below 0.05, showing that the variable of production stages significantly affects enteric CH_4 emission rates. The p value of effects from various sub-classifications is 0.0939, meaning that the variable of sub-classification does not show significant effects. For dairy cattle, the p values of effects from the variables of sub-classification and production stage are above 0.05, indicating that those variables do not show significant effects.

Table 4-14 Results of effects from sub-classification and production stage on enteric CH_4 emissions when the unit is %GEI

	P values of causes of variation	
variables	**Beef**	**Dairy**
Sub-classification	0.0939	0.9440
Production Stage	***0.0001***	0.0576

Production stage effects

Table 4-15 shows results of multiple pairwise comparisons of least-squares means of enteric CH_4 emission rates at various production stages from beef. Least-squares means of enteric CH_4 emission rates at the stage of growing have significant differences from other stages such as crossed, finishing, and yearling.

Table 4-15 Pr> | t | H0: LSMEAN (i) = LSMEAN (j) for beef at production stages when the unit is %GEI

	Fettening	Finishing	Growing	Yearling
Fattening	/	/	**/**	/
Finishing	/	--	**<0.0001**	0.5617
Growing	***/***	***<0.0001***	--	<***0.0001***
Yearling	/	0.0.5617	<***0.0001***	--

4) Comparison of effects from variables of sub-classification and production stages on enteric CH4 emissions between beef and dairy with three units

Table 4-16 summarizes effects from variables of sub-classification and production stage on enteric CH_4 emissions. When the unit is g/head/d, emissions from dairy cattle are significant differences in different sub-classifications and in different product stages. When the units is %GEI, emissions from beef cattle are significant differences in different production stages.

Table 4-16 Effects from variables of sub-classification and production stage on enteric CH_4 emissions

	g/head/d		g/kg DMI		% GEI	
	Beef	Dairy	Beef	Dairy	Beef	Dairy
Sub-classification	--	+	--	--	--	--
Production stage	--	+	--	--	+	--

Note: -- means that there were no significant effects on enteric CH_4 emissions; + means that there were significant effects on enteric CH_4 emissions.

4.2.4 Analysis of Diet mitigation Strategies on Enteric CH_4 Emissions

1) Concentration effects

Table 4-17 summarizes enteric CH_4 emission reductions caused by different proportions of concentrate within the diet across the studies. According to Table 4-20, the relationship between enteric CH_4 emission reductions and concentrate proportions within the diet is a positive association (i.e., increasing concentrate proportions within the diet can reduce enteric CH_4 emissions).

Table 4-17 Effectiveness of various concentrate proportions on enteric CH_4 emission reduction

References	Concentrate proportion in diet (%)	Relative Reduction Percentages in enteric CH_4 emissions (%)		
		Kg/head/d	g/kg DMI	%GEI
(Ding et al., 2010)	40	29.58	26.72	31.94
	60	39.93	31.46	38.89
	4.5	4.86	1.159	--
(DK Lovett et al., 2005)	24.40	--	10.08	--
	35	62.33	31.26	20.37
(D Lovett et al., 2003)	60	50.78	28.03	12.88
	90	68.92	53.09	41.66
	10	2.80	3.15	2.44
(Patel et al., 2011)	30	9.16	5.96	5.92
	50	14.61	12.98	11.15

Differences of relative reduction percentages of enteric CH_4 emissions caused by various proportions within the diet were significant (i.e., p value was 0.0047 when the unit was g/head/d; p value was 0.0001 when the unit was g/kg DMI, and p value was 0.0115 when the unit was %

GEI). Linear regression equations are shown in Table 4-18. The slope is 0.74±0.19, 0.56±0.088, and 0.45±0.13 for unit of g/head/d, g/kg DMI, and %GEI, respectively.

Table 4-18 Regression models between relative reduction percentages in enteric CH_4 emissions and concentration proportions within the diet

units	association	equations	R^2	n	Fit plot
g/head/d	positive	b=(0.39±8.83)+(0.74±0.19)*a	0.524	10	b
g/kg DMI	positive	c=(-1.95±3.96)+(0.56±0.088)*a	0.818	11	c
% GEI	positive	d=(-0.53±6.54)+(0.45±0.13)*a	0.6228	9	d

Note: a is concentration proportion in the diet; b is relative reduction percentage in enteric CH_4 emissions when the unit is g/head/d; c is relative reduction percentage in enteric CH_4 emissions when the unit is g/kg DMI; d is relative reduction percentage in enteric CH_4 emissions when the unit is %GEI; Relative reduction percentage = (control emission-mitigation emission)/(control emission)X100%)

2) Feed additive and plant secondary compound effects

Table 4-19 provides mitigation effects through feed additives or plant secondary compounds across the studies. Chemicals such as alga, archaeol, canola, fumaric-acid, and nitrate are feed additives that can reduce CH_4 emissions from intensive ruminant production systems.

Table 4-19 Effectiveness of various chemicals on enteric CH_4 emission reduction

Chemical	Content in the diet (%)	Relative Reduction Percentages in enteric CH_4 emissions (%)			References
		g/head/d	g/kg DMI	%GEI	
Algal	10.4	-3.68	-3.98	--	(Moate et al., 2013)
	20.8	-1.84	-8.41	--	
	31.2	4.23	-7.96	--	
Archaeol	0.12	18.54	--	--	(McCartney et al., 2013)
	0.065	5.64	--	--	
	0.011	16.39	--	--	
	0.0072	--	--	--	
Canola	4.60	32.2	14.90	20.55	Beauchemin et al., 2006
	9.32	9.55	15.95	18.36	Beauchemin et al., 2009
Coconut	1.3	3.46	--	--	(Hollmann et al., 2010; Jordan et al., 2006)
	2.7	37.01	--	--	
	3.3	45.88	--	--	
	7.1	18.78	19.80	22.78	
Copra	86.00	14.89	14.37	15.18	(Jordan et al., 2006)
Cottonseed	9.26	17.05	9.64	--	(Grainger, Williams, Clarke, et al., 2010)
Essential-oil	0.017	-2.38	-7.84	2.32	Beauchemin et al., 2006
Flaxseed	9.32	17.74	17.79	-7.57	Beauchemin et al., 2009
Fumaric-acid	2.8	-7.09	-10.19	20.40	Beauchemin et al., 2006
	--	--	--	-11.60	
Linseed	5	11.65	--	-5.61	(Chung et al., 2011; Martin et al., 2008)
	5	38.27	--	14.93	
	15	.	--	28.36	
	15	.	--	20.27	
	5	64.31	--	25.63	

Malic-acid	8	1.388518	--	55.22	(Foley et al., 2009)
Monensin	0.235	-1.11607	-1.80	8.66	(Grainger et al., 2008; Grainger, Williams, Clarke, et al., 2010)
	0.24	-2.10084	-3.60	--	
	1.69	0.970874	-1.79	--	
	1.69	-7.03812	--	--	
Nitrate	2.2	32	26.92	--	(Brown et al., 2011; Hulshof et al., 2012; Van Zijderveld, Gerrits, et al., 2011)
	8.8	17.0088	17.27	28.81	
	8.8	15.63342	18.88	17.54	
	8.8	15.87302	14.87	17.54	
	8.8	14.88251	15.38	16.39	
	1.15	16.51516	16.93	16.39	
	2.3	20.30303	7.50	19.24	
	4.6	22.87879	16.98	9.18	
Soybean	34.1	25.25399	15.04	2.80	(Jordan et al., 2006)
Soy-oil	6.7	39.11466	37.39	5.13	(Jordan et al., 2006)
Sunflower	10.55	9.897611	10.43	41.03	(K. Beauchemin et al., 2009; K. A. Beauchemin et al., 2006; K. A. Beauchemin et al., 2007; Boadi et al., 2004)
	.	.	.	12.25	
	3.4	13.92334	11.50	21.48	
	14	.	.	16.04	
	8.9	32.58174	23.00	.	
Tallow	3.4	13.52875	11.00	25.49	(K. A. Beauchemin et al., 2007)
Tannin	4.00	28.22	--	--	Beauchemin et al., 2007; Grainger et al., 2009
	0.90	14.25	10.04	--	
	1.8	28.96	22.37	--	
Quillaja saponaria	1.0	3.69	4.34	3.99	Holtshausen et al., 2009
Yucca scgudugera	1.0	-1.90	-5.59	-5.67	Holtshausen et al., 2009

According to data from twenty studies, -3.68 % - 64% reductions in enteric CH_4 emissions could be achieved by feed additives. Chemical, such as tannin, quillaja saponaria, yucca scgudugera, and fat, are plant secondary compounds, which can reduce enteric CH_4 emissions through a direct toxic effect on methanogens. Tannin can reduce enteric CH_4 production, but percentage relative reduction increases with increasing content of tannin at very low content; however, no changes of relative reduction percentage occur when tannin content increases from 1.8% to 4.0%. Quillaja saponaria can also reduce enteric, and relative reduction percentage is low comparison with tannin. Fat has negative effects on enteric CH_4 emissions, but mitigation effects are dependent on fat composition. In Table 4-21, coconut oil could achieve 45.88% of relative reduction percentages while linseed could achieve 64.5%.

Table 4-20 shows overall effectiveness analysis of feed additive or plant secondary compound mitigation. According to p values of feed additive or plant secondary compound mitigation in Table 4-20, different chemicals have significant mitigation effects on enteric CH_4 emissions with three units. Least-squares means of relative reduction percentages were computed and are presented in Table 4-20. Soy-oil is one of the most effective chemicals to reduce enteric CH_4 emission, and the least-squares means of relative reduction percentage could be above 35 % with three units. Other chemicals, including canola, coconut, linseed, nitrate, and tannin, also have significant effects on reduction of enteric CH_4 emission and their least-squares means of percentage relative reduction are all above 15%.

Table 4-20 Overall effectiveness analysis of feed additive or plant secondary compound mitigation

parameters	P values of feed additive or plant secondary compound mitigation		
	g/head/d	g/kg DMI	%GEI
Chemical	0.0453	0.0015	0.0265
	Least-squares means of relative reduction percentages (%)		
algal	-0.42±7.18	-6.78±3.87	--
archaeol	13.53±7.18	--	--
canola	***20.87±8.80***	***16.17±3.58***	***19.46±6.43***
coconut	***26.28±6.22***	***19.80±5.16***	***22.78±9.10***
copra	14.89±12.45	14.37±5.16	15.18±9.10
cottonseed	17.05±12.45	9.64±5.16	--
essential-oil	-2.38±12.45	-7.40±5.00	-7.56±9.10
flaxseed	***17.74±12.45***	***18.85±4.87***	***20.40±9.10***
fumaric-acid	-7.09±12.45	-9.75±5.00	-7.69±6.43
Linseed	***38.07±7.18***	--	***28.88±4.07***
malic-acid	1.38±12.45	--	1.38±12.6
monensin	-2.32±6.22	-2.33±3.27	8.65±9.10
nitrate	***19.38±4.40***	***17.73±2.37***	***18.40±3.21***
soy-oil	***39.11±12.45***	***37.39±5.16***	***41.02±9.10***
soybean	25.25±12.45	15.04±5.16	5.12±9.10
sunflower	18.80±7.18	14.32±3.23	18.81±4.55
tallow	13.52±12.45	9.494.97	14.24±9.10
Tannin	***23.81±7.01***	***16.20±4.34***	**--**
Quillaja saponaria	3.69±12.14	4.34±5.54	3.99±8.95
Yucca scgudugera	-1.90±12.14	-5.59±5.54	-5.67±8.95

4.3 Aim 3: Evaluation of the Intergovernmental Panel on Climate Change Approaches

4.3.1 Overall Comparison of Measured Emissions and IPCC (2006) Estimated Emissions

Figure 4-15, 4-16, and 4-17[4] show differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on total cattle data pool, the beef cattle data pool, and the dairy cattle pool, respectively. Table 4-23, 4-24, and 4-25 present test results of normality distribution of the differences.

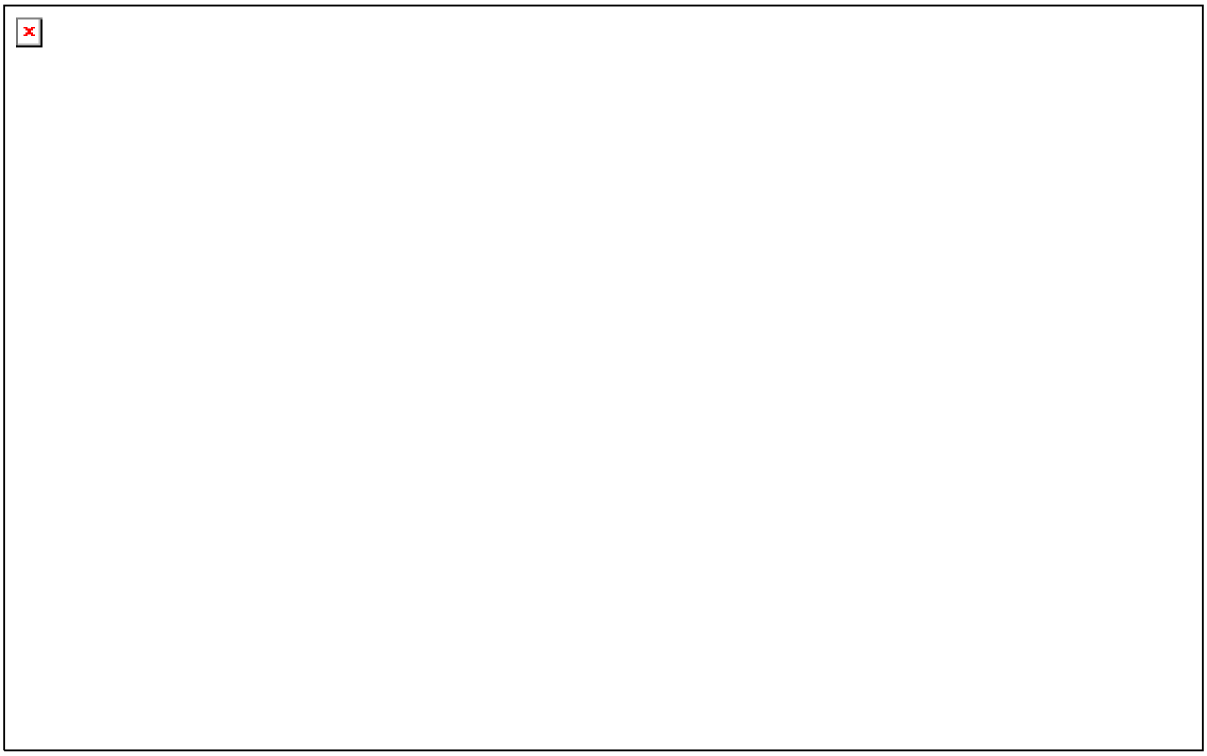


Figure 4-15 Box plot of differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the total cattle data pool

[4] The data of moments (including skewness and kurtosis), means, medians, and extreme values are attached in Appendix F

In Figure 4-15, most data points are observed when differences between measured emissions and IPCC Tier 1 and Tier 2 estimated emissions are approximate to 0, indicating effectiveness of IPCC Tier 1 and Tier 2. Results of normal distribution test are shown in the Table 4-21. Differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on total cattle data pool have not a normal distribution with Kolmogorov-Smirnov (p=0.049 for IPCC Tier 1, and p=0.0391 for IPCC Tier 2) and Anderson-Darling's test (p=0.005 for IPCC Tier 1, and p=0.0129 for IPCC Tier 2), therefore, some emission factors of IPCC Tier 1 and Tier 2 need to be revised.

Table 4-21 Normality test for differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on total cattle data pool

	Tier 1		Tier 2	
	Test	P-value	Test	P-value
Kolmogorov-Smirnov	0.0696	0.0490	0.105	*0.0391*
Anderson-Darling	1.218	0.005	0.994	*0.0129*

In Figure 4-16, most data points are observed when differences between measured emissions and IPCC Tier 1 and Tier 2 estimated emissions for beef cattle are approximate to 0. Results of normal distribution test are shown in Table 4-22. Differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the beef cattle data pool have not a normal distribution with Kolmogorov-Smirnov (p=0.0168 for IPCC Tier 1 and p=0.0010 for IPCC Tier 2) and Anderson-Darling's test (p=0.005 for IPCC Tier 1 and p=0.0050 for IPCC Tier 2), therefore, some emission factors of IPCC Tier 1 and Tier 2 for beef cattle need to be revised.

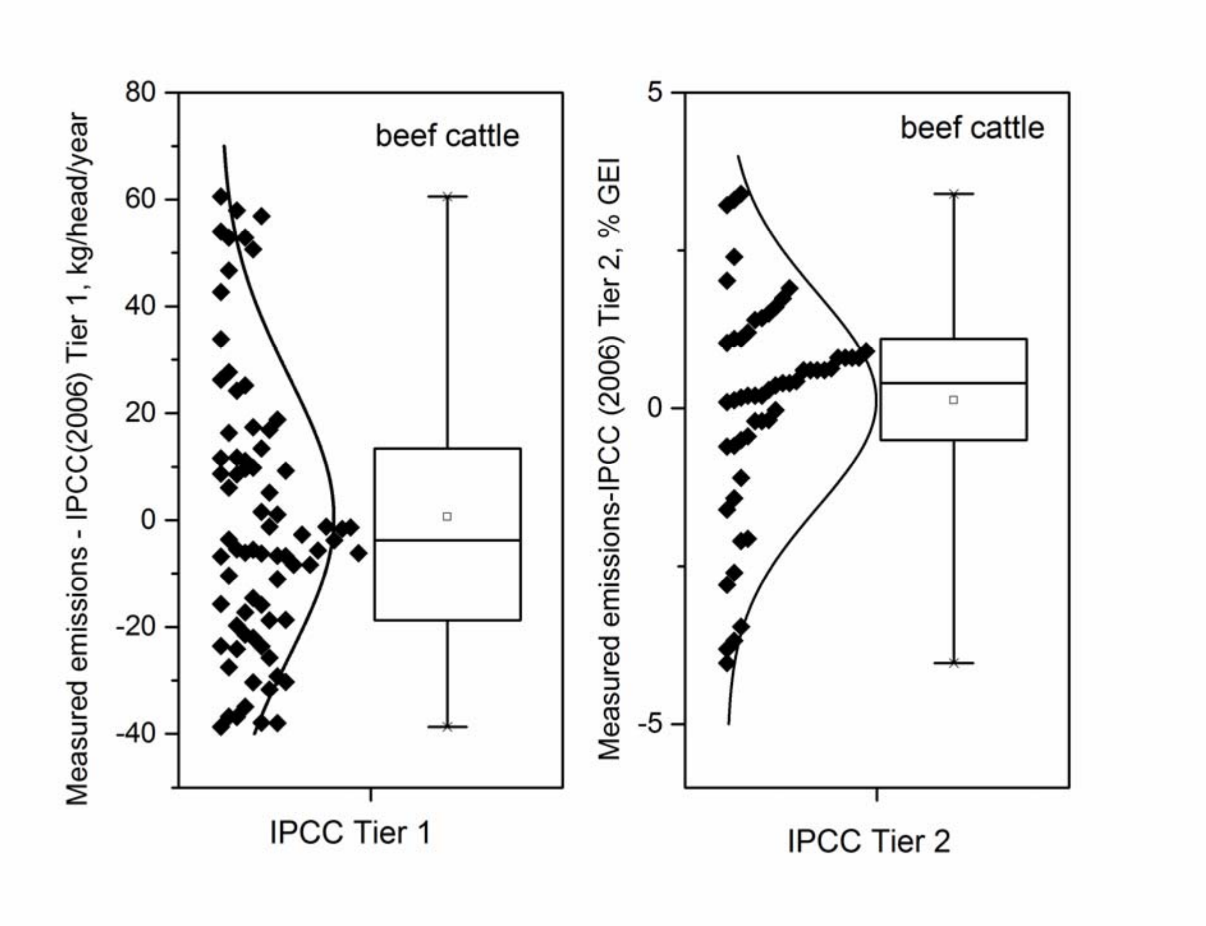


Figure 4-16 Box plot of differences between measured emissions and IPCC (2006) estimated emissions based on the beef cattle data pool

Table 4-22 Normality test for differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the beef cattle data pool

	Tier 1		Tier 2	
	Test	P-value	Test	P-value
Kolmogorov-Smirnov	0.114	0.0168	0.1508	0.0010
Anderson-Darling	1.159	0.005	1.391	0.0050

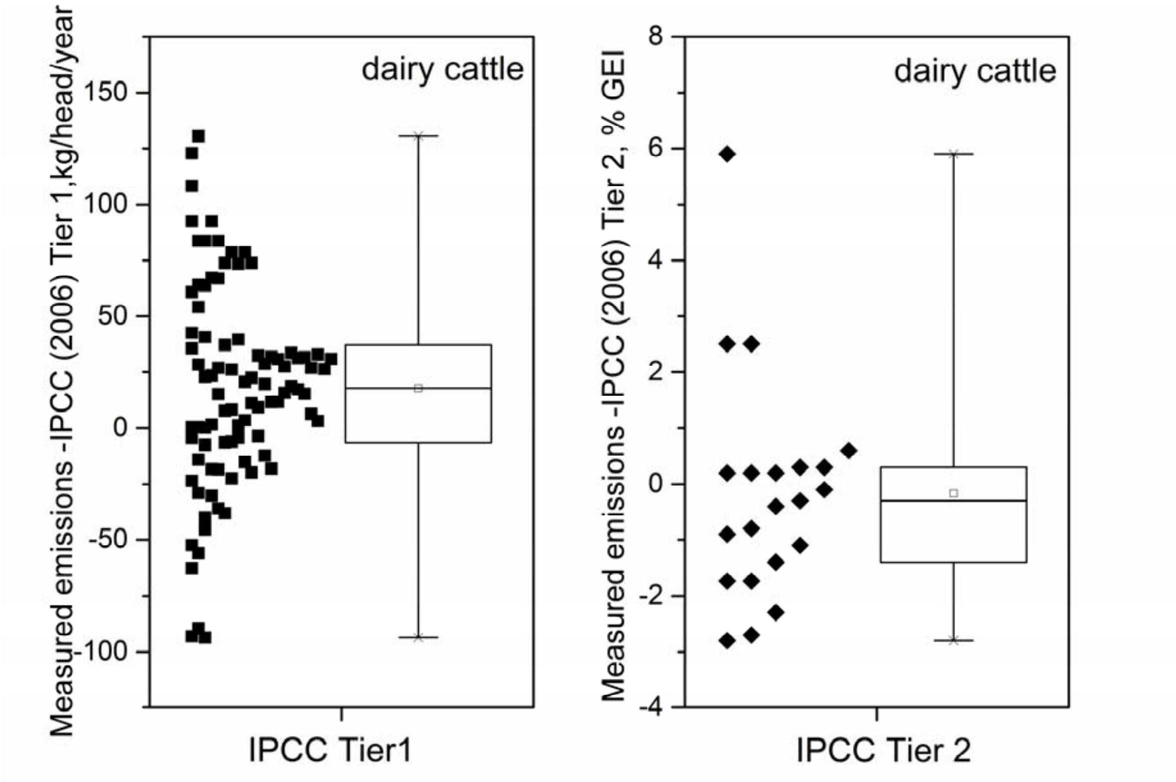


Figure 4-17 Box plot of differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the dairy cattle data pool

In Figure 4-17, most data points of differences between measured emissions and IPCC Tier 2 estimated emissions for dairy cattle lie approximate to 0 and below 0, while most data points of differences between measured emissions and IPCC Tier 1 estimated emissions lie above 0, indicating that IPCC Tier 2 may overestimate most of the enteric CH_4 emissions and IPCC Tier 1 may underestimate most of enteric CH_4 emissions. In addition, results of normal distribution test are shown in the Table 4-23. The number of data points to test the normal distribution for IPCC Tier 1 is 90 (more than 50), so the result of Kolmogorov-Smirnov has more power than that of Anderson-Darling's test. Results show that differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the dairy cattle data pool have not a normal distribution with Kolmogorov-Smirnov (p=0.049 for IPCC Tier 1, and p=0.0391 for IPCC Tier 2) and Anderson-Darling's test (p=0.0129 for IPCC Tier 2). Therefore, some emission factors of IPCC Tier 1 and Tier 2 for dairy cattle need to be revised.

Table 4-23 Normality test for the differences between measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the dairy cattle data pool

	Tier 1		Tier 2	
	Test	P-value	Test	P-value
Kolmogorov-Smirnov	0.096	0.042	0.22	0.012
Anderson-Darling	0.57	***0.14***	0.78	0.038

4.3.2 Comparison of Measured Emissions and IPCC (2006) Estimated Emissions on Study-level and on Region-level

A comparison of results of measured emissions and IPCC (2006) estimated emissions across the studies are delineated in Figures 4-18 to 4-24 and Tables 4-26 to 4-28. Figures 4-18 to 4-20 display forest plots with two evaluation methods: PRD (aggregated study-level effect size and region-level effect size) and paired t-test (aggregated study-level effect size and region-level effect size). Study-level effect sizes of PRD are represented by squares and lines represent SD, while Study-level effect sizes of paired t-test are numerical. Diamonds illustrate effect sizes of region-level with the center line of the diamond representing means and lines representing associated 95% confidence intervals (CIs). Figures 4-26 and 4-28 show results based on total cattle data pool across the studies. IPCC effectiveness through two evaluation methods of PRD and paired t-test in various regions are summarized in Table 4-24. Figures 4-20 to 4-22 depict results based on the beef cattle data pool across the studies. IPCC effectiveness for beef cattle in various regions is outlined in Table 4-25. Figures 4-23 to 4-25 demonstrate results based on dairy cattle data pool across the studies. IPCC effectiveness for dairy cattle in various regions is recapitulated in Table 4-26.

1) The total cattle data pool across the studies

According to Figure 4-18, 52 studies were evaluated by PRD and 37 studies by paired t-test. In three Asian studies, all of PRD intervals are either above 0 or below 0, indicating the ineffectiveness of IPCC Tier 1, and p values of paired t-tests also show significant differences between measured enteric CH_4 emissions and IPCC Tier 1 estimated emissions in studies of Chaokaur (2011) ($p=0.0024$) and Ding (2010) ($p=0.0061$) and no significances in the study of Kasuya (2010) ($p=0.0545$).

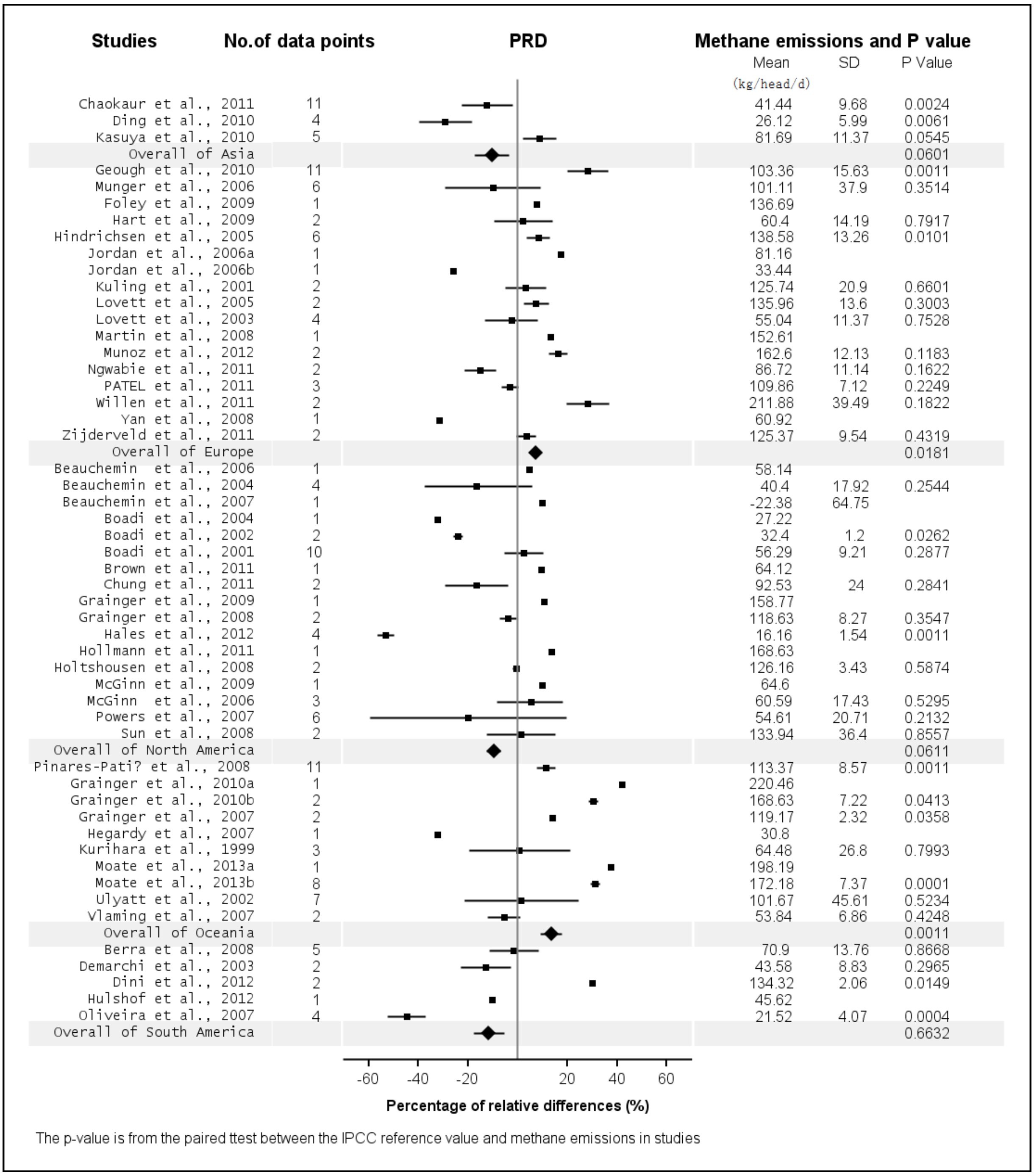


Figure 4-18 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 1 estimated emissions based on the total cattle data pool across the studies

In seventeen European[5] studies, PRD intervals from thirteen studies are either above 0 or below 0 and other four studies are not, and p values from twelve studies show significant differences in studies of Geough (2010) (p=0.001) and Hindrichsen (2005) (p=0.0101) and no significances in other ten studies. In seventeen North American studies, PRD intervals from twelve studies are either above 0 or below 0 and other five studies are not, and p values of ten studies' paired t-tests show significant differences in the studies of Boadi (2002) (p=0.0262) and Hales (2005) (p=0.001) and no significances in other eight studies. In ten Oceanian studies, PRD intervals from seven studies are either above 0 or below 0 and other three studies are not, and p values of seven studies' paired t-tests show significant differences in studies of Pinares-Patino (2008) (p=0.001), Grainger (2010b) (p=0.0413), Grainger (2007) (p=0.0358), and Moate (2013b) (p=0.0001) and no significances in other three studies. In five South American studies, PRD intervals from four studies are either above 0 or below 0 and only one study is not, and p values of four studies' paired t-tests show significant differences in studies of Dini (2012) (p=0.0149) and Oliveira (2007) (p=0.0004) and no significances in other two studies. Therefore, 38 studies show ineffective estimation of IPCC Tier 1 among total 52 studies by PRD method and 11 studies show significant differences between measured enteric CH_4 emissions and IPCC Tier 1 estimated emissions among total 37 studies by paired t-tests based on total cattle data pool.

[5] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

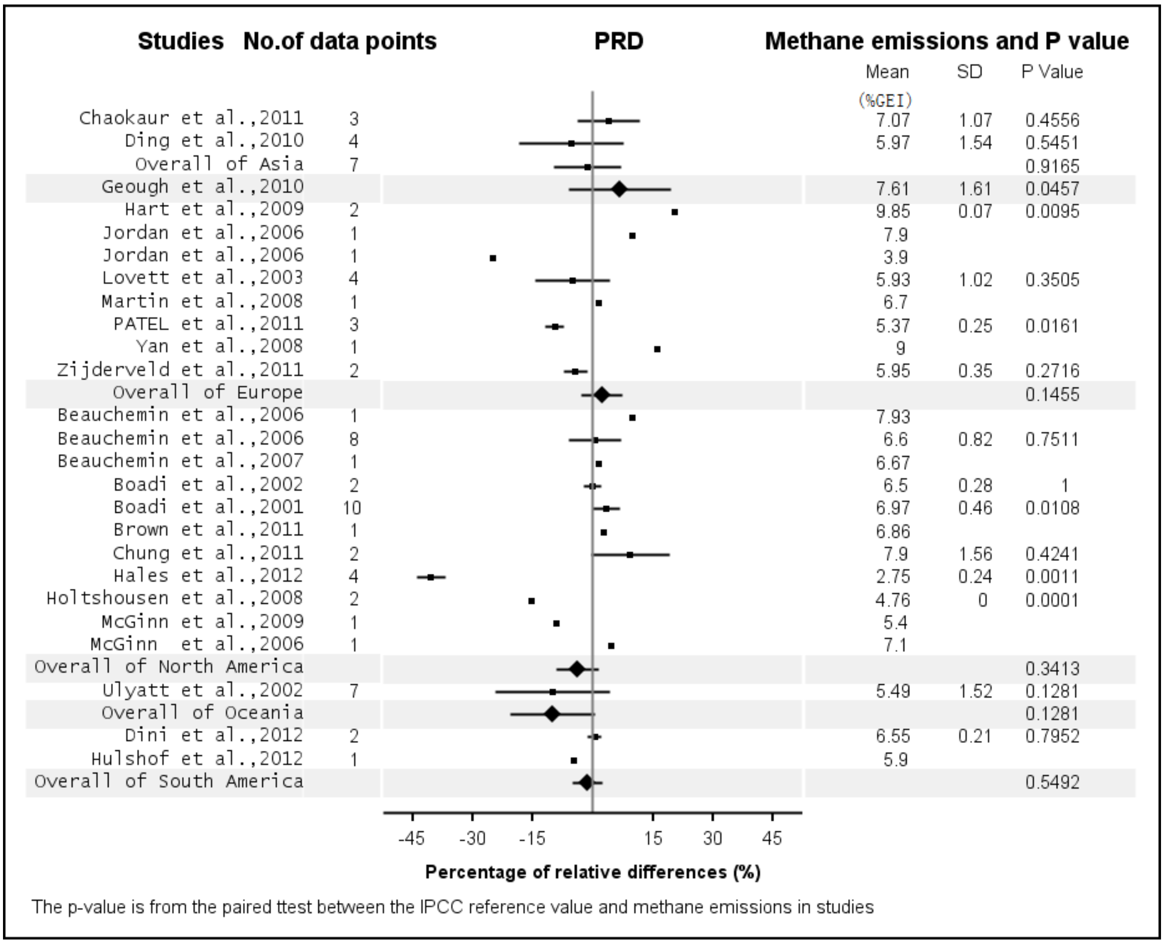


Figure 4-19 Forest plot of the differences between measured enteric CH_4 emissions and IPCC (2006) Tier 2 estimated emissions for all types of cattle across the studies

In Figure 4-19, 25 studies were evaluated by PRD and 15 studies by paired t-test. In two Asian studies, PRD intervals include 0, indicating the effectiveness of IPCC Tier 2, and p values of paired t-tests also do not show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions. In nine European[6] studies, PRD intervals from seven studies are either above 0 or below 0 and other two studies are not, and p values from five studies show significant differences in studies of Geough (2010) (p=0.0457), Hart (2009) (p=0.0095), and Patel (2011) (p=0.0016) and no significances in other two studies. In eleven

[6] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

North American studies, PRD intervals from eight studies are either above 0 or below 0 and other three studies are not, and p values of six studies' paired t-tests show significant differences in studies of Boadi (2001) (p=0.0108), Hales (2012) (p=0.001) and Holtshousen (2008) (p=0.0001) and no significances in other three studies; in one Oceanian studies, PRD interval and p value of paired t-test do not show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions. In two South American studies, PRD interval from one study is below 0 and PRD interval from the other study includes 0, and p values of (p=0.7952) paired t-tests do not show significant differences. Thus, 16 studies show ineffective estimation of IPCC Tier 2 among total 25 studies by PRD method and 6 studies which show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions among total 15 studies by paired t-test based on total cattle data pool.

Table 4-24 Summary of different IPCC estimated approaches for all types of cattle on region-level

Region	PRD value		P value	
	Tier 1	Tier 2	Tier 1	Tier 2
Asia	-17.46 to -3.45	-9.95 to 6.97	0.06	0.9165
Europe[7]	5.19 to 9.17	-2.96 to 7.34	***0.018***	0.1455
North America	-12.39 to -6.79	-9.15 to 1.35	0.061	0.3413
Oceania	9.197 to 17.75	-20.65 to 0.61	***0.001***	0.128
South America	-17.76 to -5.53	-5.01 to 2.27	0.663	0.5492

Table 4-24 summarizes the effectiveness of IPCC estimated approaches from various regional studies based on the total cattle data pool. In Table 4-9, PRD intervals from IPCC Tier 1 are either above 0 or below 0, suggesting that IPCC Tier 1 either underestimates or overestimates on the regional studies level. P values of paired t-test from European studies (p=0.018) and

[7] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

Oceanian studies (p=0.001) are less than 0.05, indicating significant differences between the IPCC Tier 1 estimated emissions and measured enteric CH_4 emissions. However, PRD intervals from IPCC Tier 2 include 0 and p values of paired t-test from all regional studies are above 0.05, indicating effectiveness of IPCC Tier 2 estimation on region-level. When comparing IPCC Tier 1 to IPCC Tier 2, IPCC Tier 2 offers more powerful estimation.

2) Beef cattle data pool across the studies

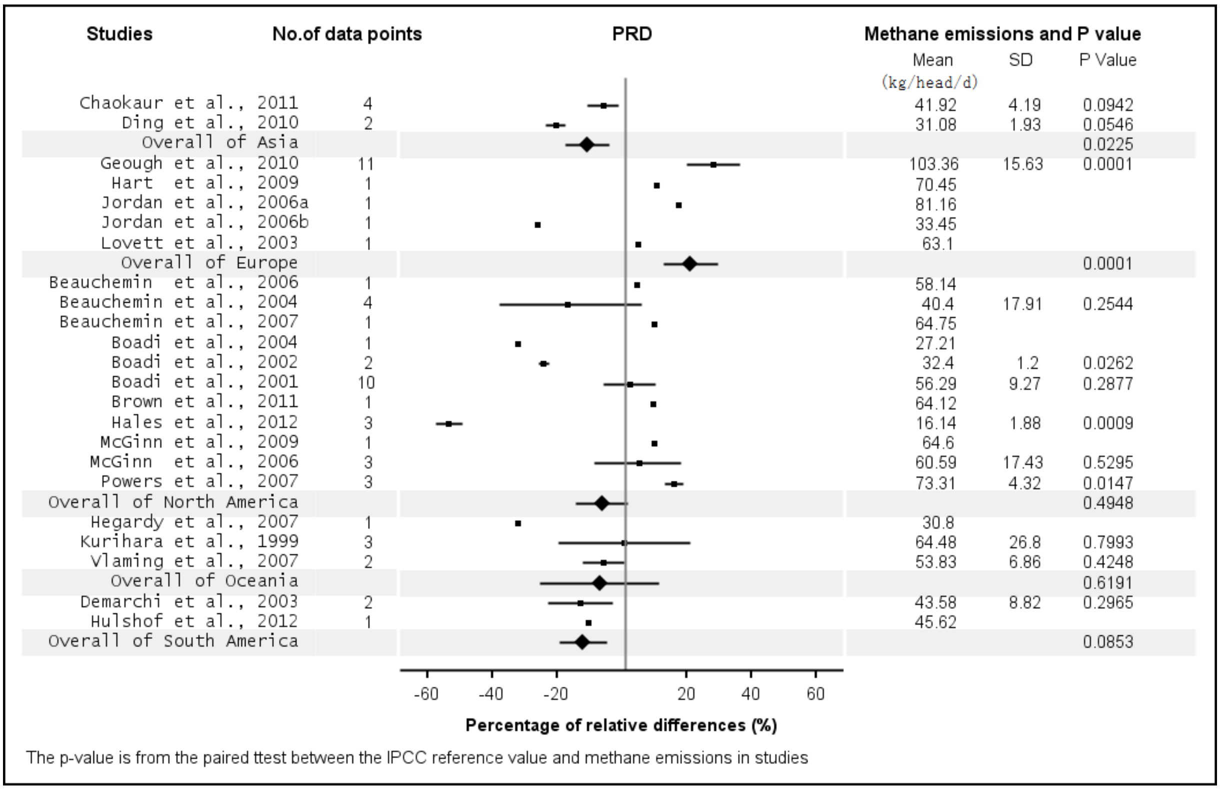
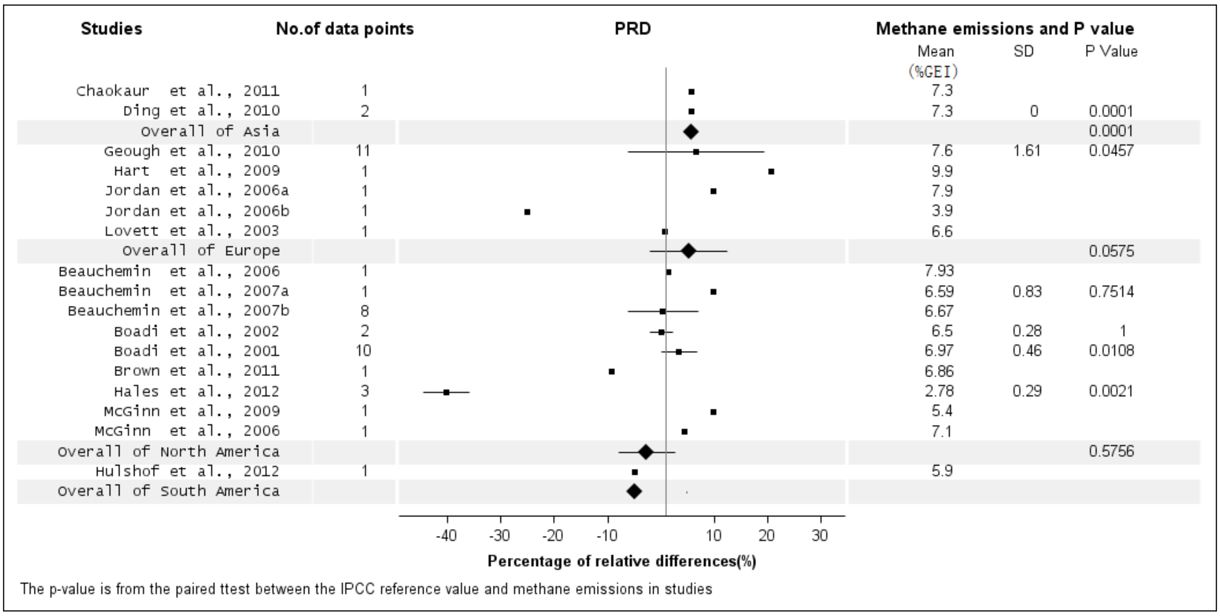


Figure 4-20 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 1 estimated emissions for beef cattle by regions (kg/head/day)

In Figure 4-20, 23 studies were evaluated by PRD and 12 studies by paired t-test. In two Asian studies, PRD intervals are below 0, indicating the overestimation of IPCC Tier 1, but p values of paired t-tests do not show significant differences between measured enteric CH_4

emissions and IPCC Tier 1 estimated emissions. In five European[8] studies, all PRD intervals are either above 0 or below 0, and only one p value from the study of Geough (2010) (p=0.0001) show significant differences. In eleven North American studies, PRD intervals from eight studies are either above 0 or below 0 and other three studies are not, and p values of six studies' paired t-tests show significant differences in studies of Boadi (2002) (p=0.0262), Hales (2012) (p=0.0009) and Powers (2007) (p=0.0147) and no significances in other three studies. In three Oceanian studies, PRD intervals from two studies are below 0 and a study is not, but p values of two studies' paired t-tests do not show significant differences. In two South American studies, PRD intervals are below 0, but p value of a study's paired t-tests does not show significant differences (p=0.2965). Hence, 19 studies show ineffective estimation of IPCC Tier 1 among total 23 studies by PRD method and 4 studies which show significant differences between measured enteric CH_4 emissions and IPCC Tier 1 estimated emissions among total 12 studies by paired t-tests based on the beef cattle data pool.



[8] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

Figure 4-21 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 2 estimated emissions for beef cattle by regions (% GEI)

In Figure 4-21, 17 studies were evaluated by PRD and 6 studies by paired t-test. In two Asian studies, PRD intervals are above 0, indicating the underestimation of IPCC Tier 2 approaches, and p value of paired t-test from a study shows significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions. In five European studies, PRD intervals from three studies are either above 0 or below 0, and one p value from Geough (2010) (p=0.0457) also show significant differences. In nine North American studies, PRD intervals from six studies are either above 0 or below 0 and other three studies are not, and p values of four studies' paired t-tests show significant differences in studies of Boadi (2001) (p=0.0108) and Hales (2012) (p=0.002) and no significances in other two studies. In a South American study, PRD interval is below 0. Hence, 12 studies show the ineffective estimation of IPCC Tier 2 among total 17 studies by PRD method and 4 studies show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions among total 6 studies by paired t-tests based on the beef cattle data pool.

Table 4-25 summarizes the effectiveness of IPCC estimated approaches from varous regional studies based on the beef cattle data pool. First, PRD intervals of IPCC Tier 1 in Asian and South American studies are below 0, and PRD interval in European studies is above 0, suggesting that IPCC Tier 1 either overestimates or underestimates. P values of paired t-test in Asian studies and European studies are less than 0.05, also showing significant differences between IPCC Tier 1 estimated emissions and measured enteric CH_4 emissions. However, PRD intervals in North American and Oceanian studies include 0 and p values are above 0.05, demonstrating effectiveness of IPCC Tier 1. Second, PRD interval of IPCC Tier 2 in Asian studies is above 0, indicating ineffectiveness of IPCC Tier 2, and the p value is 0.001, further showing significant differences between measured emissions and IPCC Tier 2 estimated emissions. However, PRD intervals of IPCC Tier 2 in other regional studies include 0 and the p values are above 0.05, representing effectiveness of IPCC Tier 2. Therefore, IPCC Tier 2 may have a more powerful estimation for beef cattle compared to IPCC Tier 1, but this result needs further more data to verify.

Table 4-25 Summary of different IPCC estimated approaches for beef cattle on the region-level

Region	PRD value		P value	
	Tier 1	Tier 2	Tier 1	Tier 2
Asia	-17.51 to -3.93	5.80	***0.0001***	***0.0001***
Europe[9]	12.77 to 29.51	-1.99 to 12.41	***0.0001***	0.0575
North America	-14.11 to 1.79	-7.92 to 2.58	0.4948	0.5756
Oceania	-25.21 to 11.46	/	0.6191	---
South America	-19.26 to -4.77	-4.84	0.0853	---

[9] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

3) Dairy cattle data pool across the studies

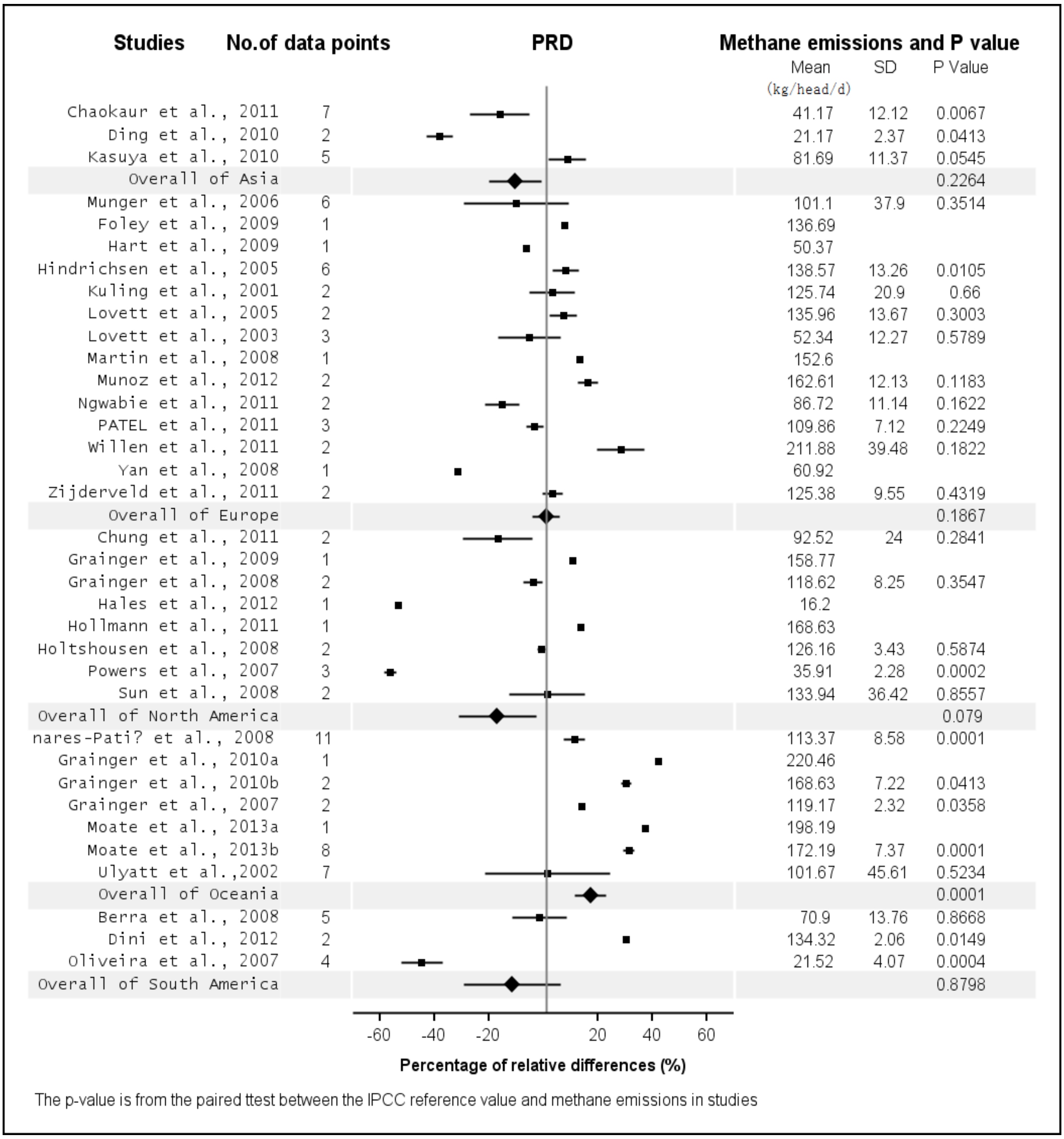


Figure 4-22 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 1 estimated emissions for dairy cattle by regions (kg/head/day)

In Figure 4-22, 35 studies were evaluated by PRD and 26 studies by paired t-test. In three Asian studies, PRD intervals are either above 0 or below 0, indicating the ineffectiveness of

IPCC Tier 1 approaches, and p values of three studies' paired t-tests show significant differences between measured enteric CH_4 emissions and IPCC Tier 1 estimated emissions in studies of Chaokaur (2011) (p=0.0067) and Ding (2010) (p=0.0413) and no significances in study of Kasuya (2010) (p=0.0545). In fourteen European[10] studies, PRD intervals from ten studies are either above 0 or below 0 and other four studies are not, and p values from ten studies show significant differences in the study of Hindrichsen (2005) (p=0.0105) and no significances in other nine studies. In eight North American studies, PRD intervals from seven studies are either above 0 or below 0 and a study is not, and p values of five studies' paired t-tests show significant differences in the study of Powers (2007) (p=0.0002) and no significances in other four studies. In seven Oceanian studies, PRD intervals from six studies are either above 0 or below 0 and only a study is not, and p values of five studies' paired t-tests show significant differences in studies of Pinares-Patino (2008) (p=0.0001), Grainger (2010b) (p=0.0413), Grainger (2007) (p=0.0358), and Moate (2013b) (p=0.0001) and no significances in a study. In three South American studies, PRD intervals from two studies are either above 0 or below 0 and a study is not, and p values of three studies' paired t-tests show significant differences in studies of Dini (2012) (p=0.0149) and Oliveira (2007) (p=0.0004) and no significances in a study. Therefore, 28 studies show ineffective estimation of IPCC Tier 1 among total 35 studies by PRD method and 10 studies show significant differences between measured enteric CH_4 emissions and IPCC Tier 1 estimated emissions among total 26 studies by paired t-test based on the dairy cattle data pool.

[10] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

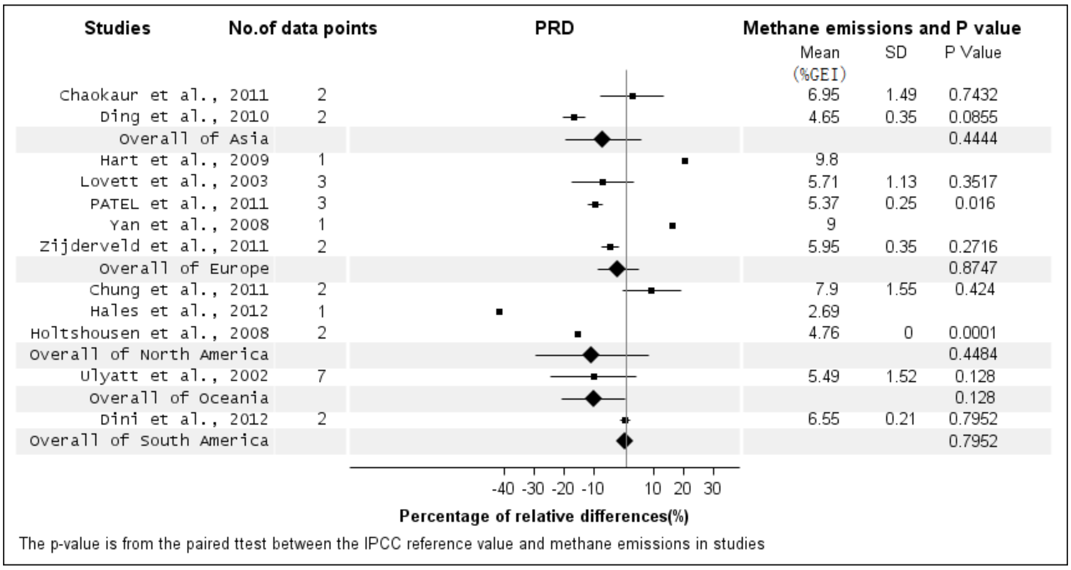


Figure 4-23 Forest plot of differences between measured enteric CH_4 emissions and IPCC (2006) Tier 2 estimated emissions for dairy cattle by region (% GEI)

In Figure 4-23, 12 studies were evaluated by PRD and 9 studies by paired t-test. In two Asian studies, PRD interval from Ding (2010) is below 0 and the other is not, and p values of both studies' paired t-tests also do not show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions. In five European[11] studies, PRD intervals from four studies are either above 0 or below 0 and a study is not, and p values from three studies show significant differences in the study of Patel (2011) (p=0.0016) and no significances in other two studies. In three North American studies, PRD intervals from two studies are either above 0 or below 0 and a study is not, and p values of two studies' paired t-tests show significant differences in the study of Holtshousen (2008) (p=0.0001) and no significances in the other study. In a Oceanian studies, PRD interval and p value of paired t-test do not show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions. In a South American studies, PRD interval and p value of paired t-test do not show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions.

[11] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

Thus, 7 studies show ineffective estimation of IPCC Tier 2 among total 12 studies by PRD method and 2 studies show significant differences between measured enteric CH_4 emissions and IPCC Tier 2 estimated emissions among total 9 studies by paired t-test based on the dairy cattle data pool.

Table 4-26 summarizes the effectiveness of IPCC estimated approaches from different regional studies based on the dairy cattle data pool. In Table 4-11, PRD intervals of IPCC Tier 1 estimation are less than 0 in Asian studies and North American studies, indicating overestimation of IPCC Tier 1 in Asia and North America. However, p values of paired t-test are above 0.05, suggesting no significant differences between measured emissions and IPCC Tier 1 estimated emissions in Asian and North American studies. The PRD interval of IPCC Tier 1 estimation is below 0 in Oceanian studies, and p value of paired t-test is below 0.05, suggesting ineffectiveness of IPCC Tier 1. In European and South American studies, the PRD intervals (including 0) and p values of paired t-test ($p > 0.05$) show effectiveness of IPCC Tier 1. All PRD intervals (including 0) and the p values ($p > 0.05$) demonstrate that IPCC Tier 2 has strong power to estimate enteric methane emission for dairy cattle, but this result also need further more data to verify because of small sample size.

Table 4-26 Summary of IPCC estimated approaches for dairy cattle on region level

Region	PRD value		P value	
	Tier 1	Tier 2	Tier 1	Tier 2
Asia	-20.10 to -0.60	-19.67 to 5.77	0.2264	0.4444
Europe[12]	-4.08 to 6.10	-8.75 to 4.91	0.1867	0.8747
North America	-31.15 to -2.77	-29.79 to 8.19	0.079	0.4484
Oceania	11.56 to 23.02	-20.65 to 0.61	***0.0001***	0.128
South America	-29.19 to 6.21	-1.87 to 2.61	0.8798	0.7952

[12] Europe here is belong to Western Europe in IPCC Tier 1 regional characteristics

4.3.3 Causes of the ineffectiveness of IPCC Tier 1 and Tier 2

IPCC Tier 1 is characterized by region-specific research and cattle category. However, when the unit is g/head/d, enteric CH_4 emissions are significantly influenced by sub-classification, production stage, humidity, temperature, body weight, and feed intake besides geographic region and cattle classification. In addition, the linear regression model between emissions and feed intake is fitted well with R^2 value of 0.7496 (n=148). Therefore, body weight and feed intake might be important causes of ineffectiveness of IPCC Tier 1.

IPCC Tier 2 methodology calculates CH_4 production based on default CH_4 conversion factor (6.5 $\pm$1 for beef and dairy cattle and 3$\pm$1 for feedlot cattle); however, when the unit is %GEI, emissions are significantly associated with production stage and body weight. In addition, IPCC Tier 2 underestimated emissions in Asian studies for beef cattle. Thus, the ineffectiveness of IPCC Tier 2 might result from production stage or body weight.

Chapter 5 - CONCLUSIONS

5.1 Statistics of Enteric CH_4 Emission Rates

Variances of enteric CH_4 emission rates with the unit of g/Kg DMI or %GEI are smaller than those with the unit of g/head/d. When the normality and homogeneity of data from individual studies are considered, data with the unit of %GEI has less variation compared to data with the units of g/head/d and g/kg DMI for meta-analysis.

5.2 Effects of Variables on Enteric CH_4 Emission Rates

5.2.1 Effects of environmental variables, cattle characteristics, feed situation and feed intake on enteric CH_4 emission across the studies

Geographic region, temperature, humidity, cattle classification, body weight and feed intake significantly affect enteric CH_4 emissions with the unit of g/head/d, while humidity, production stage, and body weight have significant effects on enteric CH_4 emissions with the unit of g/kg DMI, and only humidity and body weight have significant effects on enteric CH_4 emissions with the unit of %GEI.

Numeric variables of temperature, humidity, body weight and feed intake have many effects on enteric CH_4 emissions. First, enteric CH_4 emissions have positive relationships with temperature, body weight, and feed intake, and negative relationships with humidity when the unit was g/head/d. In addition, good linear regression models exist between enteric CH_4 emissions with the unit of g/head/d and humidity or feed intake with R^2 values of 0.5244 (n=30) or 0.7496 (n=148), respectively. Second, enteric CH_4 emissions have a negative relationship with humidity and positive relationship with body weight and feed intake when the unit is g/kg DMI.

Third, enteric CH_4 emissions have positive association with humidity or body weight when the unit is % GEI. Good linear regression model with the R^2 value of 0.654 (n=10) between the enteric CH_4 emissions with the unit of %GEI and humidity.

Comparing effects of sub-classification and production stage on enteric CH_4 emissions leads to results. First, no significant differences of enteric CH_4 emissions occur between sub-classifications, but significant differences of enteric CH_4 emissions occur between various production stages with three units for beef cattle. Second, significant differences of enteric CH_4 emissions occur between sub-classifications and various production stages when the unit is g/head/d, but no significant differences of enteric CH_4 emissions occur when the units are g/kg DMI and % GEI for dairy cattle.

5.2.2 Diet mitigation strategies' effects on enteric CH4 emission across the studies

Increasing proportions of concentrate within the diet can reduce enteric CH_4 emissions. Relationships between relative reduction percentages of enteric CH_4 emissions and concentrate proportions are linear: the slope is 0.74 ± 0.19, 0.56 ± 0.088, and 0.45 ± 0.13 for unit of g/head/d, g/kg DMI, and %GEI respectively.

Mitigation through feed additive and plant secondary compound also can be achieved. According to data across the studies, -3.68 %-64% reduction in enteric CH_4 emissions could be achieved by feed additives and plant secondary compound, especially soy-oil, which has least-squares means of relative reduction percentage above 35 % with three units, canola, coconut, linseed, nitrate and tannin, all of which have least-squares means of percentage relative reduction above 15%.

5.3 Evaluation of the Intergovernmental Panel on Climate Change Approaches

5.3.1 Overall evaluation of IPCC (2006)

Based on the total cattle data, the beef cattle data, and the dairy cattle data, IPCC Tier 1 and Tier 2 estimated emission results indicated their effectiveness to estimate most of enteric CH_4 emissions; however, they are not perfect and some emission factors need to be revised.

5.3.2 Evaluation of IPCC (2006) on region-level

IPCC Tier 1: the results of PRD method show that IPCC Tier 1 estimated emission lack comparable results in Asian, European and South American studies for beef cattle, and in Asian, North American and Oceanian for dairy cattle. The results of paired t-tests demonstrate the significant differences in Asian and European studies for beef cattle and in Oceanian studies for dairy cattle.

IPCC Tier 2: the results of PRD method show the ineffective estimation in Asian and South American studies for beef cattle; meanwhile, the results of paired t-tests demonstrate the significant differences in Asian studies for beef cattle.

5.3.3 Relationship of two evaluation methods

P values of paired t-test show no significance when the PRD interval includes 0; all p values of paired t-test show significance when the PRD is above 0 or below 0. Therefore, the method of PRD is stricter than the method of paired t-test.

5.4 Research Implications and Future Work

Current meta-analysis has at least two limitations. First, enteric CH_4 emission research time and money and the number of studies included in most influent variables' analyses is small, especially when the unit is %GEI. In addition, for mitigation strategies, the number of studies included in various mitigation techniques is much smaller, and effect analyses of mitigations are likewise limited by the small number of studies. Therefore, it is difficult to assess which types of variables are truly effective when power is low. Second, data across the studies are heterogeneous when the units are g/head/d and g/kg DMI. Variance among size effect might still be caused by the heterogeneity between studies although MIXED procedure was used for this research. Therefore, future research should consider the effects of sample size, statistical power and different measurement techniques.

In addition to study limitations, Aim 2 focuses on identifying significant associations between simple independent variable and dependent variable but not significant relationships between multiple independent variables and dependent variable. Also, linear regressions are not weighted to account for within study variances and residual between study heterogeneity.

Appendix A - Designing the Meta-analysis in the Key Six Areas

1 Development of the Study Question

The objectives of a meta-analysis and the question being addressed must be explicitly stated and may include primary and secondary objectives. The question at the focus of a meta-analysis should not have already been answered satisfactorily by the results of multiple well-conducted randomized studies. It can lead on to some inclusion and exclusion criteria and interesting, novel, relevant and feasible are the four basic considerations. Good questions may be narrowly focused or broad, depending on the overall objectives of review. In general, the more focused the question is, the more likely the study group will be homogenous while broad questions might increase the applicability of the results and facilitate detection of bias, exploratory analyses, and sensitivity analyses. Whether narrowly focused or broad, precisely stated objectives are critical and the results of a meta-analysis are used to highlight the weaknesses of previous studies or method and to recommend how improve the future studies(Mulrow et al., 1996; Rothman et al., 2008).

2 Comprehensive Literature Search

One of the first steps when carrying a meta-analysis is to determine whether the authors conducted a comprehensive search for these types of studies, some of which may be unpublished. The information sources that were searched should be provided. Literature searches can include computerized and manual searches(Wilson, 2001).

At least two reviewers should search sources for articles relevant to the meta-analysis, and the keywords used in the online searches should be provided in the article. Many authors include only full-length papers because abstracts do not always provide enough information to score the paper. The number of studies that were included and excluded should also be provided, as well as the reasons for exclusion.

3 Data Abstraction

Data abstraction is one of the most important steps in conducting a meta-analysis, and the methods of data abstraction that were used by the authors should be described in detail. In high-quality meta-analyses, a standardized data abstraction form is developed and utilized by the authors and may be provided in the paper as a figure/table. The reader of a meta-analysis should be provided with enough information to determine whether the studies that were included were appropriate for a combined analysis.

Two or more authors of a meta-analysis should abstract information from studies independently. It should be stated whether the reviewers were blinded to the authors and institution of the studies undergoing review. The results from the data abstraction are compared only after completing the review of the articles. The article should state any discrepancies between authors and how the discrepancies were resolved.

Results should be collected only from separate sets of research organization, and the authors should be careful to avoid studies that published the same subjects or overlapping groups of subjects that appeared in different studies under duplicate publications.

A quality score for each study included in a meta-analysis may be useful to ensure that better studies receive more weight. In the clinical trial, more than 20 instruments have been identified for the assessment for quality in meta-analyses of prospective cohort studies(Jüni et al., 1999). Results can vary by the type of quality instrument, and a sensitivity analysis may need to be performed to determine the impact of the quality score on the results. As with data abstraction, two reviewers should score the quality of the studies using the same quality instrument, and results from the quality assessment should be compared. Agreement among the reviewers should be reported, and differences in quality scores should be reconciled through discussion.

In addition, inclusion and exclusion criteria for the studies in the meta-analysis need to be well defined and established beforehand(Greenhalgh, 1997). One goal of inclusion and exclusion criteria is to create a homogenous study population for the meta-analysis. The rationale for choosing the criteria should be stated, as it may not be apparent to the reader. Inclusion criteria may be based on study design, sample size, and characteristics of the subject. Examples of exclusion criteria include studies not published in English or as full-length manuscripts. It has been reported that meta-analysis that restrict studies by language overestimate treatment effect only by 2% (Liberati et al., 2009; Moher et al., 1999). The number of studies excluded from the meta-analysis and the reasons for the exclusions should also be provided.

4 Statistical Techniques

When determining whether a meta-analysis was properly performed, the statistical techniques used to combine the data are not as important as the methods used to determine whether the results from the studies should have been combined. If the data across the studies should not have been combined in the first place because their populations or designs were heterogeneous, statistical methods will not be able to correct these mistakes.

There are two common statistical methods to combine the data: Mantel_haenszel method and DerSimonian Laird method. The first method is based on the fixed effects theory and the second one is based on the random effects theory. One of the goals of both methods is to provide a summary statistic of an intervention's effect, as well as a confidence interval(Deeks et al., 2001). The fixed effects model examines whether the treatment produced a benefit in the studies that were conducted. In contrast, the random effects model assumes that the studies included in the meta-analysis are a random sample of a hypothetical population of studies. The summary statistic is typically reported as a risk ratio, but it can be reported as a rate difference or percentage.

Issues can be made for using either the fixed effects or random effects models, and sometimes results from both models are included. The random effects model provides a more conservative estimate of the combined data, with a wider confidence interval, and the summary statistic is less likely to be significant. Therefore, the fixed effects model can be applied to odds ratios, rate ratios, and risk ratios, whereas the random effects model can be applied to ratios and rate differences.

The statistical test for homogeneity, which is also referred to as the test for heterogeneity, is frequently misused and misinterpreted as a test to validate whether the studies were similar and appropriate (e.g., homogenous) to combine. The test may complement the results from data abstraction, supporting the interpretation that the studies were homogeneous and appropriate to combine. The test for homogeneity investigates the hypothesis that the size of the effect is equal in all included studies. $P<.1$ is considered to be a conservative estimate. If the test for homogeneity is significant, calculating a combined estimate may not be appropriate. If this is the case, the reviewer should re-examine the studies included in the analysis for substantial differences among study designs or characteristics of subjects.

5 Evaluating the Results

Data abstraction results should be clearly presented in order for the reader to determine whether the included studies should have been combined in the first place. The meta-analysis should provide a table outlining the features of the studies, such as the characteristics of subjects, study design, sample size, and intervention. Substantial differences in the study design or measurement methods signify heterogeneity and suggest that the data from the studies should not have been combined(Wilson, 2001).

The typical graphic displaying meta-analysis data is a Forest plot, in which the point estimate for the risk ratio is represented by a square or circle and the confidence interval for each study is represented by a horizontal line. The size of the circle or square corresponds to the weight of the study in the meta-analysis, with larger shapes given to studies with larger sample sizes or data of better quality or both. The 95% confidence interval is represented by a horizontal line except for the summary statistic, which can be shown by a diamond, the length of which represents the confidence interval.

Sensitivity analysis is an evaluation method employed when there is uncertainty in one or more variables included in the model or when determining whether the conclusions of the analysis are robust when a range of estimates is used. A sensitivity analysis is usually included in a meta-analysis because of uncertainty regarding the effectiveness or safety of an intervention. The values at the extremes of the 95% confidence intervals for risk estimates of key variables or areas with the most uncertainty can be included in additional modeling to determine the stability of the conclusions.

6 Assessing for Publication Bias

Meta-analyses are subject to publication bias because studies with negative results are less likely to be published and, therefore, results from meta-analyses may overstate a treatment effect. One strategy to minimize publication bias is to contact well-known investigators in the field of interest to discover whether they have conducted a negative study that remains unpublished. As mentioned the above, Publication bias may lead to the overestimation of a treatment effect by up to 12%(Moher et al., 1999).

A funnel plot can visually reveal the presence of a publication bias(Rothstein et al., 2006). A funnel plot is a graphic representation in which the size of the study on the y axis is plotted against the measure of effect on the x axis. Sampling error decreases as sample size increases and, therefore, larger studies should provide more precise estimates of the true treatment effect. In the absence of publication bias, smaller studies are scattered evenly around the base of the funnel .In the presence of publication bias, small studies cluster around high-risk estimates with no or few small studies in the area of low-risk estimates. Another method employed to address publication bias is a sensitivity analysis to determine the number of negative trials required to convert a statistically significant combined difference into a no significant difference. Examples of these statistical methods to address publication bias include regression analysis, file-drawer analysis (failsafe N), and trim and fill analysis(Rothstein et al., 2006).

Appendix B - Tree Structure of Code

- Study level
    - Name of Authors
    - Year of publication
    - Title of the study
- Comparison level
    - Environmental variables
        - Geographic regions
        - Temperature
        - Humidity
    - Cattle characteristics
        - Cattle classification
            - Dairy
                - Sub-classification of dairy
                - Production stage of dairy
            - Beef
                - Sub-classification of beef
                - Production stage of beef
        - Body weight
    - Feed situation
    - Feed intake
    - Mitigation strategies
        - Concentrates within diet
            - Types of concentrates
            - Content
        - Forage quality
            - Composition of forage

        - Qualitative
    - Dietary additives
        - Chemicals
        - content
    - Plant secondary compounds
        - Chemicals
        - Content
- Effects level
    - CH_4 concentration measurement
    - CH_4 sampling method
    - CH_4 emission
        - Unit of g/hd/d
            - Mean
            - SED
        - Unit of g/Kg DMI
            - Mean
            - SED
        - Unit of % GEI
            - Mean
            - SED

Appendix C - Tier 1 enteric fermentation emission factors for cattle (IPCC, 2006)

Regional characteristics	Cattle category	Emission factor (kg CH_4 head^{-1} yr^{-1})	Comments
North America: Highly productive commercialized dairy sector feeding high quality forage and grain.	Dairy	128	Average milk production of 8,400 kg head^{-1} yr^{-1}.
Separate beef cow herd, primarily grazing with feed supplements seasonally. Fast-growing beef steers/heifers finished in feedlots on grain. Dairy cows are a small part of the population.	Other Cattle	53	Includes beef cows, bulls, calves, growing steers/heifers, and feedlot cattle.
Western Europe: Highly productive commercialized dairy sector feeding high quality forage and grain.	Dairy	117	Average milk production of 6,000 kg head^{-1} yr^{-1}.
Dairy cows also used for beef calf production. Very small dedicated beef cow herd. Minor amount of feedlot feeding with grains.	Other Cattle	57	Includes bulls, calves, and growing steers/heifers.
Eastern Europe: Commercialised dairy sector feeding mostly forages. Separate beef cow herd, primarily grazing. Minor amount of feedlot feeding with grains.	Dairy	99	Average milk production of 2,550 kg head^{-1} yr^{-1}.
	Other Cattle	58	Includes beef cows, bulls, and young.
Oceania: Commercialised dairy sector based on grazing. Separate beef cow herd, primarily grazing rangelands of widely varying quality. Growing amount of feedlot feeding with grains. Dairy cows are a small part of the population.	Dairy	90	Average milk production of 2,200 kg head^{-1} yr^{-1}.
	Other Cattle	60	Includes beef cows, bulls, and young.
Latin America: Commercialised dairy sector based on grazing. Separate beef cow herd grazing pastures and rangelands. Minor amount of feedlot feeding with grains. Growing non-dairy cattle comprise a large portion of the population.	Dairy	72	Average milk production of 800 kg head^{-1} yr^{-1}
	Other Cattle	56	Includes beef cows, bulls, and young.
Asia: Small commercialised dairy sector. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Small grazing population. Cattle of all types are smaller than those found in most other regions.	Dairy	68	Average milk production of 1,650 kg head^{-1} yr^{-1}
	Other Cattle	47	Includes multi-purpose cows, bulls, and young
Africa and Middle East: Commercialised dairy sector based on grazing with low production per	Dairy	46	Average milk production of 475 kg head^{-1} yr^{-1}

cow. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Some cattle graze over very large areas. Cattle are smaller than those found in most other regions.	Other Cattle	31	Includes multi-purpose cows, bulls, and young
Indian Subcontinent: Commercialised dairy sector based on crop by-product feeding with low production per cow. Most bullocks provide draft power and cows provide some milk in farming regions. Small grazing population. Cattle in this region are the smallest compared to cattle found in all other regions.	Dairy Other Cattle	58 27	Average milk production of 900 kg $head^{-1}$ yr^{-1} Includes cows, bulls, and young. Young comprise a large portion of the population

Appendix D - Tier 2 cattle/buffalo conversion factor (Ym) (IPCC, 2006)

Livestock category	Ym
Feedlot fed Cattle	3.0%± 1.0%
Dairy Cows (Cattle and Buffalo) and their young	6.5% ± 1.0%
Other Cattle and Buffaloes that are primarily fed low quality crop residues and byproducts	6.5% ± 1.0%
Other Cattle or Buffalo – grazing	6.5% ± 1.0%

Appendix E - Moments (including skewness and kurtosis), means, medians, and extreme values of the enteric CH_4 emissions from different geographic regions, from different cattle, from different feed situations, and overall

Different geographic regions

Regions	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Asia	20	132.73	110.97	263.85	53.4	3800.70	0.8485	-0.2655
Europe	49	302.32	304.00	657.00	91.64	12185.26	0.4360	0.9681
North America	44	181.34	164.95	462.00	39.11	11734.14	1.0567	0.5867
South America	14	164.78	142.13	372.00	49.27	11084.90	0.93981249	0.1469
Oceania	38	336.16	331.55	604.00	84.40	17523.72	-0.1174886	-0.7914
Overall	165	245.62	216.00	657.00	39.10	17996	0.5019	-0.4815

Note: the unit of CH_4 emission rate is g/head/d. N: number of data points

Regions	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Asia	7	6.44	7.30	8.00	4.40	1.91286	-0.5903176	-1.4886
Europe	26	7.02	6.74	9.90	3.71	3.15618	-0.1047169	-0.7866
North America	33	6.23	6.70	9.00	2.47	2.47533	-1.1886593	0.9628
South America	3	6.33	6.40	6.70	5.90	0.16333333	-0.7221086	--
Oceania	7	5.49	6.10	7.1	3.7	2.31143	-0.2729371	-2.5117
Overall	76	6.45	6.70	9.90	2.47	2.67	-0.3961079	0.1959

Note: the unit of CH_4 emission rate is % GEI. N: number of data points

Regions	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Asia	20	19.90	19.64	26.38	14.90	10.3391503	0.37071273	-0.8101
Europe	43	22.96	24.60	35.60	9.14	28.2264	-0.5829953	0.5522
North America	29	18.83	20.76	26.40	7.75	30.45620	-0.9109103	-0.2801
South America	7	16.08	14.02	22.70	11.62	22.28053	0.55057196	-1.8326
Oceania	35	20.24	19.70	36.30	12.30	19.33660	1.10291185	4.1464
Overall	134	20.54	20.83	36.3	7.75	26.4101	-0.1529695	0.5815

Note: the unit of CH_4 emission rate is g/Kg DMI. N: number of data points

	Shapiro-Wilk		**Kolmogorov-Smirnov**		**Cramer-von Mises**		**Anderson-Darling**		N
	Test	P-value	Test	P-value	Test	P-value	Test	P-value	
Overall	0.957041	0.0001	0.102659	0.01	0.354004	0.005	2.107701	0.005	165
Asia	0.907006	*0.0559*	0.183693	*0.0766*	0.135748	*0.0351*	0.74254	*0.0453*	20
Europe	0.968855	*0.2180*	0.085795	*0.1500*	0.057547	*0.2500*	0.382774	*0.2500*	49
North America	0.897784	0.0009	0.170511	0.0100	0.262763	0.0050	1.512138	0.0050	44
South America	0.890473	*0.0821*	0.147359	*0.15*	0.067359	*0.25*	0.517199	*0.1612*	14
Oceania	0.963038	*0.2380*	0.116699	*0.1500*	0.086964	*0.1670*	0.55236	*0.1478*	38

Note: the unit is g/head/d, N: number of data points

Overall	0.968315	*0.0542*	0.113330	*0.0170*	0.189940	0.0071	0.977637	*0.0144*	76
Asia	0.87446	*0.2030*	0.303715	*0.0487*	0.086976	*0.1416*	0.484427	*0.1527*	7
Europe	0.969988	*0.6230*	0.090737	*0.1500*	0.028622	*0.2500*	0.202394	*0.2500*	26
North America	0.855178	0.0004	0.214862	0.0100	0.360678	0.0050	2.025853	0.0050	33
South America	0.979592	*0.7262*	0.232178	*0.1500*	0.032927	*0.2500*	0.212348	*0.2500*	3
Oceania	0.823978	*0.0701*	0.229705	*0.1500*	0.097143	*0.0998*	0.578406	*0.0851*	7
Note: the unit is % GEI, N: number of data points									
Overall	0.979951	*0.0453*	0.056875	*0.1500*	0.098873	*0.1183*	0.730915	*0.0570*	134
Asian	0.958894	*0.5220*	0.126164	*0.1500*	0.051746	*0.2500*	0.331684	*0.2500*	20
Europe	0.948772	*0.0538*	0.157923	0.0010	0.175575	*0.0102*	0.996101	*0.0119*	43
North America	0.869818	0.0020	0.242233	0.01	0.266831	0.0050	1.535761	0.0050	29
South America	0.854511	*0.1351*	0.239833	*0.1500*	0.075708	*0.2081*	0.463568	*0.1791*	7
Oceania	0.904279	0.0052	0.123657	*0.1500*	0.087403	*0.1638*	0.701675	*0.0640*	35
Note: the unit is g/kg DMI, N: number of data points									

Different cattle

Cattle classification	N	Mean	Median	max	min	variance	skewness	Kurtosis
Dairy	90	325.83	330.50	657.00	94.10	14150	0.08611456	-0.2376206
Beef	75	149.38	135.39	322.00	39.11	5654.07407	0.71641977	-0.1685461
Overall	165	245.62	216.00	657.00	39.10	17996	0.5019	-0.4815

Note: the unit of CH_4 emission rate is g/head/d. N: number of data points

Cattle classification	N	Mean	Median	max	min	variance	skewness	Kurtosis
Dairy	21	6.02	6.10	9.0	3.7	2.00184	0.42061771	0.37907976
Beef	55	6.63	6.90	2.47	9.90	2.86616377	-0.6791319	0.57932066
Overall	76	6.45	6.70	9.90	2.47	2.67	-0.3961079	0.19593647

Note: the unit of CH4 emission rate is % GEI. N: number of data points

Cattle classification	N	Mean	Median	max	min	variance	skewness	Kurtosis
Dairy	72	20.96	20.60	36.3	12.3	16.06688	0.59601536	1.84493628
Beef	62	20.05	21.05	35.60	7.75	38.42552	-0.2390658	-0.4070498
Overall	134	20.54	20.83	36.3	7.75	26.4101	-0.1529695	0.58153058

Note: the unit of CH4 emission rate is g/Kg DMI. N: number of data points

	Shapiro-Wilk		**Kolmogorov-Smirnov**		**Cramer-von Mises**		**Anderson-Darling**		N
	Test	P-value	Test	P-value	Test	P-value	Test	P-value	
Overall	0.957041	0.0001	0.102659	0.01	0.354004	0.005	2.107701	0.005	165
Dairy	0.985986	*0.4489*	0.05541	*0.1500*	0.042076	*0.2500*	0.310689	*0.2500*	90
Beef	0.933503	0.0007	0.112418	*0.0197*	0.176664	*0.0101*	1.342199	0.0050	75
Note: the unit is g/head/d, N: number of data points									
Overall	0.968315	*0.0542*	0.113330	*0.0170*	0.189940	0.0071	0.977637	*0.0144*	76
Dairy	0.945444	*0.2786*	0.14786	*0.1500*	0.047951	*0.2500*	0.387791	*0.2500*	21
Beef	0.936784	0.0062	0.150798	0.0100	0.256581	0.0050	1.394084	0.0050	55
Note: the unit is %GEI, N: number of data points									
Overall	0.979951	*0.0453*	0.056875	*0.1500*	0.098873	*0.1183*	0.730915	*0.0570*	134
Dairy	0.964711	*0.0410*	0.056978	*0.1500*	0.046626	*0.2500*	0.392749	*0.2500*	72
Beef	0.964891	*0.0732*	0.119461	*0.0261*	0.151697	*0.0225*	0.859346	*0.0256*	62
Note: the unit is g/kg DMI, N: number of data points									

Different feed situations

Feed situation	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Pasture/range	78	235.63	243.67	543.00	39.11	16196	0.25059521	-0.8068928
Stall feed	36	293.10	300.20	604.00	53.40	21121	0.05779594	-0.8661737

Note: the unit of CH4 emission rate is g/head/d. N: number of data points

Feed situation	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Pasture/range	36	6.34	6.75	9.72	2.47	3.91005	-0.4635175	-0.6375536
Stall feed	16	6.36	6.40	7.93	4.40	1.09831833	-0.3538491	-0.9301164

Note: the unit of CH4 emission rate is % GEI. N: number of data points

Feed situation	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Pasture/range	70	20.11	20.15	35.60	7.750	29.87942	-0.0796754	0.31756235
Stall feed	31	20.61	20.50			23.27447	0.60319346	3.07687819

Note: the unit of CH4 emission rate is g/Kg DMI. N: number of data points

	Shapiro-Wilk		**Kolmogorov-Smirnov**		**Cramer-von Mises**		**Anderson-Darling**		N
	Test	P-value	Test	P-value	Test	P-value	Test	P-value	
g/head/d(165)	0.957041	0.0001	0.102659	0.01	0.354004	0.005	2.107701	0.005	165
Pasture/range(78)	0.956742	0.0098	0.105657	*0.0303*	0.194692	0.0061	1.106188	0.0067	78
Stall feed(36)	0.966477	*0.3373*	0.090215	*0.1500*	0.044258	*0.2500*	0.344858	*0.2500*	36
Note: the unit is g/head/d, N: number of data points									

%GEI (76)	0.968315	*0.0542*	0.113330	*0.0170*	0.189940	0.0071	0.977637	*0.0144*	76
Pasture/range(36)	0.948701	*0.0952*	0.127126	*0.1449*	0.099338	*0.1126*	0.628047	*0.0954*	36
Stall feed (16)	0.959634	*0.6552*	0.145471	*0.1500*	0.041254	*0.2500*	0.265012	*0.2500*	16
Note: the unit is %GEI, N: number of data points									
g/Kg DMI(134)	0.979951	*0.0453*	0.056875	*0.1500*	0.098873	*0.1183*	0.730915	*0.0570*	134
Pasture/range (70)	0.984716	*0.5528*	0.082491	*0.1500*	0.059316	*0.2500*	0.376321	*0.2500*	70
Stall feed(31)	0.934337	*0.0576*	0.123239	*0.1500*	0.057192	*0.2500*	0.520443	*0.1794*	31
Note: the unit is g/kg DMI, N: number of data points									

Appendix F - Moments (including skewness and kurtosis), means, medians, and extreme values of differences between the measured enteric CH_4 emissions and IPCC (2006) estimated emissions based on the total cattle data pool, the beef cattle data pool, and the dairy cattle data pool.

IPCC	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Tier 1	165	9.99	6.37	130.46	-93.65	1466	0.3784	0.8016
Tier 2	75	0.044	0.20	5.90	-4.03	3.13	0.0574	1.1023

Note: the total cattle data pool

IPCC	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Tier 1	75	0.6298	-3.725	60.53	-38.72	679.94	0.6605	-0.1643
Tier 2	55	0.13	0.40	3.4	-4.03	2.8662	-0.6791	0.5793

Note: the beef cattle data pool

IPCC	N	Mean	Median	Max	Min	Variance	Skewness	Kurtosis
Tier 1	90	17.79	17.89	130.46	-93.65	2000	-0.0177	0.3823
Tier 2	21	-0.17	-0.30	5.9	-2.8	3.93	1.4689	3.3040

Note: the dairy cattle data pool

	Shapiro-Wilk		**Kolmogorov-Smirnov**		**Cramer-von Mises**		**Anderson-Darling**		N
	Test	P-value	Test	P-value	Test	P-value	Test	P-value	
Tier 1	0.9776	0.0091	0.06956	*0.0490*	0.1998	0.0051	1.2184	0.005	165
Tier 2	0.9671	*0.0459*	0.1046	*0.0391*	0.1951	0.006	0.9940	*0.0129*	75
Note: the total cattle data pool									
Tier 1	0.9421	*0.0019*	0.114182	*0.0168*	0.1588	*0.0191*	1.1589	*0.005*	75
Tier 2	0.9367	*0.0062*	0.1508	*0.0010*	0.2565	*0.0050*	1.39084	*0.0050*	55
Note: the beef cattle data pool									
Tier 1	0.9834	*0.3114*	0.095622	*0.0418*	0.102941	*0.1019*	0.573943	*0.1372*	90
Tier 2	0.8787	*0.0139*	0.2157	*0.0115*	0.1265	*0.0460*	0.777823	*0.0381*	21
Note: the dairy cattle data pool									

Region	Emission factor of IPCC Tier 1 （kg CH_4/head/d）	Statistics （kg CH_4/head/d）	P-value
North America	53	49.50	0.4948
Western Europe	57	83.81	0.0001
Eastern Europe	58	/	/
Oceania	60	55.32	0.6191
Latin America	56	31.27	0.0853
Asia	47	34.27	0.0225
Africa and Middle East	31	/	/
Indian Subcontinent	27	/	/

Note: for other cattle

Region	Emission factor of IPCC Tier 1 （kg CH_4/head/d）	Statistics means （kg CH_4/head/d）	P-value
North America	128	105.97	0.079
Western Europe	117	127.15	0.1867
Eastern Europe	99	/	/
Oceania	90	135.33	0.0001
Latin America	72	89.02	0.8798
Asia	68	69.70	0.2264
Africa and Middle East	46	/	/
Indian Subcontinent	58	/	/

Note: for dairy

Region	Conversion factor of IPCC Tier 2 （%GEI）	Statistics means （%GEI）	P-value
North America	6.5	6.22	0.5756
Western Europe	6.5	7.31	0.0575
Eastern Europe	6.5	/	/
Oceania	6.5	/	0.2418
Latin America	6.5	5.9	/
Asia	6.5	7.3	0.0001
Africa and Middle East	6.5	/	/
Indian Subcontinent	6.5	/	/

Note: for other cattle

Region	Conversion factor of IPCC Tier 2 （%GEI）	Statistics means （%GEI）	P-value
North America	6.5	6.33	0.4484
Western Europe	6.5	6.24	0.8747
Eastern Europe	6.5	/	/
Oceania	6.5	5.49	0.128
Latin America	6.5	6.55	0.7952
Asia	6.5	5.9	0.4444
Africa and Middle East	6.5	/	/
Indian Subcontinent	6.5	/	/

Note: for dairy

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