ESTIMATING ENTERIC METHANE EMISSIONS FROM SMALLHOLDER DAIRY COWS UNDER SEASONAL AND AGRO-ECOLOGICAL VARIATIONS IN FEED DIGESTIBILITY IN KENYA

NDUNG'U PHYLLIS WANJUGU

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DECLARATION AND RECOMMENDATION

Declaration

This research thesis is my original work and has not been presented in this or any other University for the award of a degree

Signature Date 12/03/2018

Ndung'u Phyllis Wanjugu

KM11/13501/14

Recommendation

This Research thesis has been submitted with our approval as University Supervisors for examination according to Egerton regulations.

Signature Date 13/03/2018

Prof. B.O. Bebe, PhD

Professor of Livestock Production Systems,
Department of Animal Science, Egerton University

Signature Date 13/03/2018

Dr. J.O. Ondiek, PhD

Senior Lecturer,
Department of Animal Science, Egerton University

Signature Date 12/03/2018

Dr. J.P. Goopy, PhD

Research Scientist, International Livestock Research Institute, Nairobi

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DEDICATION

I dedicate this work to my daughter Angel Lyla Wamuyu.

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ABSTRACT

In Sub-Saharan Africa, national greenhouse gas (GHG) inventories are computed with non-country specific Emission Factors (EF) of the Intergovernmental Panel on Climate Change (IPCC) Tier I approach. An alternative is Tier II or Tier III approach, which is country-specific using detailed animal performance and feed characteristics data and more accurate EF for developing Nationally Appropriate Mitigation Actions (NAMAs) and Low Emission Development Strategies (LEDS).This study sought to provide improved EF with data from a typical African livestock system sampled in Nandi County in Kenya. The EF were computed from methane production based on animal performance measurements using a sample of 487cows in 127 households across 36 villages spread over three major agro-ecological zones (AEZs). The cows were monitored for a period of one years. The mean EF estimate was50.6kg CH_4/head/year for dairy cows (>2yrs), and was 23.4% higher than the IPCC Tier I estimates for unspecified African adult cattle. The dry matter digestibility (DMD) of feeds across the AEZs and seasons (60.0 – 68.4%) were not different and but the daily methane production (DMP) across the AEZs and seasons were significantly different ($p<0.001$ and $p<0.001$ respectively), which suggest that AEZs and seasons have influence on enteric methane emissions. The study showed that an increase in DMD caused a decrease in DMP ($r=-0.06$) implying that DMD across AEZs and seasons affected DMP. Daily methane production increased with increase in milk yield. This influence was because of energy required for high milk production associated with dry matter intake (DMI) where an increase in DMI caused an increase in DMP. The use of IPCC Tier IEFs to develop Kenya's national inventory for enteric methane emissions from livestock sector can lead to high uncertainties hence similar research is needed to develop emission factors for other livestock systems in other AEZs. Feeding management that includes high digestible feeds will lead to reduced enteric methane emissions and improved production with lower emission intensities associated with dairy farming.

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AEZ	Agro ecological zones
CD	Cold Dry season
CH_4	Methane
CO_2	Carbon dioxide
DMD	Dry matter digestibility
DMI	Daily matter Intake
DMP	Daily methane production
EF	Emission factor
EPA	Environmental Protection Agency
GE	Gross energy
GHG	Greenhouse gases
GWP	Global warming potential
HD	Hot dry season
ME	Metabolizable energy
MER	Metabolizable energy requirement
$MER_{G/L}$	Metabolizable energy requirement for live-weight gain/loss
MER_L	Metabolizable energy requirement for lactation
MER_M	Metabolizable energy requirement for maintenance
MER_T	Metabolizable energy requirement for travel/grazing/locomotion
MER_{Total}	Total metabolizable energy requirement
MJ	Mega joules
MY	Milk yield
NAMA	Nationally Appropriate Mitigation Actions
IPCC	Intergovernmental Panel on Climate Change
INDC	Intended Nationally Determined Contribution
LH1	Lower highland 1
LH2	Lower highland 2
LR	Long rains season
N	Total Nitrogen
N_2O	Nitrous oxide
NFE	Nitrogen free extracts
SR	Short rains season
TDN	Total digestible nutrients

UM	Upper midland
VFA	Volatile fatty acids
Y_m	Methane conversion factor

CHAPTER ONE

INTRODUCTION

1.1 Background information

Methane (CH_4) is the second most prevalent greenhouse gas (GHG) after carbon dioxide (CO_2) with global warming potential (GWP) of 20 to 23 greater thanCO_2over a 100-year period (Steinfeld *et al.*, 2006). Methane has a lifetime of about 9 to 15 years in the atmosphere (Yan *et al.*, 2010).Globally, 6,875 million metric tons of CO_2 equivalent (MMTCO_2 eq.) of methane are released annually from anthropogenic sources, half of which is from agricultural sources and mainly from ruminants, manure management, biomass burning and rice cultivation (EPA, 2008; Haque *et al.*, 2014; Tubiello *et al.*, 2013).

Enteric fermentation from ruminant livestock is responsible for close to 40% of the agricultural sources: dairy cattle (19.4%), buffaloes (10.3%), sheep (7.2%), goats (4.2%), non-dairy cattle (56%) and others (2.9%) (Pickering *et al.*, 2013). In the agriculture sector, ruminants are thus primary producers of methane (Moss *et al.*, 2000) which result from enteric fermentation process in their rumen and to a lesser extent in their hindgut. The rumen houses different species of microbes- mostly carbohydrate fermenters that facilitate breakdown of fibrous feeds through anaerobic fermentation into microbial cells, volatile fatty acids (VFA; propionate, acetate and butyrate) and free hydrogen (H) and CO_2. The formation of CH_4occurs during reaction; $2CO_2+4H_2 \Longrightarrow CH_4+2H_2O$ (Moss *et al.*, 2000) produced by methanogenic archaea.

Dairy and beef cattle are the greatest CH_4 emitters because of their large rumen. Methane is released to the atmosphere through belching, exhaling or excretion. The proportion of CO_2 and CH_4 in the rumen is dependent on the rumen ecology, fermentation balance, and amount and quality of feeds. Besides being an environmental hazard, methane gas represents a loss of energy from the animal of about 5-10% of the gross energy (Haque *et al.*, 2014; Johnson and Johnson, 1995; Madsen *et al.*, 2010). This proportion is significant as it represents a loss of dietary nutrients (Liu *et al.*, 2017) which would otherwise be used for production (milk and meat).

The Intergovernmental Panel on Climate Change (IPCC) has developed three approaches for estimating methane emissions: - simple Tier I to more complex Tier II and Tier III approaches. Tier I approach uses default emission factors and livestock population to estimate enteric methane emissions. Tier II and III approaches require more detailed activity data on animal and feed characteristics to be used in developing emission factors. The IPCC Tier II approach can be suitable for estimation of enteric methane emissions from dairy cattle in smallholder dairy farms because it generates region specific enteric methane emission factors. Use of this approach would yield more accurate emission factors relevant for developing Nationally Appropriate Mitigation Actions (NAMAs) and Low Emission Development Strategies (LEDS). Kenya, where dairy production is a prominent productive sector, could benefit from development of NAMAs and LEDS to inform mitigation strategies for lowering GHG emissions.

1.2 Statement of the problem

Kenya has a large population of dairy (4,316,153) and beef cattle (13,495,692) under smallholder and pastoral systems (GoK, 2014),which are a significant source of enteric methane emissions. Current enteric methane estimates have been calculated using Tier I default emission factors that were derived from data obtained in developed countries with different conditions which may not depict the smallholder livestock systems in Kenya. Enteric methane emissions are high when cows are fed poor quality fibrous feeds with low digestibility, which in smallholder dairy farms is a pervasive challenge. The quality of feed varies with agro-ecological zones (AEZs) as it is a function of season, amounts of rainfall, temperature and altitude. Enteric methane emission is, therefore, likely to vary with AEZs, seasons and feed digestibility and herd milk productivity resulting from influence of quality of feeds fed. The options for mitigation of enteric methane emissions in smallholder dairy farms are presently not informed by local empirical data. Generating more accurate emission factors to calculate baseline estimates on enteric methane emissions can better inform design of appropriate mitigation options.

1.3 Objective of the study

The overall objective of this study was to contribute to mitigating greenhouse gas emissions by informing options for reducing enteric methane emissions from dairy cattle in smallholder production systems.

Specific objectives

i. To estimate Tier II region-specific enteric methane emission factors for dairy cattle.

ii. To estimate the amount of enteric methane emissions from feeds varying in digestibility levels in different agro-ecological zones and seasons.
iii. To determine the influence of herd milk productivity on the amount of enteric methane emissions.

1.4 Hypotheses

i. The estimated Tier II region-specific enteric methane emission factors are not significantly different from IPCC Tier I default emission factors.
ii. The amount of enteric methane emissions do not significantly vary with the levels of feed digestibility across the agro-ecological zones and seasons
iii. The amount of enteric methane emissions do not significantly vary with milk productivity levels attained on the farms.

1.5 Justification

Methane is a potent greenhouse gas that dairy cattle are major emitters after enteric fermentation process. Mitigating emissions from smallholder dairy production systems targets one critical source of methane, which will contribute in achieving the United Nations Framework Convention on Climate Change (UNFCCC) agenda on Climate Smart Agriculture (CSA). Smallholder dairy production is rain-fed system vulnerable to fluctuating feed quality, which can influence feed energy conversion into methane representing loss to the farmer and animal in energy and negative externality on the environment. Seasonality of feed quality is a pervasive characteristic feature in smallholder dairy farms therefore it is important to quantify enteric methane associated with feed quality, seasons and the agro-ecology that influence feed quality offered to ruminants.

Smallholder dairy farmers own 80% of the dairy cattle in Kenya and produce 56% of the total milk (Odero-Waitituh, 2017). These farmers are faced with a major challenge of low quantity and quality of feeds (Odero-Waitituh, 2017), which is likely to contribute more enteric methane emissions. This may be because most of smallholder dairy systems in Kenya are under feeding system in the grazing systems which has shown to result to high emission intensities than mixed systems due to the difference in quality and quantity of feeds and herd management in the two systems (Gerber *et al.*, 2013). Hence, smallholder dairy farmers need knowledge of options to reduce its emission to mitigate the emissions directly linked to animal agriculture. This study will provide baseline data on enteric methane emissions for smallholder dairy systems, which at the moment is insufficient to draw mitigation measures used by the Ministry of Environment and Natural Resources to contribute to Kenya's INDCs. This is because the IPCC default Tier I EFs for Africa either underestimate emission factors for cattle (Du Toit *et al.*, 2014) or overestimate the emissions. Therefore, estimating emission factors that will be used to calculate total enteric emissions for Kenya's smallholder dairy system will be very relevant in addressing the challenge of insufficient data.

CHAPTER TWO

LITERATURE REVIEW

2.1. Occurrence and Properties of Methane gas

Methane (CH_4) gas is classified as a trace gas estimated to have 1774±1.8 parts per billion (ppb) total global concentration (Hook *et al.*, 2010). It is a colourless, tasteless and odourless gas at room temperature and standard pressure (Heshner and Button, 2003) with main reactions being combustion and halogenations. It contributes to greenhouse effect, which is the exchange of incoming and outgoing radiation that warms the earth causing substantial changes in climate. As concentrations of atmospheric methane increases, concentrations of hydroxyl radicals decrease. This effectively prolongs the atmospheric lifetime of methane (Encyclopædia_Britannica, 2015).

Methanogenesis is a biological process that occurs in wetlands and rumen of ruminants. Globally, 60% of the methane emissions come from human activities such as industry, agriculture and waste management. However, agriculture is the primary source of methane emissions mainly from domestic livestock such as cattle, buffalo, sheep, goats and camels because it’s part of their normal digestive process and also comes from animal manure (EPA, 2010).

2.2 Sources of Methane Production

Methane is a natural occurring gas whose major sources are natural wetlands, landfills, rice paddies and animal agriculture (enteric fermentation and animal waste). Natural wetlands are the largest source of natural CH_4 emissions as they are characterized by water-logged soils and distinctive communities of plants and animal species and it is ideally anaerobic promoting anaerobic fermentation as well as methanogenesis. Wetlands contribute between 15-45% of global methane emissions (Segers, 1998)or170 Tetra grams (Tg) CH_4 annually (EPA, 2010). Methane emissions from natural wetlands are the main drivers of global inter-annual variability of the methane emissions (Zhu *et al.*, 2014).

Landfills generate methane as organic waste decomposes and in the treatment of waste water designed to be anaerobic. Landfill gas in which 50% is methane is a by-product of the digestion of organic materials by organisms that thrive in these anaerobic conditions. Emissions from this source can be mitigated by composting or combustion of the organic waste. However, landfill methane is also a source of energy, and some landfills capture and use it for energy. In addition, many materials in landfills do not decompose fully, and the carbon that remains is sequestered in the landfill and not released into the atmosphere (EPA, 2010).

Rice paddies are a source of increased atmospheric methane production with annual emissions of about 115 Tetra grams (Tg) per year (Thorpe, 2009). Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by diffusive transport through the rice plants during the growing season (IPCC, 1996). Microscopic organisms present in rice paddies respires carbon dioxide and more carbon dioxide in the atmosphere makes rice plants grow faster and the extra growth supplies soil microorganisms with extra energy and as a result, the amount of methane emitted per kilogram of rice yield increases. Major pathways of methane production in flooded soils are the reduction of CO_2 with H_2, with fatty acids or alcohols as hydrogen donor, and the trans-methylation of acetic acid or methanol by methane-producing bacteria (IPCC, 1996).

Farm animals consume forages and feeds to produce meat, milk, eggs and manure as the inevitable by-product of this process (Meer, 2008).Livestock manure is composed of organic material and water and when under anaerobic conditions, the organic material is decomposed by anaerobic and facultative bacteria producing methane, carbon dioxide and stable organic material (IPCC, 2006b). This occurs when manure is managed in liquid form, e.g. in a lagoon or tank producing almost 18 million metric tons of annual methane emissions (Steinfeld *et al.*, 2006) and probably in surface waters and methane discharge or runoff of manure (Meer, 2008). When manure is managed in solid form, in stacks or piles it tends to decompose aerobically with less methane produced. Methane from manure depends on feed quality in that high-quality feeds have a high digestibility thereby less of the organic material is excreted and less methane is produced (IPCC, 2006a). Low quality feeds have low digestibility, more organic material is excreted and more methane is produced (IPCC, 2006a). The main basic characteristic of manure which is the importance for the potential of methane production is the content of volatile solids (VS - amount of carbon) which can be calculated from the digestibility of the feed or by analysing the manure in the laboratory (IPCC, 2006a).

Enteric methane from ruminant livestock are major source of agricultural methane accounting for close to 40% of agricultural emissions (Tubiello *et al.*, 2013)contributing about 18% of the total global anthropogenic GHGs measured in CO_2 equivalent (Steinfeld *et al.*, 2006) alongside manure, rice paddies and landfills. Enteric fermentation is responsible for 37% of emissions from anthropogenic source (Steinfeld *et al.*, 2006) generating approximately 86 million metric tons of methane emissions worldwide (Shrestha *et al.*, 2013).

Methane in the rumen is produced by methane-producing archaea also known as methanogens which are a distinct group of anaerobe organisms normally found in the rumen microbial ecosystem (Baker, 1999) that grow in neutral pH of 6-8 (Boadi *et al.*, 2004; Clark, 2009). The methanogens that have been identified from the rumen are *Methanobrevibacter ruminantium, Methanobacterium formicicum*, *Methanomicrobium mobile, Methanosarcinabarkeri* and *Methanosarcinamazei* but only *Methanobrevibacter ruminantium* and *Methanosarcinabarkeri* have been found in the rumen at populations greater than 10^6 mL^{-1} (McAllister *et al.*, 1996). These methanogens use H_2, CO_2, formate, acetate, methanol, methylamines and dimethyl sulphide in the process of methane formation to generate energy for growth (Boadi *et al.*, 2004). These micro-organisms break down ingested feeds to volatile fatty acids (VFA), CO_2, H_2 and finally reduce carbon dioxide to methane preventing the accumulation of hydrogen which result in a decline in pH, and subsequent inhibition of many organisms that are essential for fibre digestion (Ominski and Wittenberg, 2004). The VFA's produced in the rumen are absorbed and used as an energy source, but most of the CO_2 and methane are removed from the rumen by eructation.

The quantity of methane released by enteric fermentation depends on the type of digestive tract, age, and weight of the animal, the quality of feed that affects the rate at which feed energy is converted to methane and quantity of the feed consumed, and the energy expended by the animal (Shrestha *et al.*, 2013). It is estimated that between 2000 and 2020, global methane emissions from livestock production will increase about 30% as population grows and higher incomes increase the demand for meat and dairy products (Shrestha *et al.*, 2013). Livestock inventories are expected to double by 2050 with most increases occurring in the developing world and as the numbers of farm animals reared for meat, egg, and dairy production rise, so do their methane emissions (Steinfeld *et al.*, 2006).

2.3 Global Enteric Methane Production

As stated earlier, global enteric methane emissions are on the rise due to increase in population, increased demand in livestock products and urbanization. Livestock production contributes significantly to enteric methane whereby approximately 87% of enteric methane originates in the reticulo-rumen while the remainder is produced in the hindgut (Ominski and Wittenberg, 2004). In this section, enteric methane emission from developed and developing countries will be reviewed to identify their contribution. Amongst the developed countries, the section will concentrate on Australia, New Zealand, USA, Canada and Sweden, which according to United Nations have 0.933, 0.910, 0.914, 0.902 and 0.898 Human Development Index (HDI), respectively.

In Australia, approximately 12% of agricultural emissions are from enteric fermentation (Moate *et al.*, 2014). Emissions represented as 66%, 11% and 3% are from grazing cattle, dairy cattle and feedlot cattle respectively due to the size of the livestock herd. The population is mainly driven by export demand and climate conditions. This increased export demand could increase the national herd and hence emissions (Lines-Kelly, 2014). In New Zealand, methane emissions from ruminants comprise 31.5% of the world's total emissions putting the agriculture sector in New Zealand in a unique position within the developed world. Meanwhile, reducing methane emissions from ruminant livestock is technically challenging and has to be achieved against a rising demand for animal products (Clark, 2009). In 2012, the agriculture sector was responsible for 8.1% of total US greenhouse gases emissions where enteric fermentation represented 25% of the total methane emissions from anthropogenic activities and of all domestic animals, beef and dairy cattle are by far the largest emitters of methane due to their large population, large size, and their digestive characteristics with 71% and 25%, respectively (EPA, 2014). From 1990 to 2012, emissions from enteric fermentation have increased by 2.3% (EPA, 2014). Texas and California are the greatest contributors due to their immense dairy and beef cattle populations (USDA, 2015). Using IPCC estimates, it has been determined that Canadian cattle account for 97% of total livestock enteric methane with 25% attributed to dairy and 72% coming from beef cattle (Ominski *et al.*, 2007).Agriculture in Sweden causes 13% of the total greenhouse gas emissions where 21% of the emissions come from the livestock sector mainly from enteric fermentation (Allard, 2009). Between the year 1990 to 2011 enteric methane emissions decreased by about 12% due to reduced livestock farming activities such as decreased population of cattle and in the year 2011, methane production from enteric fermentation contributed one-third of the emissions from agriculture (Naturvardsverket, 2013).

Africa and Asia are among the developing continents where extensive and pasture-based methods of farming are most practiced (Orodho, 2006). In 2050, livestock numbers in developing countries are expected to double leading to an increase in enteric and manure methane gas production (Steinfeld *et al.*, 2006). Developing countries have contributed 48.1% of the global GHGs over 160years (1850-2010) (Wen *et al.*, 2016). Sub-Saharan Africa's GHG emissions per FPCM (fat protein correlated milk) is 7.5Kg CO_2 – eq./Kg FPCM (FAO, 2010), the highest amongst developing continents, out of which 52% comes from methane. This is because feeds and feedstuff in Africa are characterized as low quality. This low quality feed is characterized by high fibre content which results to higher enteric methane emission rate than the developed countries in the temperate regions. High emissions are also due to large cattle populations developing world.

2.4 Enteric methane Production in Ruminants Production Systems

Ruminant methane production occurs as a normal digestive process in the rumen through enteric fermentation (Steinfeld *et al.*, 2006). The nature of ruminants' digestive system promotes anaerobic fermentation, which contains diverse rumen microbes that break down fibrous feeds to volatile fatty acids that can be absorbed and utilized for maintenance, reproduction and production. The amount of methane produced depends on animal's age, body weight, dry matter intake, quality of feed, type of volatile fatty acid produced in the rumen and energy expenditure (Johnson and Johnson, 1995; Shrestha *et al.*, 2013; Steinfeld *et al.*, 2006).

2.4.1 Animal's Age

From birth to weaning, the reticulo-rumen of calves are largely undeveloped and non-functional hence has no ability to produce methane. During the weaning stage the calves are introduced to dry and fibrous feeds like hay to stimulate rumen development i.e. rumen microbes proliferation which results to production of microbial fermentation end products (VFAs) (Pinares-Pantino and Waghorn, 2012) and methane. According to Ramin (2013), methane production begins at 4 weeks of age when the solid particles are retained in the reticulo-rumen. This gas production increases as the animal matures due to increases in feed intake causing an increase in rumen microbes' population and more feed is anaerobically fermented to produce VFAs, CO_2 and hydrogen and subsequent methane formation. As the animal grows, the type and amount of feed consumed can lead to variations in the rumen micro biota and this could be permanent therefore affecting methane production at a later growth stage (Robinson *et al.*, 2014).

2.4.2 *Live-body weight*

Maintenance requirements are calculated as a function of the animal's live-weight. An increase in body weight increases the metabolizable energy requirement for maintenance which will lead to an increase in feed intake (Hegarty *et al.*, 2010). Large ruminants have a higher body weight than small ruminants thereby emitting methane 7-9 times. This increased feed intake is directly related to increased methane production (Johnson and Johnson, 1995). Animal growth involves an animal increasing in size leading to increased feed intake to cater for the energy required for maintenance of the added body weight.

2.4.3 *Dry matter intake*

Enteric methane production is directly affected by dry matter intake (Goopy *et al.*, 2014; Hegarty *et al.*, 2010). As quantity of feed consumed by the ruminant increases so does methane production (Blaxter and Clapperton, 1965) per unit additional intake especially for feeds with low to moderate digestibility (Hegarty *et al.*, 2010). Research by Robinson *et al.*, (2014) showed that there is a relationship between methane emission and feed consumed by sheep confined in respiration chamber. It has also been recognized that methane emission is almost proportional to feed intake (Berndt *et al.*, 2014). The IPCC Tier II method uses average daily feed intake as one of the factor to estimate methane emission making it an important aspect. Johnson and Johnson (1995) also reported that amount of feed consumed directly affects methane emissions. To know how feed intake influences methane yield, it is important to measure the intake. However, it is challenging to measure the intake under grazing conditions. There are a few methods used to measure such as, conducting pasture biomass before and after grazing though this method may fail due to feed intake based on plant part of species palatability and nature of pasture (Berndt and Tomkins, 2013). Feed intake can also be measured by use of C-isotopes which are dosed regularly and faeces collected over a period of time (Berndt and Tomkins, 2013). Another method is by use of live-weight and live-weight gain data using existing algorithms (Berndt and Tomkins, 2013). The latter method can be used in IPCC Tier II methodology for estimating enteric methane emissions.

2.4.4 *Quality of Feed and Feed Digestibility*

Quality of feed influences methane production in ruminants in that it influences the presence and activities of the rumen microbes as well the pattern of volatile fatty acids (VFA). One of the measure used to describe quality of feed is digestibility as it gives the measure of energy value of a feed which is an important factor in determining methane emissions (Blaxter and Clapperton, 1965). Digestibility affects the rate at which feed energy is converted to methane by altering the amount of energy extracted by the microbes for maintenance and production (Knapp *et al.*, 2014). Feed with high digestibility has a low conversion rate of feed energy to methane thereby decreasing methane production (Knapp *et al.*, 2014). Similarly, feed with high quality promotes faster passage in the rumen that leads to lower extent of rumen fermentation and also less methane production as opposed to low quality feed which require more time in the rumen to be broken down into soluble nutrients (Knapp *et al.*, 2014). Berndt and Tomkins (2013) reported methane emission depends on pasture origin whereby temperate pastures such as ryegrass has an emission value of 0.49g CH_4/Kg LW than tropical pasture such as Rhodes grass with an emission value of 0.61g CH_4/Kg LW. This is because temperate pasture are improved and mostly of high quality due to the well-developed soils and rapid nutrient cycling (Shrestha *et al.*, 2013).

Kenya is located geographically in the tropics where tropical pasture is dominant in the grazing lands and characterized by high lignification; which is a defence mechanism adopted to reduce loss of water through transpiration. Weather or seasons may also affect methane emission due to the seasonal fluctuations in rainfall which affect pasture biomass, quality and digestibility (Berndt and Tomkins, 2013). During the wet season, the quantity and quality of feed is high while in the dry seasons, pasture is scarce and highly lignified rendering it of low quality due the decrease in rainfall amounts resulting in reduced pasture growth that affects feed digestibility. Therefore, this can be used to show seasonal effects in enteric methane production from grazing cattle.

Emissions are also affected by the growth rate of animals that ultimately depends on quantity and quality of feeds available. A study on enteric methane emissions from cattle fed on grass pasture showed high enteric methane emission when pasture quality and availability was low (Berndt and Tomkins, 2013). This situation led to slow growth rate that led to high emissions per kilogram (kg) of meat as well as longer life leading to more emissions for beef cattle production whereas there was lower emissions per kg of meat when the pasture quality and availability was high (Berndt and Tomkins, 2013; Ominski *et al.*, 2007). Livestock species kept in an area are a function of agro-ecological zones (AEZs) because it influence feed resource base (Bebe, 2003). These AEZs have different amounts of rainfall, temperatures, and different altitudes influencing pasture digestibility. This therefore can affect the amount of enteric methane emitted.

2.4.5 *Type of Volatile Fatty Acid (VFA) produced in the Rumen*

During fermentation in the rumen, feed ingested is broken down by rumen microbes to produce VFAs, carbon dioxide, ammonia and methane (Jayanegara and Toharmat, 2013). The end products of rumen microbial fermentation include the volatile fatty acids and are the main source of energy for ruminants. The animals meet their energy requirements for growth, maintenance, production and reproduction from the absorption of VFAs. Propionate, acetate or butyrate, among others, are the VFAs produced from the fermentation process and production of each depends on the quality and quantity of carbohydrates ingested. Methane production greatly depends on VFAs' profile which have different efficiency levels in the use of energy (Wolin, 1960). The ratio of VFAs produced regulates supply of hydrogen and subsequently methane production (Johnson and Johnson, 1995).

Propionate is a primary product of starch and soluble sugars digestion which is produced by *Clostridium propionicum* from lactate; an intermediate product in the production of propionate. Janssen (2010) regarded propionate as an alternative of hydrogen gas sink. This is because propionate formation pathways accept electrons thereby accepting the metabolic hydrogen that is often in form of reduced proton (Jayanegara and Toharmat, 2013). High ratio of grain to roughage in a diet promotes production of more propionate. This type of diet leads to a high propionate: acetate ratio which reduces methane production to as low as 2-3% (Johnson and Johnson, 1995) because the pathway to propionate production is very competitive in hydrogen utilization (Jayanegara and Toharmat, 2013).

Acetic acid is a primary product of cellulose and hemi-cellulose degradation (Janssen, 2010). Acetate and butyrate are produced by *Clostridium butyricum*. These two VFAs increase methane production by providing hydrogen to the methanogens, which are hydrogen-utilizing bacteria. High roughage to grain ratio in a diet promotes the production of acetate and butyrate, therefore, more methane is produced.

2.4.6 Energy expenditure (EE)

This is the amount of energy that grazing animal use on movement during grazing, ruminating, and standing. Shrestha *et al.*, (2013) noted energy expended by the animal as one of the factor affecting methane production. This is because EE is included in the metabolizable energy for maintenance. This energy varies with availability and digestibility of feed. The IPCC Tier II method estimates feed intake by use of computing net energy requirements where energy expenditure noted as NE_{work}.

2.5 Enteric Methane Production in Smallholder dairy farms

Globally, methane is an important contributor, 52% of GHG emissions from both developed and developing countries, to the total greenhouse gas emissions from milk production. Sub-Saharan Africa's GHG emissions per FPCM (fat protein correlated milk) is 7.5Kg CO_2 – eq./Kg FPCM (FAO, 2010), the highest amongst developing continents. Kenya's total GHG emissions stands at 73 MTCO2eq in 2010 and the land use, land-use change and forestry and agriculture sectors contribute 75% of total emissions (GoK, 2015). Enteric methane is the largest source of agricultural methane. However, there has been inadequate data to quantify the emissions attributed to Kenya's smallholder dairy which is the largest sector in the agricultural subsector comprising of 1.8 million smallholder dairy farms owning approximately 2.64 million dairy cattle and contribute 90-95% of 2.5 million tons of raw milk annually and 80% of the marketed milk (FAO, 2014; Orodho, 2006; Waithaka *et al.*, 2002). Kenya's dairy production will mainly non-commercialized system in the early 90s with small east African zebu as the common breed until in 1920's when the European settlers introduced *Bos taurus* cattle breeds which had high milk production and, therefore, commercialized dairy production.

Smallholder dairy farming was initiated by labourers from the European settlers' farms which were located in the high potential areas of Kenya (highlands) through purchase of culled *Bos taurus* cows. These cows would then provide them with milk for consumption as milk was an integral part of their diet (Bebe *et al.*, 2002) and led to most smallholder dairy systems comprising of upgraded cattle breeds being in the Kenyan highlands. After independence, lands owned by the settlers were subdivided and given to the locals. Smallholder dairy farming is characterized by farms of less than 10 acres, an average herd of 1-5 cows in an intensive production system and 1-10 in an extensive system and dominate in crop-dairy high potential areas (Bebe, 2003; Orodho, 2006; Waithaka *et al.*,

2002) of Central Kenya, Central Rift Valley and Western Kenya. Friesian and Ayrshire breeds are most dominant (Bebe, 2003). Since liberalization of the dairy sub-sector in Kenya, smallholder dairying has increased. Kenya has integrated dairy into smallholder farming systems especially in the highlands (Udo *et al.*, 2011) hence Kenya has one of the most prominent smallholder dairy system in Sub-Saharan Africa with 1.8 million farms (FAO, 2014).

Feeding system in smallholder dairy production systems ranges from cut and carry system supplemented with purchased feeds to free grazing system on unimproved natural pastures (Steinfeld *et al.*, 2006). The main feeds available being natural grass, planted fodder crops such as Napier grass (*Pennisetum purpurem*), Rhodes grass (*Chloris gayana*), Seteria (*Seteria sphacelata*) and Kikuyu grass (*Pennisetum clandestinum*) and crop residues such as maize Stover, bananas pseudo stems, sugarcane tops, milling by-products and weeds such as *Amaranthas* spp. Which have seasonal and regional availability. Feeds and feeding are a major factor affecting methane production. Smallholder dairy farming faces feed constraints such as inadequate feed resources due to the declining farm sizes. In the Kenyan highlands, smallholder dairy farmers ranked lack of feed as the leading major constraint (Bebe *et al.*, 2002). Other factors are poor quality feedstuffs due to varying climatic conditions, high cost of purchased feeds and concentrates and lack or limited knowledge on utilization of locally available feed resources and conservation methods of excess feedstuff.

Feeding practices by most smallholder farmers was found to be dependent on seasons where the amount and type of feed livestock were offered differs in wet and dry season. Research was conducted in Kaptumo, Nandi County on feed availability and results showed that during the wet season, farmers offered 35kg fresh weight of Napier grass to a milking cow while half the amount is offered during the dry season (Lukuyu *et al.*, 2011). This was realized due to high moisture in soils that promoted fast plant growth during the wet season while there was limited moisture available for plant growth (Lukuyu *et al.*, 2011) in the dry season. The feed offered also differs with agro-ecological zones, which affect feed availability, quality and feed type. In Lower highland zones, for example, there is high amount of rainfall and the zone is characterized by tea plantation, maize plantations and dairy production and feed available mainly is Napier grass, Kikuyu grass among others all which are leafy and crop residues such as maize Stover and bean husks though are seasonally available. Smallholder dairying is dominant in these Kenya highlands.

Generally, the feeding system in smallholder dairy production systems does not consider that feeding that is compromised on quality and quantity fails to meet the energy requirements and can affect methane production. The effect on methane can be because of either increasing the number of animals to increase farm production, which will lead to increase in total methane emissions, or increasing methane intensity per kilogram of milk produced due to low herd productivity.

2.6 Methods of Measuring Enteric Methane production by Ruminants

There are methods developed to directly or indirectly measure and estimate enteric methane and vary from the basic principles, ideologies, capacity of animals to be experimented on, cost and feeding situations. Most common methods are calorimetric and which are accurate in principle but cannot be applied to a large number of animals in one experiment (Pinares-Patiño *et al.*, 2003). Other methods involve estimation techniques (Brouček, 2014). In this section, different types of method will be reviewed.

2.6.1 Respiration Chambers

This is an animal calorimetric system technique whose principle is to collect all exhaled air through mouth, nostrils and rectum from an animal placed in a chamber and measure in this case methane concentration (Storm *et al.*, 2012). There are two types of respiration chambers; closed-circuit chamber which is not commonly used and open-circuit, an indirect-respiration technique (Johnson and Johnson, 1995) is commonly used and constitutes precise means of measuring methane gas. In these chambers, air is passed through a chamber containing an animal and methane concentration is measured in the inlet and outlet flows (Storm *et al.*, 2012) using infrared analysers at 0-500parts per million (ppm) range (Johnson and Johnson, 1995). The difference between methane concentration in the incoming air and outgoing air from the chamber is the emitted methane (Storm *et al.*, 2012). This chamber system is regarded as a standard method of estimating enteric methane emission because the environment can be controlled (Johnson and Johnson, 1995). However, there are limitations such as effect of an animal’s dry matter intake, which is directly related to total enteric methane emitted. This will limit use of the data on livestock under semi-intensive and extensive production systems (Storm *et al.*, 2012).The restricted animal movement may also affect animal's behaviour and cost of the chambers, maintenance and labour are huge limiting factors tor use of these chambers.

2.6.2 Sulphur Hexafluoride (SF_6) Tracer Technique

This is a non-isotopic tracer technique developed by Zimmerman in early 90's with the purpose of investigating energy efficiency (Storm *et al.*, 2012). It is suitable for grazing animals. This method monitors emission continuously and only determines methane emissions from eructation and breathing unlike the chamber system which allows estimation of methane from mouth, nasal cavity and rectum (Berndt *et al.*, 2014). The basis of the technique is that excretions of two gases sourced from the rumen disperse identically into the animal's environment, and thus have identical probability of interception by a breath sampler located near the nasal cavity. The SF_6 is an inert gas tracer that is placed in the rumen in a permeation tube with a known release rate while methane is the gas under investigation (Berndt *et al.*, 2014). The animal is then fitted with a halter and a capillary tube that is connected to an evacuated sampling light and unobtrusive canister made of PVC, aluminium or stainless steel placed on the head (Johnson and Johnson, 1995). Air sample is steadily taken as the vacuum in the sampling canister deplete and the air sample is pressurized with nitrogen to aid in determining methane and SF6 concentrations using gas chromatography. Methane emission is then calculated using the formula $QCH_4 = QSF_6 \times [CH_4] / [SF_6]$ where QCH_4 is the emission rate being investigated, QSF_6 is the known rate and $[CH_4] / [SF_6]$ is the measured rate in the canister (Johnson and Johnson, 1995). This method gives good estimate on variations between and within animals (Storm *et al.*, 2012).

2.6.3 In-vitro Gas Production Technique (IVGPT)

This is a technique that estimates methane production without actually relying on an individual animal (Johnson and Johnson, 1995). This technique was initiated to understand ruminal fermentation of feedstuff (Storm *et al.*, 2012). The principle of IVGPT is to ferment feed under controlled laboratory conditions employing natural rumen microbes. Feedstuffs are subjected to different treatments, incubated at 39°C with a mixture of rumen fluid, buffer and minerals for a certain time. Typical time interval used is 24, 48, 72, 96 or 144 hours and the amount of total gas produced during incubation is measured and its composition analysed, to obtain data on the *in-vitro* production of methane (Storm *et al.*, 2012).

2.6.4 IPCC Standard Models

The IPCC is a scientific body formed in 1988 by United Nations Environmental Programme (UNEP) and World Meteorological Organization to provide governments with scientific basis to develop policies on climate as well as underlying negotiations at the UN Climate Conference, the United Nations Framework Convention on Climate Change (UNFCCC). IPCC has 3 different estimation methodologies known as Tier I, Tier II and Tier III. Tier I is known to be the simplest and relies on default emission factors sourced from the literature (IPCC, 2006a) while Tier II which is one of the feature in the Global Livestock Environmental Assessment Model (GLEAM) uses data on gross energy (GE) intake and methane conversion factors (Y_m) most appropriate for characteristics of each livestock category in a country (IPCC, 2006a). Tier III methodology is more sophisticated adding more country-specific information than Tier II.

Choice of methodology depends on availability of country-specific data. Method of interest is Tier II that follows three major steps in approaching enteric methane emission. Step 1 involves obtaining animal population data and field activity data for a livestock subcategory to use to estimate the feed intake, which is an important factor in estimating enteric methane emission. This data includes weight, average weight gain, milk production per day in Kg/day and its fat content in percentage units respectively for lactating animals, feed digestibility (%), average amount of work performed per day in hours/day for draft animals, percentage of females that give birth and wool growth for wool sheep.

IPCC recommends use of net energy systems to estimate emissions. This includes net energy requirements for maintenance (NE_m), growth (NE_g), lactation (NE_l), pregnancy (NE_p), animal activity (NE_a) like grazing activity and locomotion, work (NE_{work}), ratio of net energy available in diet for maintenance to digestible energy consumed (REM) and ratio of net energy available for growth in a diet to digestible energy consumed (REG) for growing animals using equations in the IPCC (2006) good practice guidelines. The sum of these net energies requirements and energy available a diet derive gross energy (GE) requirement estimate. Step 2 uses estimated GE derived in step one and emission conversion factor Y_m assigned to livestock category of interest to develop the emission factor (EF) using an equation in the IPCC (2006) good practice guidelines. EF represents an estimate of amount of methane (kg) produced per animal. Step 3 calculates the estimated total emissions using the emission factor developed with the animal population associated with the EFs.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Site selection

The study site was Nandi County located in the western part of the Rift Valley of Kenya in Zone III (Otolo and Wakhungu, 2013). This site represents a growing importance of dairying in the local economy. Sampling protocol involved participatory mapping exercise conducted using expert knowledge of personnel from International Livestock Research Institute (ILRI) and Nandi County government. Three Agro-Ecological Zones (AEZ); Lower Highland 1 (LH1: 1900-2400m above sea level), Lower Highland 2 (LH2: 1400-1900m above sea level) and Upper Midlands (UM: 1200-1400m above sea level) were identified based on altitude, rainfall and temperature and predominant land use data. The number of sampling points in each AEZ was based on the total sample size (~120 households) weighted by the total area of each AEZ. Thirty-six GPS points across the three AEZs were selected, restricted by proximity to roads of 2 km GPS points. These points were allocated across LH1 (n=22), LH2 (n=8) and UM (n=6) respectively and the points used to navigate to the nearest village, where 3-4 farmers were selected with the assistance of local administration and recruited during the initial household visits.

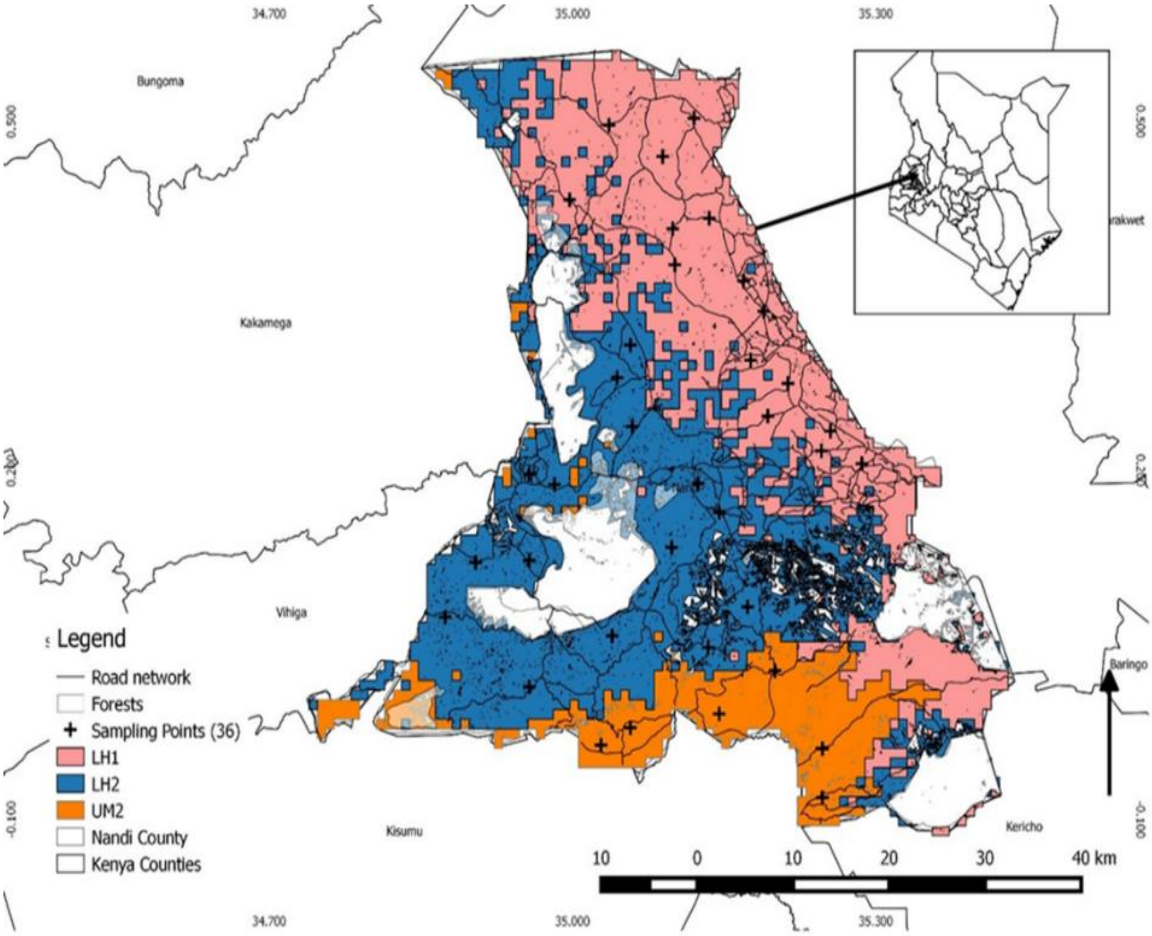

Figure 1: Map of Nandi County and its three agro-ecological zones (AEZs)

3.2. Estimation of Enteric CH_4 emission

Enteric methane emission was estimated according to the general approach of IPCC Tier II, which integrates the animal activity performance and production data andmetabolizable energy requirements (MER) to compute the daily methane production (DMP) and emission factor (EF) as illustrated in figure 2. A brief explanation of this approach is subsequently presented.

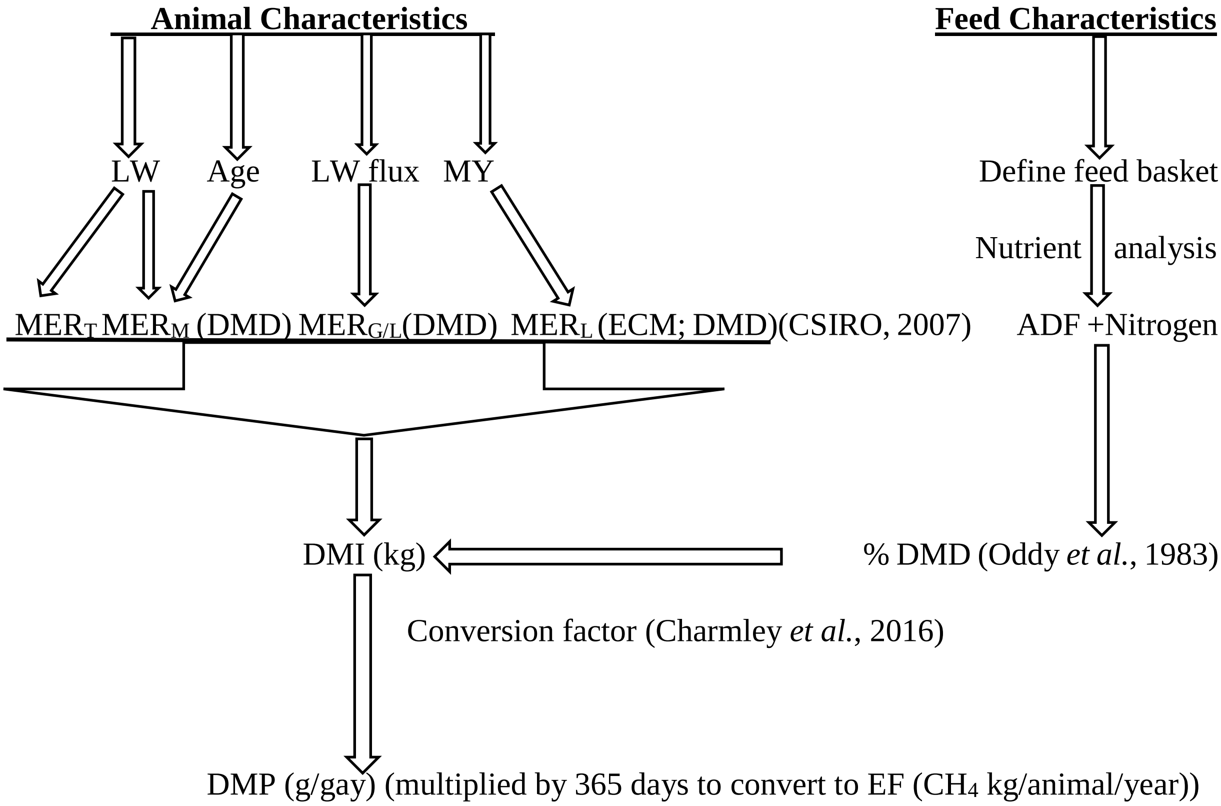

Figure 2: Methodological framework of estimating enteric methane emission factor using metabolizable energy requirement (MER) system following the IPCC Tier II approach.

Animal performance and production data

Total Metabolic Energy Requirements (MER_{Total}) of individual cattle on a seasonal basis was calculated by summing the estimated MER for maintenance (MER_M), growth ($MER_{G/L}$), lactation (MER_L) and locomotion/traction (MER_T). Dry Matter Intake (DMI) was inferred as a function of MER_{Total} and the weighted mean dry matter digestibility (DMD) of the seasonal feed baskets in each AEZ. The DMI was used as the basis for calculation of daily methane production rate (MPR).

Data collection on animal performance and production was on all animals in the farm, following the sampling protocol described by Goopy *et al.,* (2017). Animal performance and production were measured on 487 cows in LH1, LH2 and UM zones. The animals were ear tagged with unique numbers (Alflex Europe SA, Vitre) and their ages determined by dentition (Torell *et al.*, 1998) or by farmer recall for young cattle. A portable animal weighing scale fitted with LED display (Model EKW Endeavour Instrument Africa Limited, Nairobi) was used to determine live weight (LW). Heart girth (HG) was measured using a HG measuring tape. Body condition scoring (BCS) was assessed on a scale of 1-5 (Edmonson *et al.*, 1989). Parity and physiological status (pregnant or lactating) was obtained from farmer recall. All measurements were recorded every three months from the second household visit and dates recorded (November 2015 to October 2016). Intervals coincided with the beginning of each of the four sub-seasons in Nandi region (Short Rains (SR): November to January, Hot Dry (HD): February to April, Long Rains (LR): May to July and Cold Dry (CD): August to October).

Daily milk yield data was measured on an individual basis by farmers using a Mazzican graduated milk urn (http://mazzican.com/Ashut Engineers Limited, Kenya) and recorded in an exercise book for the duration of the study. Milk samples were collected in every season, bulked by household, then analysed for butterfat (BF) (Gerber method) and milk density (FAO, 1998) by New Kenya Co-operative Creameries (KCC), Kapsabet. Milk solid non-fat (SNF) was calculated from BF and density using Richmond's formula (Bector and Sharma, 1980):

$$\mathrm{SNF} = \left(\frac{\text{milk density}}{4}\right) + (0.22 * \mathrm{BF}) + 0.72 \tag{1}$$

Milk energy content (ECM) was calculated from the equation by Tyrell &Reid (1965):

$$\mathrm{ECM} = 0.0386\mathrm{F}(\mathrm{g/kg\ milk}) + 0.0205\mathrm{SNF}(\mathrm{g/kg\ milk}) - 0.236 \tag{2}$$

Distance covered during grazing was determined by using GPS collar recorders (Allan *et al.*, 2013) fitted to an animal for2consecutive days (November-December 2016). Twelve animals in total were recorded over the three AEZs: LH1 (5), LH2 (3) and UM (4), with selection based on diversity of grazing practices. Distance travelled was deemed the mean distance covered by animals measured in each AEZ.

Farm size, identification of fields and crops planted in each field was conducted twice over the study period (November 2015, June 2016). Information on farm boundaries was provided by the farmers and the areas of individual farms and fields were determined using a laser range finder (Truth Laser Range Finder, Bushnell Outdoor Products, U.S.A) and the use of the plots were recorded. Samples of forages and fodder crops identified during these visits were collected, fresh weight recorded using a digital scale (T28 scale, @weigh scales Melbourne, Australia), then oven-dried (50°C, 3-5days). Then it was ground through a 1mm screen (IKA Handheld analytical mill; Cole-Parmer Scientific Experts, UK) and stored at room temperature until analyzed.

Pasture yield was estimated by placing exclusion cages (n=36; 0.5mH X 0.5mL X 0.5mW) at the study sites, one per village per season and extrapolating the yield to area recorded as under pasture. Grass was harvested at 3-month interval by harvesting the biomass above 2.5cm, and then weighed. Biomass of Napier grass available was estimated by multiplying the area under cultivation with published yield estimates of 6.84Tons/ha (Van Man and Wiktorsson, 2003). Where Rhodes grass was grown as a crop, biomass was estimated using the yield index of 3.66t/ha (Muyekho *et al.*, 2003). Maize Stover biomass was estimated by applying farmer recall of grain yield to a harvest index of 0.41(Remison and Fajemisin, 1982). Sugarcane tops biomass was estimated by multiplying area under cultivation by the yield (39Tons/ha) and assuming 4.89% as the leaf yield of the crop (Kapur *et al.*, 2013). Banana pseudo-stems in the diet were estimated from farmer recall.

Estimation of Metabolizable energy requirements (MER)

Nutrient analysis of feed was performed by wet chemistry for dry matter (DM) (AOAC method 930.15), total N (AOAC method 990.03), neutral detergent fibre (NDF) and acid detergent fibre (ADF:AOAC method 973.18(A-D)) (AOAC, 1990).The DMD was estimated using the equation of Oddy *et al.*, (1983):

$$\mathrm{DMD(g/100g\ DM)} = 83.58 - 0.824 * \mathrm{ADF(g/100g\ DM)} + (2.626 * \mathrm{N(g/100g\ DM)}) \quad (3)$$

where:

DMD = dry matter digestibility

ADF =acid detergent fibre

N = total nitrogen

DM = dry matter

Energy expenditure was calculated using equations from Goopy *et al.*,(2017) derived from equations published in "Nutrient Requirements of Domestic Ruminants"(CSIRO, 2007). Animal data was then analyzed. The $\mathrm{MER_M}$ was estimated as follows:

$$\mathrm{MERM\ (MJ/day) = K * S * M(0.26 * MLW^{0.75}\ * exp(-0.03A)/((0.02 * M/D) + 0.5)} \quad (4)$$

where:

K=1.3(the intermediate value for *Bos taurus/Bos indicus*)

S=1 for females

M=1

MLW= mean live weight for each season calculated as; (start live weight of a season + end live weight at the end of the season)/2

A= age in years

M/D= metabolizable energy content (ME MJ/DM kg) where;

$$\mathrm{M/D = 0.172DMD - 1.707} \quad (5)$$

The energy expended for weight gain (loss) ($\mathrm{MER_{G/L}}$) was calculated as follows;

$$\mathrm{MER_G(MJ/day) = (ADWG\ (Kg) * 0.92 * EC)/(0.043 * M/D)} \quad (6)$$

$$\mathrm{MER_L(MJ/day) = ADWL\ (Kg) * 0.92 * EC)/0.8} \quad (7)$$

where:

ADWG/L (kg) =average daily weight gain or loss being the difference between live weight at initial season and live weight at the end of the season divided by the number of days in the period

EC (MJ/kg) = energy content of the tissue taken as a mid-range value of 18MJ/kg.

Daily milk consumption of pre-ruminant calves (DCMC) was estimated using average live weight (LW) plus the average daily live weight gain (LWG) of calves between 0 to 3.5 months using equation from Radostits and Bell, (1970).

DCMC (L) = (LW (kg)*0.107 L/kg) + (0.154L/0.1kg LWG) (8)

The $\mathrm{MER_L}$ was calculated by calculating the daily milk yield (MY):

$$MY(L) = \frac{Total\ milk\ recorded\ per\ season\ (L)}{Number\ of\ days\ in\ season\ (L)} + DCMC\ (L) \quad (9)$$

The $\mathrm{MER_L}$ was calculated as:

$$\mathrm{MER_L\ (MJ/day) = \left[(MY(L) * ECM(MJ)) * \left((0.02 * M/D) + 0.4\right)\right]} \quad (10)$$

Energy expended for travel/grazing was estimated as follows:

$$\mathrm{MER_T\ (MJ/day) = DIST(km) * MLW(kg) * 0.0026(11)}$$

where:
DIST= average distance covered
MLW= mean live weight for each season calculated as live weight at the start of a season summed with live weight at the end of the season divided by two
0.0026= the energy expended (MJ/LW kg).
The daily total energy expenditure (MER_{Total}) for each animal category in each AEZ and season was then calculated as:

$$MER_{TOTAL}(\mathrm{MJ/day}) = MER_M + MER_{G/L} + MER_L + MER_T \quad (12)$$

Computation of daily methane production (DMP) and emission factor (EF)

The daily methane production (DMP) was estimated as a factor of dry matter intake (DMI) (Charmley *et al.*, 2016). Hence, DMI was calculated as:

$$\mathrm{DMI(kg)} = \mathrm{MER_{Total}(MJ/day)} / (\mathrm{GE\ (MJ/Kg)} * (\mathrm{DMD}/100))/0.81 \quad (13)$$

where:
GE= gross energy of the diet assumed to be 18.1MJ/kg DM
0.81 =the factor to convert metabolizable energy to digestible energy.
The estimated DMI was used to calculate DMP using equation by Charmley *et al.* 2016:

$$\mathrm{DMP\ (g)} = 20.7 * \mathrm{DMI\ (Kg/day)} \quad (14)$$

Mean DMP for each class of animal in each season was calculated. This was then used to calculate an annual enteric methane EF (CH_4kg/head/year):

$$\mathrm{EF} = \frac{(\mathrm{DMP_{SHORT\ RAINS}} + \mathrm{DMP_{HOT\ DRY}} + \mathrm{DMP_{LONG\ RAINS}} + \mathrm{DMP_{COLD\ DRY}}) * 365}{4 * 1000} \quad (15)$$

3.3. Data analysis

Statistical analysis of the data collected used linear regression model and analysis of variance (ANOVA). Descriptive statistics (mean and standard error of means (SEM)) were calculated for live-weight, live weight change, daily milk yield, total MER, DMI and DMP for each AEZ and season. The linear regression model fitted tested the association of methane emissions with dry matter digestibility and the influence of milk yield on energy required for lactation and total metabolizable energy. The dependent variables were daily methane production, MER_L and total MER being explained by feed digestibility and daily milk yield, expressed in a model form:

$$Yi = \beta 0 + \beta 1X + \varepsilon \quad (16)$$

where:

Yi = Daily methane production or MER for Lactation or total MER

$\beta 0,$ = constant

$\beta 1$= Regression parameters

X = dry matter digestibility or and daily milk yield

ε = random error

The effect of AEZs and season on DMD and DMP was analysed using ANOVA fitting season (SR, HD, LR and CD) and agro-ecological zone (AEZ) (LH1, LH2 and UM2) as factors in a general linear model in the form:

$$Yijk = \mu + \tau i + \beta j + \varepsilon ij \qquad with\ i = 1, 2, 3;\ j = 1, 2, 3, 4 \tag{17}$$

where:

$Yijk$= Dry matter digestibility or daily methane production

μ= overall mean

τi= level effect of AEZ (LH1, LH2 or UM2)

βj=level effect of season (SR, HD, LR or CD)

εij= random error

CHAPTER FOUR

RESULTS

4.1 Estimated region-specific Tier II methane emission factors for dairy cattle

Table 1 shows the number of dairy cattle by AEZ and season and the herd dynamics on the farms as used in computing methane emissions. Cattle population was highest in the LH1 and during the short rains and was lowest in UM and during the cold dry season. Cattle exits through sales and deaths were 5 to 6%, while entries through purchases were 2.5% across the AEZ and across the seasons with deaths coinciding with calving down events.

Table 1: Cow population and herd dynamics observed over the four seasons and agro-ecological zones in Nandi County, Kenya

		Agro-ecological zones			
		Lower highland 1	Lower highland 2	Upper midlands	Total
Season					
	Short rains	291	92	66	449
	Hot dry	287	89	61	437
	Long rains	280	84	59	423
	Cold dry	267	80	55	402
Herd dynamics					
	Sales	51	17	12	80
	Purchases	31	7	5	43
	Deaths	4	2	3	9
	Loans	0	0	1	1

Dairy cattle were heaviest in LH1and lightest in the UM zone (Table 2). Cows attained the highest live-weight gain in the short dry season but lost weight in the hot dry season in LH1 and LH2.

Table 2: Mean live weight (kg) and weight change (kg/day) ±SEM of cows by seasons in Lower Highland 1, Lower Highland 2 and Upper Midlands agro-ecological zones in Nandi County, Kenya

	Seasons	Agro-ecological zones			**Mean**
		Lower Highland 1	Lower Highland 2	Upper Midlands	
Mean Live-weight (kg)	Short Rains	323.7 ± 3.6	284.6 ± 6.6	251.7 ± 7.3	305.1 ± 3.4
	Hot Dry	327.5 ± 4.1	288.4 ± 6.8	258.4 ± 8.0	309.9 ± 3.7
	Long Rains	318.7 ± 3.9	284.1 ± 7.1	262.4 ± 8.3	304.3 ± 3.6
	Cold Dry	320.0 ± 3.9	291.7 ± 7.4	271.2 ± 8.1	308.1 ± 3.5
Daily average weight gain (kg/day)	Short Rains	0.20± 0.02	0.17 ± 0.04	0.11 ± 0.04	0.16 ± 0.03
	Hot Dry	-0.12 ± 0.02	-0.22 ± 0.05	0.05 ± 0.03	-0.10 ± 0.03
	Long Rains	-0.04 ± 0.02	0.05 ± 0.04	0.10 ± 0.04	0.04 ± 0.03
	Cold Dry	0.03 ± 0.02	0.05± 0.04	0.11 ± 0.04	0.06 ± 0.04

The Whisker plot (Figure 3) for milk yields show that mean daily milk yield was highest in LH1 (5.4 litres) and lowest in UM (3.7 litres) but with presence of several outliers. There was a significant difference between LH2 – UM (p= 0.00043) and LH1-UM (p=0.0000) zones and as for the seasons the difference was only in short rains-hot dry (p= 0.033) season and cold dry – hot dry (p=0.0001) season.

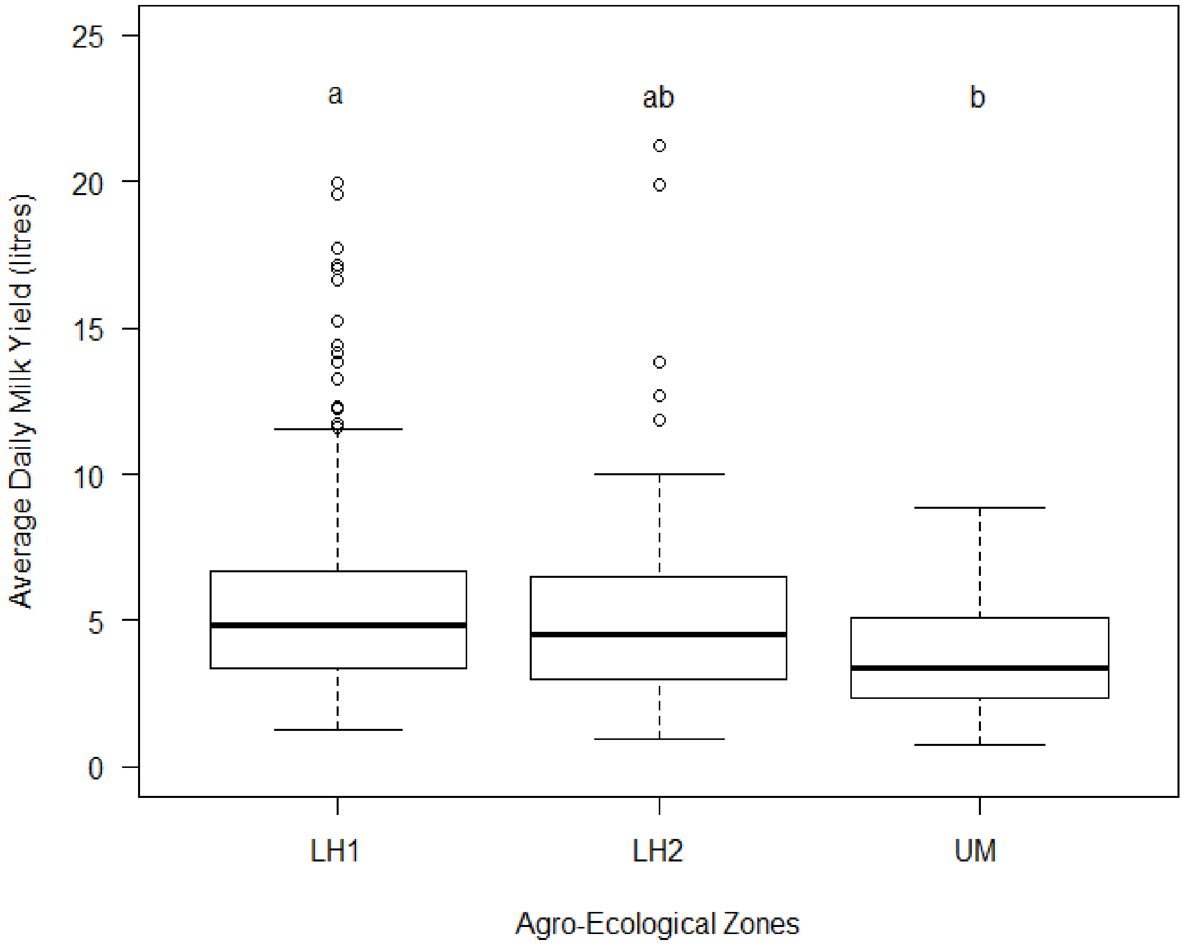

Figure 3: Box and whisker plot of mean daily milk production for Lower Highland 1 (LH1), Lower Highland 2 (LH2) and Upper Midlands (UM) with significance denoted by different letters

Weighted mean DMD of the feed basket varied between seasons and AEZs (Table 3), but within a narrow range (60.0 to 68.4%), though consistently greater than the IPCC default values (55%). The common crop residue available for animal feeding in the region was maize Stover but was seasonally available while sugarcane tops which were available all year and dominant in the UM zone only.

Table 3: Seasonal feed-baskets and their dry matter digestibility (DMD) in Lower highland 1, Lower highland 2 and Upper Midlands AEZs in Nandi County

		Short rains		Hot Dry		Long Rains		Cold Dry	
Agro-Ecological Zone	Feedstuff	Proportion (%)	% DMD	Proportion (%)	% DMD	Proportion (%)	% DMD	Proportion (%)	% DMD
Lower Highland 1	Pasture	68.2	64.9	68.2	64.9	80.7	66.7	81.0	70.1
	Napier	13.1	62.7	13.1	62.7	16.2	62.7	15.9	62.7
	Rhodes grass	2.5	53.1	2.5	53.1	3.1	53.1	3.1	53.1
	Maize Stover	16.2	59.3	16.2	59.3	na	-	na	-
	Average DMD		63.4		63.4		65.6		68.4
Lower Highland 2	Pasture	54.7	59.2	54.7	59.2	79.8	64.8	80.1	66.0
	Napier	12.1	67.9	12.1	67.9	16.3	67.9	16.1	67.9
	Rhodes grass	2.1	53.1	2.1	53.1	2.9	53.1	2.8	53.1
	Maize Stover	30.1	59.3	30.1	59.3	na	-	na	-
	Banana Pseudo stems	1.0	69.6	1.0	69.6	1.0	69.6	1.0	69.6
	Average DMD		60.3		60.3		65.1		66.0
Upper Midlands	Pasture	55.1	69.4	55.1	69.4	56.4	62.3	53.0	63.4
	Napier	8.3	61.2	8.3	61.2	11.1	61.2	11.9	61.2
	Rhodes grass	0.2	53.1	0.2	53.1	0.2	53.1	0.2	53.1
	Maize Stover	11.8	59.3	11.8	59.3	na	-	na	-
	Banana Pseudo stems	1.0	69.6	1.0	69.6	1.0	69.6	1.0	69.6
	Sugarcane tops	23.6	55.3	23.6	55.3	31.4	55.3	33.8	55.3
	Average DMD		64.2		64.2		60.0		60.4

na= not available during the season.

The average daily distance animals covered during grazing were shorter in LH1 (4.9 Km) compared to distance covered in LH2 (11 Km) or in UM (8.5 Km). Data on live-weight, live-weight change, daily milk yield, DMD and distance walked during grazing was used to calculate average MER_M, $MER_{G/L}$, MER_L, MER_T and total MER for the four seasons and three AEZs that are presented in Table 4.

Table 4: Seasonal mean for metabolizable energy requirements (MER MJ/day) for Maintenance (MER_M), Weight Gain/Loss ($MER_{G/L}$), Lactation (MER_L), Travel (MER_T) and Total MER of cows in Lower Highland 1(LH1), Lower Highland 2 (LH2) and Upper Midlands (UM) of Nandi County, Kenya

	Lower Highland 1	Lower Highland 2	Upper Midlands
	Metabolizable energy requirements for maintenance		
Short Rains	32.15 ± 0.27	29.04 ± 0.57	26.36 ± 0.57
Hot Dry	32.51 ± 0.30	29.89 ± 0.53	26.81 ± 0.64
Long Rains	31.62 ± 0.30	28.87 ± 0.56	27.72 ± 0.66
Cold Dry	31.34 ± 0.29	29.30 ± 0.58	28.45 ± 0.64
	Metabolizable energy requirement for weight gain/loss		
Short Rains	9.71 ± 0.84	8.30 ± 1.35	5.96 ± 1.23
Hot Dry	-1.12 ± 0.55	-2.99 ± 1.19	3.28 ± 0.92
Long Rains	1.61 ± 0.71	4.36 ± 1.27	4.90 ± 1.24
Cold Dry	3.76 ± 0.79	3.93 ± 1.18	6.64 ± 1.47
	Metabolizable energy requirement for lactation		
Short Rains	14.21 ± 0.75	18.19 ± 2.02	14.28 ± 1.64
Hot Dry	11.97 ± 0.75	13.25 ± 1.59	8.47 ± 1.14
Long Rains	13.21 ± 0.78	12.90 ± 1.83	10.92 ± 1.75
Cold Dry	13.73 ± 0.81	16.21 ± 1.85	12.18 ± 1.98
	Metabolizable energy requirement for traction/locomotion		
Short Rains	4.12 ± 0.05	8.14 ± 0.19	6.48 ± 0.22
Hot Dry	4.17±0.05	8.25 ± 0.19	6.62 ± 0.24
Long Rains	4.06 ± 0.05	8.13 ± 0.19	6.73 ± 0.25
Cold Dry	4.08 ± 0.05	8.34 ± 0.21	6.98 ± 0.24
	Total metabolizable energy requirement		
Short Rains	53.55 ± 1.09	53.40 ± 2.13	44.48 ± 1.77
Hot Dry	42.97 ± 0.69	43.92 ± 1.60	40.68 ± 1.49
Long Rains	45.89 ± 0.85	49.28 ± 1.96	46.14 ± 1.99
Cold Dry	48.07 ± 0.93	52.27 ± 1.81	49.24 ± 1.86

The DMI and DMP computed from the various energy requirements in Table 4are presented in Table 5, and they show that DMP increased with increase in DMI. More DMP was produced in LH1 compared to LH2 or UM. The DMP was lowest during hot dry season in all the AEZs and highest in the short rains season. There was significant difference in DMP across the AEZs ($p<0.0001$) and seasons ($p<0.0001$). Mean separation revealed that the difference was between LH1 and LH2 ($p<0.0001$) while for seasons, the differences were between the long rains vs. hot dry ($p=0.049$), cold dry vs. hot dry ($p<0.05$), short rains vs. hot dry ($p<0.000$), short rains vs. long rains ($p= 0.0001$) and short rains vs. cold dry ($p<0.0001$).

Table 5: Dry matter intake (DMI, kg) and daily methane production (DMP, g/d) of cows across Lower highland 1, Lower highland 2 and Upper Midlands zones in short rains, hot dry, long rains and cold dry seasons.

Seasons	Agro-ecological zones					
	Lower Highland 1		Lower Highland 2		Upper Midlands	
	DMI (kg)	DMP (g/d)	DMI (kg)	DMP (g/d)	DMI (kg)	DMP (g/d)
Short rains	7.6 ± 0.21	156.6 ± 4.35	8.0 ± 0.50	166.2 ± 10.41	6.3 ± 0.39	129.5 ± 8.41
Hot dry	6.1 ± 0.17	127.0 ± 3.48	6.8 ± 0.40	141.2 ± 8.34	5.4 ± 0.29	111.7 ± 5.93
Long rains	6.5 ± 0.19	133.8 ± 3.84	6.8 ± 0.43	140.3 ± 8.81	6.3 ± 0.41	129.9 ± 8.58
Cold dry	6.4 ± 0.18	132.5 ± 3.74	7.4 ± 0.42	153.2 ± 8.78	6.8 ± 0.42	138.8 ± 8.77

Using the DMD data (Table 3) MER data (Table 4), DMI and DMP data (Table 5), the EFs for all classes of cattle in each AEZ were calculated (Table 6).The estimated EF in CH_4 kg/animal/year averaged 50.6 ± 3.34 within a range of 46.5 to 54.8 across the AEZs.

Table 6: Emission Factors (CH_4 kg/animal/annum) (±standard error of means) for females (>2 years) in the three agro-ecological zones (Lower Highland 1 and 2 and Upper Midlands) of Nandi County, Kenya

Agro-ecological zones	Emission Factors (CH_4 kg/animal /year)
Lower Highland 1	50.2 ± 1.41
Lower Highland 2	54.8 ± 3.32
Upper midlands	46.5 ± 2.87
Sample average	50.6 ± 3.34

4.2 Amount of enteric methane emissions by feed dry matter digestibility levels across the agro-ecological zones and seasons

The DMD for the feed-baskets showed no difference between the three AEZ (p>0.05) and no difference between seasons (p>0.05). The DMD was used to calculate the daily methane production (DMP). There was no difference in DMP between AEZs (p>0.05), however there was a difference between seasons (p<0.05) and this only between short rains and hot dry season (p=0.035). The DMD and DMP were negatively correlated (r= -0.06) and in linear model results reported in Table 7.The DMD explained 91.78% (adjusted R-squared) of the DMP and their relationship across the AEZs and seasons were significant (p<0.01).

Table 7: Linear model output showing the influence of dry matter digestibility (DMD) across agro-ecological zones (AEZs) and seasons on daily methane production (DMP)

Coefficients	Estimate	Std. Error	t value	p-value
Intercept	314.059	40.077	7.836	0.000543***
DMD	-2.618	0.600	-4.367	0.007245**
AEZLH2	7.475	3.286	2.275	0.072031
AEZUM	-17.173	3.486	-4.927	0.004371**
SeasonHD	-20.221	3.732	-5.418	0.002900**
SeasonLR	-9.986	3.573	-2.795	0.038231*
SeasonSR	3.912	3.732	1.048	0.342561

LH2= Lower Highland 2, UM= Upper Midlands, HD= hot dry, LR= long rains, SR= short rains. ***=p<0.0001, **= p<0.01, *=p<0.05. *The LH1 zone and cold dry (CD) seasons are reference levels, assumed to be zero*

4.3 Influence of milk productivity on enteric methane emissions

Total MER and MER constituents given in Table 6 show that MER_M was the largest component of MER across all seasons and AEZs, with MER_L being second in importance. In a linear model, 13.5% (adjusted R-squared = 0.135) of DMP was influenced by daily milk yield. This could be explained by the existence of relationship between DMI and milk yield across the AEZs and seasons where 54.7% (adjusted R-squared = 0.547) of DMI was explained by milk yield and as stated earlier, DMP is calculated as a factor of DMI. Table8shows that milk yield had significant influence on DMP across the three AEZs and in the short rains season.

Table 8: Linear model output showing the influence of milk yield agro-ecological zones (AEZs) and seasons on daily methane production (DMP)

Coefficients	Estimate	Standard Error	t-value	p-value
Intercept	107.42	2.170	49.51	<0.001***
Milk yield	0.01	0.031	0.37	0.70909
AEZLH2	12.88	0.609	4.94	<0.001***
AEZUM	4.16	3.141	1.33	0.18510
SeasonHD	-8.47	2.866	-2.96	0.00319
SeasonLR	-.1.11	2.850	-0.39	0.69787
SeasonSR	24.68	2.926	8.44	<0.001***

The Lower Highland 1(LH1) zone and cold dry (CD) seasons are reference levels, assumed to be zero. LH2= Lower Highland 2, UM= Upper Midlands, HD= hot dry season, LR= long rains season, SR= short rains season

CHAPTER FIVE

DISCUSSION

Methane is a potent greenhouse gas that dairy cattle emit through enteric fermentation process. Because methane contributes to global warming, its mitigation is a target in the United Nations Framework Convention on Climate Change (UNFCCC) agenda on Climate Smart Agriculture (CSA). Including mitigation of methane emission in smallholder dairy production is relevant, because it is a rain-fed system with pervasive feed quality fluctuation, which has influence on feed energy conversion into methane. This study aimed to provide baseline data on enteric methane emissions for smallholder dairy systems, which now is insufficiently informative to the Ministry of Environment and Natural Resources for implementing Kenya's INDCs because estimates are based on non-region specific estimation factors.

The present study used animal performance measurements in a typical livestock production system to compute the EFs based on IPCC Tier II approach. There were seasonal variations in animal performances across the different agro-ecological zones (AEZs). The Live-weights recorded across the AEZs were different with LH1 having the highest live-weights records and UM- lowest live-weights. More so, there was seasonal live-weights recorded showing LW loss (negative weight change) which was associated with seasonal effect of feed restrictions due to unavailability of feed in the dry season (Hassen *et al.*, 2010). This situation tends to worsen when keeping more livestock than can be adequately fed (Njarui *et al.*, 2011). The sample farms grazed their cows on pasture fields, and animals cover long distance during grazing to access feeds, which affects animal energy expenditure. All the ambulation measurements were made during hot dry season – when the grazing distance covered are longest and therefore a possibility that the MER_T expenditure may have been overestimated for the other seasons.

The emission factor was highest in LH1 among the AEZs. The observed differences may be largely attributed to LW which is a key determinant of MER_M (CSIRO, 2007). Enteric methane is positively correlated with feed intake (Molano and Clark, 2008) and voluntary intake is positively correlated to LW (Robinson and Oddy, 2016), so the differences in calculated EFs align with observed LW differences across the AEZs. During the hot dry season, most animals lost weight and this led to negative MER for growth that then resulted to lower total MER. This was experienced as the animals mobilized endogenous tissue to meet energy requirements rather than meeting them through consumption (and fermentation) of feed. The EF averaged at

50.6kg CH_4/head/year that was 23.4% higher than the IPCC Tier I (41 CH_4/head/year) for unspecified African cattle. This could have been because the LW for dairy cows in the IPCC (2006) good practice guidelines were much lower than dairy cows of the current study and higher milk yield than those assumed by IPCC Tier I (1866.4 vs. 475litres/head/year).This is despite the reported DMD (60.0-68.4%)being higher than that used in IPCC Tier I (55%).

The variations in feed resource base and quality across the Agro-ecological zones (AEZ) are due to the climate elements that affect herbage growth such as rainfall, temperature and altitude, because these do define AEZs (Lee *et al.*, 2017). Between the AEZs in Nandi County, the defined feed-basket differed but the DMD across all zones did not differ. The observed narrow variability in DMD between AEZs agreed generally with the work of Lee *et al.*, (2017) regarding variability in nutritive value of forage grasses across bioclimatic zones. During the wet seasons, most feed is usually lush and highly digestible due to high soil moisture content while in the dry season availability of feed is a challenge and the available feed is highly lignified and less digestible. Due to this, there were seasonal variations in DMD though not significant. This may have resulted to the difference in DMP as DMD was used in calculation of MER and DMI. There was a significant DMD influence on DMP where results showed that an increase in DMD causes in a decrease in DMP. This is because feed with high digestibility can increase feed efficiency as more energy is extracted by the rumen microbes and influence patterns of volatile fatty acids where enhance propionate production and inhibit acetate production decreasing hydrogen that would be converted to methane (Knapp *et al.*, 2014). Therefore, DMD was considered as a significant point of difference in the calculation of EFs.

Daily milk yield showed similar variations as the LW. The high-yielding cows in Nandi region were found in LH1 where cows were also the heaviest and lowest yield was in UM zone where LW were the lowest. The evident difference between AEZs in milk production is in conformity with the expectation that livestock kept in a given area is a function of agro-ecological zones (AEZs) and is influenced by the feed base and thus the potential productivity (Bebe, 2003). Milk production is an energy demanding function and the more milk is produced the more energy intake is required (Manafiazar *et al.*, 2013). Studies have shown that high quality feed provide high energy for production while the low quality feed provide low energy for production (Knapp *et al.*, 2014). To sustain high milk production with low quality feed requires high feed intake causes increased total methane production since there is more feed available for fermentation and rate of passage in the rumen will be slower leading to more methane production per unit of feed (Knapp *et al.*, 2014). Due to this, the level of milk production was associated with calculated DMI that was high and ultimately affected DMP and this explains the significant relationship between milk yield and DMP. Energy needed for lactation also depends on milk composition (percentage butterfat and Solid-non-fat) (Moran, 2005). There were differences in ECM observed between the AEZs (LH1:3.1±0.04; LH2: 3.2±0.05; UM: 3.5±0.07) (p=0.004) though there was no difference (p>0.50) in the mean ECM of milk between the seasons (SR: 3.2±0.02; HD: 3.2±0.04; LR: 3.2±0.03; CD: 3.1±0.03 MJ/L). Difference in feed digestibility causes a difference in the energy available for production as a proportion of gross energy intake (GEI) leading to difference in methane per energy corrected milk (CH_4/ECM) (Knapp *et al.*, 2014) and therefore milk nutrient composition is a factor that can potentially cause difference between EFs. This trend was also associated with the difference in DMP across AEZs and seasons. The level of milk production directly influences EF as feed intake increases and leads to high DMP. Thus, we can anticipate that enteric methane emissions will tend to increase with rising levels of milk production.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

i. Use of IPCC Tier I default EFs to quantify emissions from the livestock sector will leads to high uncertainties in the national GHG inventories.

ii. Agro-ecological zones have different feed baskets with varying feed digestibility in different seasons therefore the results are region-specific and are limited to only areas with similar agro-ecological zones and in animal and feed characteristics.

iii. Milk production has an effect on dry matter intake whereby more feed intake is required to sustain an increase in milk production. This in has an effect on methane emissions because more feed is available in the rumen for fermentation as a result if the increased level of intake.

6.2. Recommendations

i. Similar research in other dairy farming agro-ecological zones with diverse livestock systems are encouraged to produce county-specific Tier II enteric emission factors as required by the UNFCC for developing countries.

ii. Feed quality need to be emphasized to the livestock farmers by practicing proper forage harvesting and exploring methods of fodder and forage conservation with the aim of providing high quality feeds in all seasons.

iii. Feed quality affects methane produced per litre of milk in the smallholder dairy system and thus more insights on better mitigation options of increasing milk production with reduced environmental effects are needed.

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APPENDICES

Appendix 1:

Scientific Poster Presentation

Ndung'u, P. W., Bebe, B. O., Ondiek, J. O., Butterbach-Bahl, K., Merbold, L., & Goopy, J. P. (2017) Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: Livestock systems of Nandi County, Kenya. Poster presented at University of Bonn, Germany. Tropentag 2017 Future Agriculture: Social-ecological transitions and bio-cultural shifts, September 20 - 22, 2017, organized by the University of Bonn and the Center for Development Research, Bonn, Germany.

Appendix 2:

Scientific journal manuscript abstract 1

Ndung'u, P. W., Bebe, B. O., Ondiek, J. O., Butterbach-Bahl, K., Merbold, L. & Goopy, J. P. (Under Review). Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of Nandi County, Kenya. Manuscript ID. AN17809, Animal Production Science (APS) Journal.

Abstract

National greenhouse gas (GHG) inventories in most developing countries, and countries in Sub-Saharan Africa in particular use default (Tier I) GHG Emissions Factors (EFs), provided by the Intergovernmental Panel on Climate Change (IPCC) to estimate enteric methane (CH_4) emissions from livestock. Because these EFs are based on data primarily from developed countries, there is a high degree of uncertainty associated with CH_4 emission estimates from African livestock systems. Accurate Tier II GHG emission reporting from developing countries becomes particularly important following the Paris Climate agreement agreed at COP21, which encourages countries to mitigate GHG emissions from agricultural sources. In light of this, the present study provides improved enteric CH_4 emission estimates for cattle in Nandi County, Western Kenya, representing a common livestock production system found in East Africa. Using the data from measurements of live weight (LW) and LW change, milk production and locomotion collected from 1143 cattle in 127 households across 36 villages over three major agro-ecological zones covering a full year, we estimated total metabolic energy requirements. From this and assessments of digestibility from seasonally available feeds, we estimated feed intake and used this to calculate daily methane production by season, and subsequently created new EFs. Mean EFs were 50.6, 45.5, 28.5, 33.2 and 29.0kg CH_4/head/yr. for females (>2yrs), males (>2yrs), heifers (1-2yrs), young males (1-2yrs) and calves (<1yrs) respectively and were lower than the IPCC Tier I estimates for unspecified African adult cattle, but higher for calves and young males. Thus, using IPCC Tier 1 EFs may overestimate current enteric CH_4 emissions in some African livestock systems.

Keywords: enteric methane, emission factor, Kenya, smallholder, Africa

Appendix 3:

Scientific journal manuscript abstract 2

Ndung'u, P. W., Bebe, B. O., Ondiek, J. O. & Goopy, J. P. (Under Review). Effect of feed digestibility and milk yield on feed intake and daily methane production Tier II estimates. (IJLP/08.01.18/0446). International Journal of Livestock Production (IJLP). (*Submitted*)

Abstract

Enteric fermentation is one of the major sources of greenhouse gas emissions (GHG) in the livestock sector. The Intergovernmental Panel on Climate Change (IPCC) has three methodologies (Tier I, II and III) for enteric methane estimation in which Tier II and III, use feed intake and digestibility. This study quantified the amount of daily methane production from dairy cows in smallholder systems, a common livestock system in Kenya’s livestock sector. The study was conducted in Nandi County, Western Kenya. Data from 127 smallholder dairy cattle farmers spread across three agro-ecological zones (AEZs). Data on live-weight, age, daily distance walked during grazing from 487 cows were as collected at a three months interval for one year and milk records kept on a daily basis. This data was used to calculate metabolizable energy requirements (MER) for maintenance, growth, production and locomotion, total MER and dry matter intake (DMI) for individual animals. The dry matter digestibility (DMD) of feed basket for each AEZ was determined by identifying, collecting and wet chemistry analysis of common feedstuff samples for dry matter, total N, organic matter (OM), neutral detergent fibre (NDF) and acid detergent fibre (ADF). Daily methane production (DMP) was calculated as a factor of DMI. The DMD of feed basket across the AEZs and seasons (ranged from 60.0 to 68.4%) was different ($p<0.001$). This difference showed that feed quality is dependent on seasons and varied across different agro-ecological zones. The DMD showed a negative correlation with DMP ($r=-0.06$) implying that an increase in DMD caused a decrease in DMP. A linear regression model showed that an increase in milk yield led to an increase in DMI (R2 = 0.547) and DMP (R2 = 0.135) mainly because an increase in DMI led to an increase in DMP.

Keywords: Dairy, digestibility, dry matter intake, enteric methane, mitigation option

Appendix 4:

ANOVA table for dry matter digestibility (DMD) across agro-ecological zones (AEZs) and seasons Nandi County

```
            Df  Sum Sq. Mean Sq. F value Pr(>F)
AEZ          2  18.91   9.453    1.130  0.383
Season       3  10.60   3.534    0.422  0.744
Residuals    6  50.19   8.366
```

Appendix 5:
ANOVA table for daily methane production (DMP) across agro-ecological zones (AEZs) and seasons in Nandi County

```
            Df  Sum Sq. Mean Sq. F value Pr (>F)
AEZ          2  1045.0   522.5   7.220   0.0253 *
Season       3   934.8   311.6   4.306   0.0609 .
Residuals    6   434.2    72.4
---
Significant codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 6:

Linear regression analysis output showing the influence of daily milk yield on daily methane production (DMP) across agro-ecological zones (AEZs) and seasons in Nandi County

```
Call:
lm(formula = DMP ~ Lactation + AEZ + SEASON, data = DMPMILK)

Residuals:
    Min      1Q  Median      3Q     Max 
-72.763 -22.870  -3.865  18.332 169.645 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept) 107.41807    2.16980  49.506  < 2e-16 ***
Lactation     0.01182    0.03167   0.373  0.70909    
AEZLH2       12.87822    2.60888   4.936  9.31e-07 ***
AEZUM         4.16480    3.14056   1.326  0.18510    
SEASONHD     -8.47256    2.86608  -2.956  0.00319 ** 
SEASONLR     -1.10657    2.84968  -0.388  0.69787    
SEASONSR     24.68402    2.92596   8.436  < 2e-16 ***
---
Significance codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 32.51 on 1013 degrees of freedom
Multiple R-squared:  0.1399,  Adjusted R-squared:  0.1348 
F-statistic: 27.46 on 6 and 1013 DF, p-value: < 2.2e-16
```

Appendix 7:

Linear regression output showing the influence of daily milk yield on dry matter intake (DMI) across agro-ecological zones (AEZs) and seasons in Nandi County

```
Call:
lm(formula = DMI ~ MY + AEZ + season, data = MYDMI2)

Residuals:
    Min      1Q  Median      3Q     Max 
-6.0815 -1.5334 -0.5082  1.1002 10.3495 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  3.41021    0.20291  16.806  < 2e-16 ***
MY           0.71230    0.02191  32.511  < 2e-16 ***
AEZLH2       1.19690    0.18682   6.407  2.28e-10 ***
AEZUM        0.91080    0.22812   3.993  7.01e-05 ***
seasonHD     0.34498    0.20741   1.663   0.0966 .  
seasonLR     0.33534    0.20461   1.639   0.1015    
seasonSR     2.10966    0.20957  10.067  < 2e-16 ***
---
Significance codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.328 on 1010 degrees of freedom
  Multiple R-squared:  0.5495, Adjusted R-squared:  0.5468 
F-statistic: 205.3 on 6 and 1010 DF, p-value: < 2.2e-16
```

Appendix 8:

Linear regression and correlation output for the relationship between daily methane production (DMP) and dry matter digestibility (DMD) across agro-ecological zones (AEZs) and seasons.

```
Call:
lm(formula = DMP ~ DMD + AEZ + Season, data = DMDP)

Residuals:
       1        2        3        4        5        6        7        8        9       10       11       12 
 4.60779 -0.85888  0.74148 -4.49039 -1.38292 -2.24959 -0.81896  4.45147 -3.22487  3.10846  0.07748  0.03893 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) 314.0586    40.0769   7.836   0.000543 ***
DMD          -2.6180     0.5995  -4.367   0.007245 **
AEZLH2        7.4750     3.2864   2.275   0.072031 .
AEZUM       -17.1730     3.4856  -4.927   0.004371 **
SeasonHD    -20.2213     3.7323  -5.418   0.002900 **
SeasonLR     -9.9857     3.5731  -2.795   0.038231 *
SeasonSR      3.9120     3.7323   1.048   0.342561

Significant codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.248 on 5 degrees of freedom
Multiple R-squared:  0.9626,   Adjusted R-squared:  0.9178
F-statistic: 21.47 on 6 and 5 DF, p-value: 0.002014

> Cor (DMDP$DMD, DMDP$DMP)
r= -0.2347536
```