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Contribution of smallholder ruminant livestock farming to enteric methane emissions in Lower Nyando, Western Kenya

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Dedication

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Summary

Contribution of smallholder ruminant livestock farming to enteric methane emissions in Lower Nyando, Western Kenya

Ruminants emit enteric methane (CH_4) which causes climate change. Data on such emissions in sub-Saharan Africa (SSA) is rare, outdated, and/or non-specific to prevailing production systems. In Kenya, the contribution of ruminants, specifically smallholder cattle systems, to CH_4 emissions is not known. Robust and valid estimates of CH_4 emissions is hampered by challenges in accurate cattle liveweight (LW) measurements, estimation of digestibility of feedstuffs, emission factors (EF) and associated uncertainty, and emission intensities (EI) under the prevailing local conditions. These challenges are addressed while deriving estimates of EFs and EIs, and estimating the contribution of enteric CH_4 emissions from smallholder cattle systems in Western Kenya to national greenhouse gas emissions.

Estimation of enteric CH_4 emissions requires accurate LW but poor access to weighing scales for farmers in SSA leads to inference of LW from heart girth (HG) measurements from LW-HG algorithms that have not been validated for cattle in SSA smallholder systems. Two datasets, one each from West (i.e., different breed/cross-breed cattle in Thiès and Diourbel regions, Senegal) and East Africa (i.e., female crossbred dairy cattle from smallholders in Rift Valley and Western Province, Kenya) were used to develop and train the LW-HG algorithms. A third dataset from East Africa (i.e., local and cross-breed cattle in Lower Nyando, Western Kenya) was used to validate the algorithms. The LW of cattle was assessed gravimetrically using electronic weigh scales and HG measured simultaneously. The algorithms developed had similar R^2 to previous studies but lower prediction errors and were applicable to diverse cattle breeds in SSA smallholder systems for general cattle management but not in situations where high level of precision is required.

Nutritional value of local feedstuffs is required in estimation of CH_4 EFs, but also to explore possible local solutions for domestic ruminant feeding in Western Kenya. Samples of local feedstuffs fed to cattle were collected from Lower Nyando, over four seasons of one year. Samples of feedstuffs were analysed for digestibility and for nutrient, energy, and mineral concentrations. Different methods for estimating digestibility of the feedstuffs gave varying results showing a dire need to develop *in vivo* based algorithms from proximate nutrient and fibre concentrations for tropical feedstuffs with or without *in vitro* degradation kinetics or from *in vivo* measured apparent total tract digestibility. Pasture herbage had superior nutritional value to most of the local feedstuffs, but the nutritional quality declined in the long dry season. Supplement feedstuffs compensated for seasonal deficiencies in pasture vegetation only in the Highlands, suggesting there is potential for use of local feedstuff to overcome nutritional deficiencies.

Cattle in Lower Nyando were characterized by identification, estimation of age, LW measurement, and body condition score across three geographical zones and four seasons of one year. Using the cattle characterization and digestibility of feedstuffs as well as feeding practices and algorithms on net energy requirements, a Tier 2 method is proposed for estimating EF for cattle under conditions of sub-optimal intake and variable feedstuff digestibility, prevalent in smallholder systems of Western Kenya. The proposed method avoids the assumption of *ad libitum* feed intake and uniform feed digestibility across large regions found in the commonly used Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology. The EFs estimated by the proposed method were up to 40% lower than the IPCC default EFs. The findings reveal the importance of not relying on the assumption of *ad libitum* intake in systems where intake may be restricted.

Increased cattle production to meet consumer demands should rely on enhanced efficiencies and not increased stocking which increase CH_4

emissions. Farm system optimization and policy interventions require accurate reporting of emissions. Emissions from cattle in Lower Nyando were estimated using IPCC Tier 2 methodology based on energy requirements of the cattle, digestibility of seasonal diets offered to cattle, and CH_4 production factor. Uncertainty analysis was done using coefficient of variation based on standard error of mean of the cattle performance and feedstuff digestibility parameters, then total uncertainties determined using IPCC methodology. The EIs were calculated as annual emissions per annual production. Results indicate that Tier 1 EFs under- or over-estimated EFs of different cattle categories. The EIs reveal a large potential for mitigation of emissions such as through intensification although the multi-functionality of cattle in local systems must be considered for accurate estimation of EIs. Uncertainties associated with IPCC Tier 2 methodology were lower than those of Tier 1. Milk production records, LW, and diet digestibility require more accurate determination because they contributed most to uncertainty.

The present study proposed some area-specific solutions and/or recommendations to common challenges hindering accurate estimation of enteric CH_4 emissions from SSA smallholder cattle systems. The results show that enteric CH_4 from cattle systems in Kenya are an important contributor to agricultural greenhouse gases (GHG) and hence, needs close attention in the on-going process of developing Nationally Appropriate Mitigation Actions in the Kenyan livestock sector.

Zusammenfassung

Beitrag von kleinbäuerlicher Nutztierhaltung in Unterer Nyando im Westen Kenias zu enterischen Methanemissionen

Die Fermentation von Kohlenhydraten im Pansen der Wiederkäuer ist eine wesentliche Quelle von Methan (CH_4), einem Treibhausgas, welches zum Klimawandel beiträgt. Schätzungen der CH_4-Emissionen durch Wiederkäuer in Sub-Sahara Afrika (SSA) sind rar, veraltet, und/oder basieren auf Daten, die nicht spezifisch für die vorherrschenden Produktionssysteme sind. Daher ist der tatsächliche Beitrag der Wiederkäuerhaltung und insbesondere der kleinbäuerlichen Rinderhaltung in Kenia zu den nationalen CH_4-Emissionen bisher nicht bekannt.

Eine robuste und valide Schätzung der enterischen CH_4-Emissionen wird aufgrund des Mangels an präzisen Daten zum Lebensgewicht (LG) der Tiere, der Verdaulichkeit von Futtermitteln und somit die Futteraufnahme von Rindern unter den vorherrschenden lokalen Bedingungen erschwert. Die vorliegende Arbeit adressiert diese Herausforderungen in der Erhebung und Verfügbarkeit dieser grundlegenden Daten und schätzt die Emissionsfaktoren (EF) und Emissionsintensitäten (EI) sowie den Beitrag der enterischen CH_4-Emissionen aus der kleinbäuerlichen Rinderhaltung im Westen Kenias zu den nationalen Treibhausgasemissionen.

Präzise Messungen des LG von Rindern der lokalen Rassen in den kleinbäuerlichen Systemen sind aufgrund des Mangels an Waagen nicht möglich, so dass das LG der Tiere in der Regel anhand ihres Brustumfanges (BU) geschätzt wird. Der Schätzung zugrunde liegende Algorithmen wurden bisher jedoch nicht für Rinder in kleinbäuerlichen Systemen in SSA validiert. Daher wurden zwei Datensätze, ein Datensatz von West-Afrika (unterschiedliche Rinderrassen/-kreuzungen in Thiès und Diourbel Regionen, Senegal) und ein Datensatz von Ost-Afrika (Milchkuh-Kreuzungsrassen in kleinbäuerlicher Tierhaltung im Rift Valley und Westen Kenias) für die Entwicklung von spezifischen LG-BU-Algorithmen

verwendet. Ein dritter Datensatz aus Ost-Afrika für lokale und gekreuzte Rinderrassen in der Unteren Nyando Region im Westen Kenias wurde verwendet, um diese spezifischen Algorithmen zu validieren. Das LG der Rinder wurde gravimetrisch mit Hilfe von elektronischen Waagen bestimmt und zeitgleich wurden die BU-Messungen vorgenommen. Die entwickelten Algorithmen haben ähnliche R^2 wie vorherige Studien, aber niedrigere Vorhersagefehler und waren für diverse Rinderrassen in kleinbäuerlichen Systemen in SSA für allgemeines Viehmanagement anwendbar. Allerdings sind diese Algorithmen in Situationen, in denen ein hoher Grad an Präzision gefordert wird, weniger geeignet.

Daten zum Futterwert der lokal genutzten Futtermitteln sind Grundlage der Schätzung der Futteraufnahme und somit der EF und EI. Zudem sind sie besonders hilfreich, um mögliche Empfehlungen für die Fütterung von Rindern im Westen Kenias zu entwickeln. Proben von lokalen Futtermitteln, die an Rindern in der Unteren Nyando Region gefüttert werden, wurden über den Verlauf eines Jahres gesammelt. Diese Proben wurden auf die Gehalte von Rohnährstoffen, Energie und Mineralstoffen analysiert und ihre Verdaulichkeit anhand der Rohnährstoffgehalte und der Gasproduktion während der *in vitro* Inkubation geschätzt. Verschiedene Methoden zur Schätzung der Verdaulichkeit der Futtermitteln ergaben deutlich unterschiedliche Ergebnisse. Die Entwicklung spezifischer Algorithmen zur Schätzung der Verdaulichkeit anhand der Gehalte von Rohnährstoff- und Faserfraktionen und dem in vitro Abbau basierend auf *in vivo* Daten zur scheinbaren Gesamttraktverdaulichkeit sind daher notwendig. Im Vergleich zu den meisten lokalen Futtermitteln ist der Futterwert der Weidevegetation höher. Allerdings sinken Rohproteingehalte und Verdaulichkeit in der langen Trockenzeit. Die zur Zufütterung verfügbaren Futtermittel können nur zum Teil die saisonalen Defizite im Futterwert der Weidevegetation kompensieren.

Basierend auf Daten zur Herdenstruktur, LG der Rinder und zum Futterwert der Weidevegetation und im Stall gefütterten Futtermitteln sowie deren Anteil in der Ration der Tiere in der Unteren Nyando Region wurden die EF von Rindern anhand der IPCC Tier 2-Methode geschätzt. Dabei wurden eine sub-optimale Futteraufnahme der Tiere sowie räumliche und saisonale Unterschiede in der Verdaulichkeit der Futtermittel berücksichtigt. Solche Bedingungen sind vorherrschend in den kleinbäuerlichen Systemen im Westen Kenias. Die daraus resultierenden EF sind bis zu 40% niedriger als die EF der IPCC Tier 1 Methode, die standardgemäß in Ländern Afrikas angewandt wird. Die Ergebnisse unterstreichen zudem die Notwendigkeit der Berücksichtigung einer limitierten Futteraufnahme von Rindern in diesen Haltungssystemen in der Schätzung der EF.

Die Analyse der Unsicherheit in der Schätzung der EF unter Einsatz von Variationskoeffizienten, basierend auf dem Standardfehler des Mittelwertes der Leistungsfähigkeit der Rinder und den Verdaulichkeitsparametern der Futtermittel zeigte, dass insbesondere eine präzise Erhebung des LG, der Milchleistung der Verdaulichkeit notwendig ist, da diese Faktoren am meisten zur Unsicherheit beigetragen haben.

Abschließende Bewertungen zeigen, dass enterische CH_4-Emissionen von Rindersystemen ein großer Beitrag zu den Treibhausgasen aus der Landwirtschaft in Kenia leistet. Deshalb sollte im fortlaufenden Prozess der Entwicklung von national angemessenen Minderungsmaßnahmen in Kenia ein besonderes Augenmerk auf die Optimierung der kleinbäuerlichen Rinderhaltung gelegt werden. Jedoch sollte die Multifunktionalität der Tiere in diesen Systemen in Zukunft in der Bewertung der EF und EI berücksichtigt werden. Es erscheint großes Potenzial für die Minderung der Emissionen zum Beispiel durch Intensivierung der Tierhaltung und die Verbesserung der Fütterung und Leistung der Tiere. Es werden in der vorliegenden Arbeit mögliche, lokal angepasste Lösungen, um die Fütterung und Produktivität von Rindern aus kleinbäuerlichen Systemen zu

verbessern und die Emission von enterischen CH_4 zu reduzieren, aufgezeigt.

1. General introduction

1.1 Population trends and demand for livestock products

The world population of over 6 billion people (FAO, 2015) depends on agriculture for food. The most rapid global human population growth in history has occurred in the past fifty years with a continued increase being predicted for the future albeit at a slower rate (United Nations, 2001). Additionally, an increasing literacy rate (UNESCO, 2016), higher incomes (Lakner and Milanovic, 2015), rural-urban migration (United Nations, 2014), and technological advances will result in changing dietary preferences (Popkin, 2009) with higher per-capita food consumption in general and especially of animal-derived food products. Together, the increase in population, urbanization, literacy rates, and changing diets will put pressure on natural resources and will require innovative ways of agricultural production in general, and livestock farming in particular, to meet the future food demands in a sustainable way.

The challenges of using natural resources more sustainably and increasing food production will be, and in some cases are already being, felt in sub-Saharan Africa (SSA) where the human population is projected to more than double between 2010 - 2050 (Ezeh et al., 2012). Along the same line, the literacy level in SSA has increased from 57% in 1999 to 64% in 2015 (UNESCO, 2016), average per-capita incomes have risen by 2.7% per annum from 1993 to 2008 (Lakner and Milanovic, 2015), and the average rate of change in the proportion of urban compared to rural population was +1.4% per annum from 2010 to 2015 and thus highest in the world (United Nations, 2014). It is projected that the dietary consumption of meat and dairy products by people in SSA will rise from 9.5 kcal to 14 kcal/person/day for meat and from 28.3 kcal to 34 kcal/person/day for dairy products between 2001 and 2030 (United Nations, 2006). Specifically in Kenya, average human population growth is even higher at about 3% per annum. The gross national income per capita has increased by 48.5% between

2011 and 2015 and the urban population as a percentage of total human population in Kenya has increased from 7.9% in 1990 to 10.7% in 2013 (KNBS, 2016a).

In Kenya, agriculture is the second largest industry after the service sector. Agriculture provides about 25% of the gross domestic product (Omiti and Okuthe, 2008). Most Kenyans live in rural areas (about 80% of the population) and depend on agriculture for their livelihoods. Like most agriculture in sub-Saharan Africa, Kenyan smallholders contribute over 75% of total agricultural production (UNDP, 1999). For example, 50% of tea, 65% of coffee, 70% of maize, 80% of milk, and 70% beef and related products in Kenya are produced by small-scale farmers (Government of Kenya, 2010). The livestock sector contributes about 17% to agricultural gross domestic product and 7% to the overall gross domestic product (Government of Kenya, 2010). Thus, livestock supports the livelihoods of farmers in Kenya as it is the case throughout the developing world (McDermott et al., 1999; FAO, 2005; Perry & Sones, 2007).

However, livestock production and productivity, especially in SSA, have not been able to rise to the meet the demand for food, partly due to the current trend for livestock to serve other intangible, non-market roles such as insurance, financing, draught power, and status symbol (Tarawali et al., 2011). These intangible roles, for example in Western Kenya, have been shown to comprise 14 to 18% of livestock's perceived value (Ouma, 2003). In Kenya, the livestock sector's growth rate has been 1.5 % per annum from 2011 to 2014, even though its contribution to the gross domestic product has declined from 5.4 % in 2011 to 5.0 % in 2015 (KNBS, 2016b). It is not clear whether this increase is as a result of better efficiencies in the sector or whether it is as a result of increased livestock numbers. It is important that increased production should not be through increasing livestock populations but through increased productivity which addresses the

demand for food and minimizes methane (CH_4) emissions which contribute towards climate change.

1.2 Climate change and livestock production

One of the major challenges facing agriculture is the predicted and already ongoing changes in global climate, affecting agriculture around the globe. In particular, smallholder livestock systems in countries of SSA, for instance Kenya, have reported a decline in beef production due to climate variability (Government of Kenya, 2010) while shortage of forage, more incidences of disease, and breakdown of market structures are also anticipated(NEMA, 2005).

However, agriculture also contributes to climate change by emitting greenhouse gases (GHG), through natural biogeochemical cycling of carbon and nitrogen (Falkowski et al., 2000) and through anthropogenic emissions (Etheridge et al., 1998). Worldwide, the agricultural sector contributes about 10 - 12% of the total global anthropogenic non carbon dioxide (CO_2) GHG emissions measured as CO_2 equivalents (CO_2eq.)[1] (Smith et al., 2014). The livestock sector is responsible for 8 -10.8% of total global GHG (O'Mara, 2011) and up to 18% of total global GHG on the basis of lifecycle assessment (Steinfeld et al., 2006). The main sources of GHG from livestock are enteric fermentation in the digestive tract of animals releasing CH_4 (Popova et al., 2013), manure management resulting in the release of CH_4 and nitrous oxide (N_2O) (Gupta et al., 2007), and land use/land use change mainly for the production of feed that results in considerable CO_2 emissions (Paustian et al., 2000).

Enteric CH_4 represents about 40% of total agricultural GHG emissions with an annual increase of 0.95% between the years 1961 - 2010 (Tubiello et al., 2013). Ruminants are the main contributors of CH_4, as a by-product of their enteric fermentation (Thorpe, 2009), although non-ruminants also produce it

[1] Global warming potentials: CO_2 = 1, CH_4 = 25, and N_2O = 298 times that of CO_2 over a 100-year time horizon (IPCC, 2007)

to a lesser extent, mainly during fermentation in their large intestines (Tsukahara & Ushida, 2000;Wang & Huang, 2005). Emission of CH_4 through enteric fermentation poses a problem, since apart from being a GHG influencing climate change it also represents a loss of 2 - 12% of gross dietary energy (Johnson and Johnson, 1995) which translates to losses in production and income to farmers. Reducing CH_4 emissions from ruminants may thus also enhance feed energy conversion rates and animal productivity (Zhou et al., 2007a)

Contribution of livestock to GHG emissions in temperate countries is documented (Lesschen et al., 2011) and regularly monitored (Freibauer, 2003). For instance, in the European Union – 27 (EU-27), it is known that livestock farming produces about 10% of total anthropogenic GHG emissions (not considering land use change to grow feed in Latin America) with enteric fermentation accounting for 36% of the livestock GHG emissions (Lesschen et al., 2011). It is estimated that the developing countries produce roughly about 75% of the total CH_4 emissions worldwide and that annual increases in enteric CH_4 emissions from livestock are highest in Africa (Tubiello et al., 2013). Nevertheless, similar documentation and monitoring of GHG emissions is rare in SSA (Tubiello et al., 2013). In the case of Kenya, the contribution of agriculture, livestock farming and specifically cattle systems to agricultural GHG emissions in the country is indeed neither known nor monitored.

Cattle emit more CH_4 per head than small ruminants (Dong et al., 2006). In Kenya, cattle have been shown to contribute more to the country's economy than other animal species when considering direct benefits of livestock (i.e., milk and meat) (Behnke and Muthami, 2011). Additionally, the residents of Western Kenya traditionally place a high value on cattle ownership for both, its direct and non-market benefits leading to almost every household owning cattle (Weiler et al., 2014). It is for these reasons that the present study focusses on cattle systems.

1.3 Challenges in reporting climate change from smallholder cattle systems

Several challenges hamper the generation of robust and valid estimates of CH_4 emissions from smallholder cattle systems in Kenya. Estimation of enteric CH_4 emissions is done by multiplying emission factor (EF) (i.e., quantity of a pollutant typically emitted by cattle in a category (EPA, 2005)) by the number of cattle in the category. These EFs are derived from cattle characteristics (i.e., liveweight (LW), LW gain, pregnancy status, milk production and quality, and level of activity/work) and feed digestibility. In practice this means that a population of cattle in a particular area must be monitored to estimate the physiological, production, and reproduction state of all animals and then the number of cattle in each category is counted. The LW and physiological state are then used to give a measure of the net energy expenditure of each animal using empirical formulae from Intergovernmental Panel on Climate Change (IPCC). By applying appropriate efficiency factors and diet digestibility, the net energy expenditures are then used to infer the cattle gross energy intake. Knowledge of the amount of CH_4 generated per unit of gross energy, gives the EF, for a particular category of animal. Since developing countries do not have their own EFs, they use default IPCC's EF. Three different types of EFs exist that differ in the level of sophistication, namely Tier 1, Tier 2, and Tier 3. The Tier 1 EF represents default values for each cattle category that are simply multiplied by the size of the respective cattle populations and thus do not account for possible differences in CH_4 emissions between cattle of different breeds, age, and physiological states or for differences in intake levels and diet compositions. Tier 2 EF uses cattle and feed characterization to come up with regional EFs, while the Tier 3 approach uses region-specific EFs which are commonly built on years of research in that region.

Many countries especially in the developing world are generating little or no data (Du Toit et al., 2013b). Data on SSA emissions are scarce and when they exist they are based on global default Tier 1 EFs (IPCC, 2006) which are not specific to the prevalent production systems in different regions. For example, Kenya carried out only one GHG inventory, in 2005, that was based on animal population data from 1994 (over 10 years old) and used Tier 1 EFs (NEMA, 2005). The inventory showed the country was a net sink for CO_2 due to regeneration of forests. However, agriculture emits over 70% of the total CH_4 emissions (in Gigagrammes, Gg, CH_4), enteric fermentation being the largest source. Total N_2O emission was low (negligible) due to limited use of fertilizers. This information is outdated and likely does not reflect the current state due to possible changes in herd compositions and sizes, feed quality, and breed composition.

In Kenya, there are data on livestock numbers from 2009 census (KNBS, 2010). However, these data are not aggregated according to animal type, average annual population, productivity, feeding systems, or manure management as they influence GHG emissions. These data can therefore only be used to again generate very rough GHG emissions estimates using Tier 1 default EFs. A major reason for this is the challenge in collection of primary data related to, for instance, infrastructure (e.g., access to farms, appropriate research facilities, and equipped labs; quality assurance of laboratory processes), methodological approaches (e.g., region-specific methods and algorithms to estimate LW, feed digestibility, and gross energy of the feed converted to CH_4), and consensus-building and/or acceptance to participate in research (e.g., due to the large number of independent smallholders). The more sophisticated Tier 2 EFs would take into account the local smallholder farming systems and the local climatic scenario.

However, the Tier 2 EF approach relies on accurate cattle and feed characterization. To calculate energy requirements of the cattle for maintenance, growth, activity, production, and reproduction, LW and LW

gain of the animals are required. Currently, cattle LW in Kenya are commonly estimated using weight bands that have not been validated for the common breeds in the country. Feed characterization requires information on the available feed resources, seasonal diet compositions, quantity and nutritional value of feeds offered to the cattle of different classes. There is no documented information on the local feed resource base. The digestibility of the feeds on offer, which is of key importance to estimation of Tier 2 EF, is not known. Cattle numbers and data needed for estimation of EF are unavailable. Indeed, recording of milk production; livestock sales, deaths, gifts, loans; and livestock activity (such as, number of hours worked or grazed as well as distance covered by livestock in search of food and water) is hampered by high adult illiteracy among the rural poor in some areas, labour pressures, and lack of motivation to know actual output due to weak market structures. The IPCC Tier 2 methodology as a model has its weaknesses, chief being the assumption of *ad libitum* feed intake without considering the biological capacity of the animal to actually consume the predicted quantity, and whether the animal indeed has unrestricted access to the predicted quantity. Furthermore, uncertainties associated with the estimated EF should be stated in order to infer the degree of confidence with which the information can be used for decision-making. Emission intensities of the cattle systems are dependent on the efficiencies of the systems in emissions per unit of product and are useful when considering emission mitigation options. Finally, the contribution of the cattle systems in Western Kenya to CH_4 emissions is a first step towards understanding the carbon footprint of these systems and especially towards finding out whether their emissions actually matter in the overall scheme of GHG emissions.

Against this background, this thesis aims at addressing some of these challenges and deriving quantitative estimates of EF and associated

uncertainties, emission intensities, and the contribution of smallholder cattle systems in Western Kenya to enteric CH_4 emissions.

1.4 Objectives, hypotheses and expected outcomes

The purpose of this study is to quantify the contribution of smallholder cattle systems in Lower Nyando, Western Kenya to enteric CH_4 emissions by using Tier 2 methodology.

The specific objectives are:

i) To determine the strongest relationship possible between heart girth (HG) and LW considering phenotypically diverse populations, assess whether such an algorithm may be used to predict LW, and determine the applications for which HG measurements may validly be used as an alternative to weighing scales for LW determination.

ii) To determine the nutritive quality of the herbaceous pasture vegetation and supplement feedstuffs commonly offered to grazing domestic ruminants in tropical Western Kenya; and to quantify seasonal and site variations in the nutrient, energy, and mineral concentrations of the herbaceous pasture vegetation as well as its digestibility.

iii) To estimate enteric CH_4 emissions factors with associated uncertainties and emission intensities of cattle in smallholder systems in Western Kenya, including under suboptimal intake conditions, compare Tier 2 EFs estimated with default IPCC Tier 1 values, and to infer the likely contribution of smallholder cattle systems in the study area to enteric CH_4 emissions.

The hypotheses of the study were:

i) By using prediction errors and regression coefficients, an algorithm of the strongest relationship possible between HG and LW for phenotypically heterogeneous and homogenous populations can be derived and used to predict LW, as an alternative to weighing scales for LW determination.

ii) The nutritive quality and mineral concentrations of the herbaceous pasture vegetation grazed by animals in the tropical areas of Western Kenya are highly variable between seasons and zones; however, the locally available supplement feedstuffs are suitable to compensate for seasonal nutrient, energy, and mineral deficiencies in the pasture vegetation.

iii) Use of Tier 2 methodology yields appropriate and more accurate enteric CH_4 EF of low uncertainties and more accurate emission intensities of cattle in smallholder systems in Western Kenya compared to default IPCC Tier 1 EF, which can then be used to infer the likely contribution of the systems in the study area to overall enteric CH_4 emissions.

The expected outcomes of the study were:

- Algorithms of the strongest relationship between HG and LW that can be used as an alternative to weighing scales for LW determination for the shorthorn East African (SEA) zebu and other smallholder cattle populations in SSA.
- Digestibility of local feedstuffs and baseline information on the nutritive quality and mineral concentrations of the herbaceous pasture vegetation grazed by cattle in Western Kenya, variability in quality and quantity with seasons and zones, and identification of locally available supplement feedstuffs suitable for compensating for seasonal nutrient, energy, and mineral deficiencies in the pasture vegetation.
- Refined, appropriate, and more accurate Tier 2 EF than default IPCC Tier 1 EF for estimating the enteric CH_4 emissions, including under conditions of sub-optimal intake, and inferring the likely contribution of the smallholder cattle systems of Western Kenya to enteric CH_4 emissions.

1.5 Study Area

The study was conducted in a 100 km^2 area (0°13’30’’S - 0°24’0’’S, 34°54’0’’E – 35°4’30’’E, Fig. 1) located in the Lower Nyando Basin, Western Kenya. The basin covers 3517 km^2 with a population of about 750,000

mainly in Kisumu and Kericho counties. More than 80% of the population depend on agriculture for their livelihood and about 20 – 60% of population live on less than 2 dollars a day (Sijmons et al., 2013). The population is mainly Luo and Kalenjin tribes, with a high human population density and consequently small farms (< 1 ha).

The study site was selected to represent three distinct geographies that are common in the area, which we refer to as ‘zones’: the Lowlands (with a 0 - 12% gradient on slopes), the Mid-slopes (12 - 47% gradient, steeper at the escarpment), and the Highlands (> 47% gradient at escarpments and 0 - 5% at the top) with altitude from 1200 m to 1750 m above sea level (Verchot et al., 2008; Rufino et al., 2016). Soils of the Lowlands are sandy-clays to silty-loamy with visible effects of soil erosion and land degradation; the Mid-slopes are clay and silty loams, while the Highlands are silty to loamy. The climate is humid to sub-humid. The annual rainfall is about 1200 - 1725 mm with a bi-modal pattern (i.e., the long and the short rains), allowing for two cropping seasons a year. There are four marked seasons classified as long dry season (January - March), long wet season (April - June), short dry season (July - September), and the short wet season (October - December). The first two climatic seasons fall in the long rainy cropping season, whereas the last two climatic seasons fall in the short rainy cropping season (Zhou et al., 2007b).

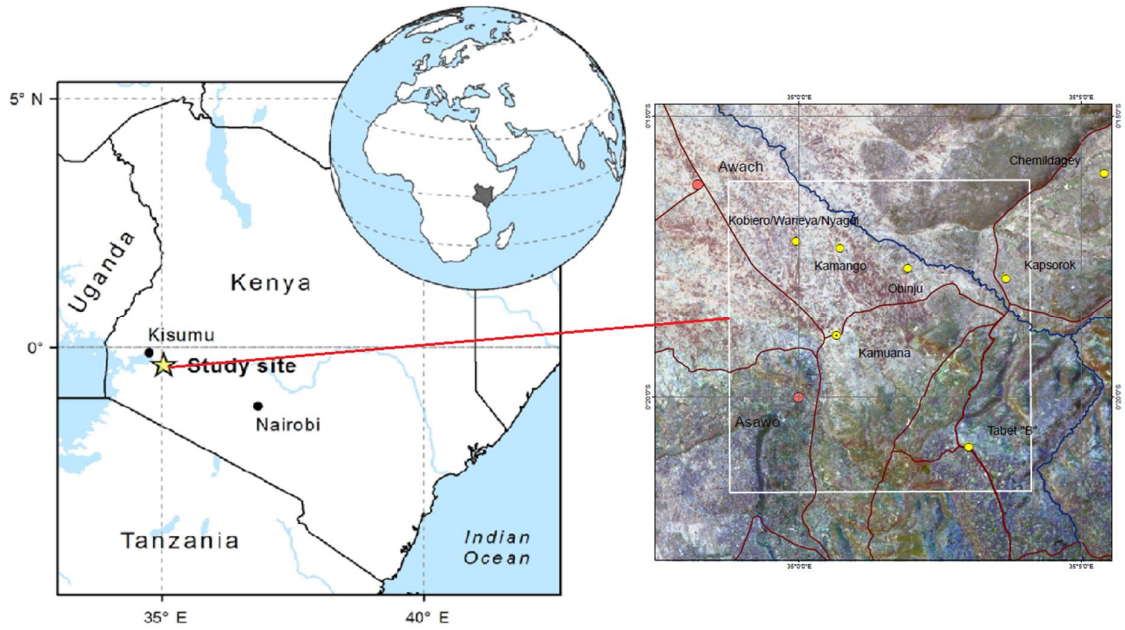

Fig. 1. Study area - Lower Nyando, Western Kenya

Source: Pelster et al. (2017) and Sijmons et al. (2013). The left map shows the satellite image of the study area while the yellow marks indicate different villages within the area which were used in the initial baseline survey on which the present study was based.

Mixed crop-livestock systems are predominant with about 40% of the land cover being rangelands mainly used for grazing livestock (Verchot et al., 2008). The main crops are maize (*Zea mays*), sorghum (*Sorghum bicolor*) in the long rains and beans (*Phaseolus vulgaris*) in the short rains. Cash crops grown are sugarcane and tea. The livestock populations consist of cattle, sheep, goats, chicken, and donkeys. The dominant species in the Highlands are cattle, in the Mid-slopes cattle and goats, and in the Lowlands a mixture of the three groups of ruminant species: cattle, sheep, and goats (Ojango et al., 2016). Important cattle breeds are SEA zebus (Kavirondo zebus in the Lowlands, Nandi zebus in the Mid-slopes, and zebu x *Bos taurus* in the more commercial dairy-oriented Highlands).

Twenty villages (i.e., eight in the Lowlands, six each in the Mid-slopes, and Highlands) were selected based on results of the IMPACTLite survey that had been conducted earlier in the area using 200 households (Silvestri et

al., 2014; Rufino et al., 2013). A detailed description of the area is available in Sijmons et al. (2013) while details on the sampling frame and region of study are available in Förch et al. (2014).

The area was part of the Western Kenya Integrated Ecosystem Management Project (WKIEMP) and has been identified by Climate Change Agriculture and Food Security (CCAFS) as one of the “hot spots” (regions and system of high mitigation potential and high vulnerability for food insecurity) (Ericksen et al., 2011).

1.6 Thesis structure

Chapter 2 provides a background on the livestock production system of the study area identifying a feed resources base with its constraints and opportunities. Chapter 3 highlights the shortcoming of existing LW determination algorithms in estimating LW of SEA zebu cattle found in the study region. This chapter focus is important because LW is one of the major determinants of the energy requirement of an animal which, in turn, is a key factor in determining the level of enteric emissions. Chapter 4 describes the feed resource base available in the study area, the nutritive value of these feeds and the possibility of having local feedstuffs to supplement pasture. This is important because it is the quantity and quality of feedstuffs on offer which ultimately influences enteric emissions. Chapter 5 describes a new approach for the determination of EFs that does not assume *ad libitum* feed intake as opposed to other methods that assume cattle have unlimited access to adequate feeds. Chapter 6 estimates EFs and associated uncertainties in IPCC Tier 2 methodology, as well as emission intensities based on IPCC Tier 2 EF and cattle production. Chapter 7 synthesizes the main findings, estimates the contribution of cattle systems to GHG emissions in Kenya, and highlights the limitations of this study while laying out the way forward for future research.

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2. Characterisation of livestock farming of the study region, Lower Nyando, Western Kenya

2.1 Introduction

Most agriculture in sub-Saharan Africa is smallholder (2 ha or less) representing 80% of all production and contribute up to 90% of the gross domestic product in some countries (Wiggins, 2009). In Kenya, smallholder systems contribute over 75% of total agricultural production in the country (Government of Kenya, 2010). However smallholder farming systems are rarely characterized. This is important because there is heterogeneity between farms mainly driven by different management (Mtambanengwe and Mapfumo, 2006; Zingore et al., 2007) apart from edaphic variation across the landscapes.

Livestock plays important roles in the domestic economy providing food, transport and support in agricultural practices through draught ploughing and provision of manure for crop performance (Thornton and Herrero, 2010). Livestock data from 2009 census in Kenya broadly gives livestock numbers (KNBS, 2010). However, the data does not characterize livestock sector in terms of husbandry and general management. Characterization is a prerequisite to understanding the livestock systems which is the basis in any engagement between farmers in these conditions and external agents.

2.2 Materials and methods

A survey was done using Feed Assessment Tool (FEAST) software developed by International Livestock Research Institute (ILRI), Nairobi (www.ilri.org/feast). This tool is designed to give rapid feedback on feed availability and highlight the areas of possible intervention to improve feed resource base based on farmer perceptions. It consists of two parts; participatory rural appraisal (PRA) done with groups of 15 - 20 farmers

each; and key informant interviews done with nine farmers, three from each wealth category (above average, average, and below average).

Twenty villages (eight in the Lowlands and six each in the Mid-slopes and the Highlands) in the study area were targeted based on a survey done earlier in the area i.e., IMPACTlite (Rufino et al., 2013; Silvestri et al., 2014; Förch et al., 2014). Village elders and local development partners picked 20 farmers per elevation zone (average 3 farmers per village) both, male and female to participate in group discussions using PRA. Out of these 20 farmers, nine from each elevation zone, i.e., three from each wealth category based on landholding were chosen for individual key informant interviews.

The PRA was done in each of the geographical zones: the Lowlands at Kasaye Onyuongo chief's camp (0°32'11''S, 35°00'47''E); the Mid-slopes at Kapsorok Dispensary (0°29'44''S, 35°05'43''E) and the Highlands at Sumoiyot Dispensary (0°34'75''S, 35°04'78''E) in October and November of 2013.

The PRA data was analysed and qualitatively reported. The key informants interview data was analysed using the FEAST tool excel template (www.ilri.org/feast).

2.3 Results

2.3.1. Livelihood and landholding

Farmers practice mixed crop-livestock farming as well as other means of earning a living. Livestock keeping is the main activity (Fig. 1). About 70% of the farmers in the Lowlands have less than 0.4 hectares of land (Table 1), while a typical household size is six people. One piece of land is used for more than one crop per year. However, the degraded pieces of land that are not suitable for crops are used as grazing land. Lack of inputs and failed seasons are also a discouragement leading to fallowing. The average

household size in the Mid-slopes is five people. About 50% of the farmers own more than 0.8 hectares of land while the typical farm size is 2 to 6 hectares. Land for cultivation is adequate and there are even pieces set aside just for grazing. Farmers reported that they practiced fallowing and intercropping as a way to manage soil fertility but not primarily due to shortage of land.

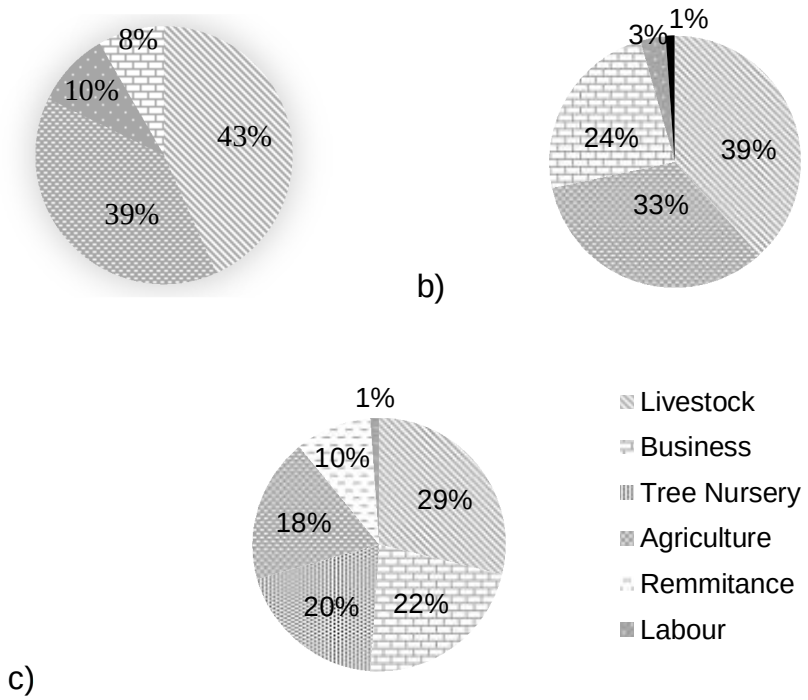


Fig. 1. Livelihood activities as a percentage of total household income in the a) Lowlands, b) Mid-slopes, and c) Highlands in October 2013 in Lower Nyando, Western Kenya.

About half the farmers in the Highlands are medium-sized farmers owning 0.3 to 0.5 hectares of land while the average household size is 5 persons. Land is in short supply and is always in use every season. Intercropping is practiced and usually a small section within the homestead is set aside for grazing and cut-and-carry feeding of livestock.

Table 1. Landholding per household by zone and farmer category in Lower Nyando, Western Kenya in October 2013 (n = 60).

Slope zone	Farmer category	Landless	Small farmer	Medium farmer	Large farmer
Lowlands	Land area (hectares)	0.0	≤ 0.3	0.4 - 0.8	> 0.8
	% of households in category	1.0	70.0	20.0	9.0
Mid-slopes	Land area (hectares)	0.0	< 0.3	0.3 - 0.8	> 0.8
	% of household in category	0.0	10.0	40.0	50.0
Highlands	Land area (hectares)	0.0	< 0.3	0.3 - 0.5	> 0.5
	% of household in category	0.0	20.0	50.0	30.0

2.3.2. Annual rainfall pattern and crop farming

The annual rainfall pattern, which determines the cropping seasons, in the block is bimodal. Long rains occur from March to May and short rains from September to November leading to two cropping seasons; February to August, and September to December. The cropping season during the long rains is shorter in the Lowlands and Mid-slopes (February to June) due to higher average daily temperatures than the Highlands (February to August). The agriculture in the block is mainly rain-fed. In the Lowlands, about 28% of the farmers who live near the rivers practice irrigation, usually by manual carrying of water from the river with buckets to water mainly horticultural crops grown near the rivers. This irrigation is however hindered by lack of inputs, distance from the river and hilly terrain. In the Mid-slopes, only about 3% of the households practice irrigation while in the Highlands, about 8% irrigate their farms.

The dominant crops in the block are maize (*Zea mays*), sorghum (*Sorghum bicolor*), common beans (*Phaseolus vulgaris*), sugarcane (*Saccharum officinarum*), finger millet (*Eleusine coracana*), cow peas (*Vigna*

ungiuculata), green grams (*V. radiata*) and assorted vegetables for household use.

2.3.3 Labour

Hired labour is available throughout the year. It is mostly required in the Lowlands during ploughing, planting and weeding; typically between February and April. Labourers work from 7 am to 1 pm at 1.5 Euros per work day (at 1 Euro being approximately 100 Kenya shillings, 2013/2014). The payment is either on a time or area basis (i.e., 25 by 6 stride lengths which is approximately 100 square metres). Ploughing is mainly done by traction bulls with the price depending on the condition of the farm, but generally costs 15 Euros per acre. In the Mid-slopes, labour is required most during ploughing (February) and harvesting (August). Labourers work for 5 hours (half-day at 1.0 Euro) and 7 hours (full-day at 1.5 Euros). Using traction bulls, the fee is 30 Euros per acre, while weeding sugarcane is 0.01 Euros per square meter. Other means of payment include chicken, milk, and maize. In the Highlands, labour is required most from March to May (ploughing, planting and weeding) and in August (harvesting). People work from 8 am to 1 pm and are paid 2.5 Euros per work day or equivalent litres of milk (milk costs 0.6 Euros per litre, 2013).

About 68% of young people in the Lowlands leave the farm for work and/or education. They consider farming to be a less profitable occupation to be engaged in in old age. In the Mid-slopes, only 15% of the young people leave the farm for work and education. This is because most people, who own land, are aware of the benefits of agriculture and claim the cost of living in town is high. The same is the case in the Highlands where 17% leave for education and only 2% for work. Usually those in the Highlands who get employment outside the farms hire labour to work on their farms so they do not completely move out.

2.3.4 Livestock holding

The highest number (heads) of livestock kept per head is free-foraging village chicken followed by dairy cattle and fattening cattle (Table 2). Commercial chicken and donkeys were very few. Improved cattle breeds (i.e., crosses of shorthorn East African zebus with *Bos taurus*) dominate in the Highlands except in Tabet and Kaptembwa villages of the Highlands which border the Mid-slopes and stock local breeds like the other two zones. Goats are mainly stocked in the Mid-slopes, Tabet, and Kaptembwa villages. Sheep are not popular in the Highlands because they compete for the pasture herbage with dairy cows which are perceived to be more profitable. Donkeys are popular in the Mid-slopes due to long distances that need to be covered between farms, rivers, and markets. However, when livestock holding is considered after conversion of liveweight (LW) to tropical livestock units (1 TLU = 250 kg LW), the most important livestock category is the dairy cattle (Fig. 2 a, b, and c).

Livestock is kept mainly for milk, manure, traction, and for financial security. Donkeys are used for carrying loads. However, improved dairy cows have not been taken up in the Lowlands due to a perception that they are expensive to purchase and maintain, and that the area is dry and hence may not yield sufficient feedstuffs. In the Lowlands, large animals are kept in open kraals made of wooden enclosures with no roofs; small ruminants and calves are kept in houses built separately for them, kitchens that are detached from the main house, or constructed indoors (or at a corner in case of one-roomed huts) with people while chickens are housed with people. In the Mid-slopes, cattle are tethered in the open; small ruminants are either kept in small structures or tethered under raised barns; donkeys are kept outside the homestead by the roadside (they act as watch-animals alerting members of households in case of a stranger approaching) while poultry are kept indoors. In the Highlands, chicken are kept indoors while the large animals are tethered outside in the open. Calves and small

ruminants are tethered under raised barns or near some structure for shelter.

Table 2. Households owning animals per category/species (as a percentage of total households) and number of animals per category/species (heads) per household in Lower Nyando, Western Kenya in October 2013 (n = 60).

Livestock species	Lowlands		Mid-slopes		Highlands	
	HHs owning (% of total)	Number of animals (heads/ HH)	HHs owning (% of total)	Number of animals (heads/ HH)	HHs owning (% of total)	Number of animals (heads/ HH)
Local dairy cows	67	2	80	5	80*	4-5
Improved dairy cows	7	1	20	4	80**	1-2
Draught cattle	25	4	80	2	8	1-2
Fattening cattle	29	4	100	3	65	2
Sheep	47	10	70	5	5	2-3
Goats	27	5	75	7	54* 5**	10 3 - 4
Village chicken	89	10	100	>10	90	6 - 7
Donkeys	< 1	1	99	1	33	1

HH = households; *Tabet and Kaptembwa villages (found on the boundary of the Highlands and the Mid-slopes and as such are not typical of both zones); **The rest of the villages in the Highlands

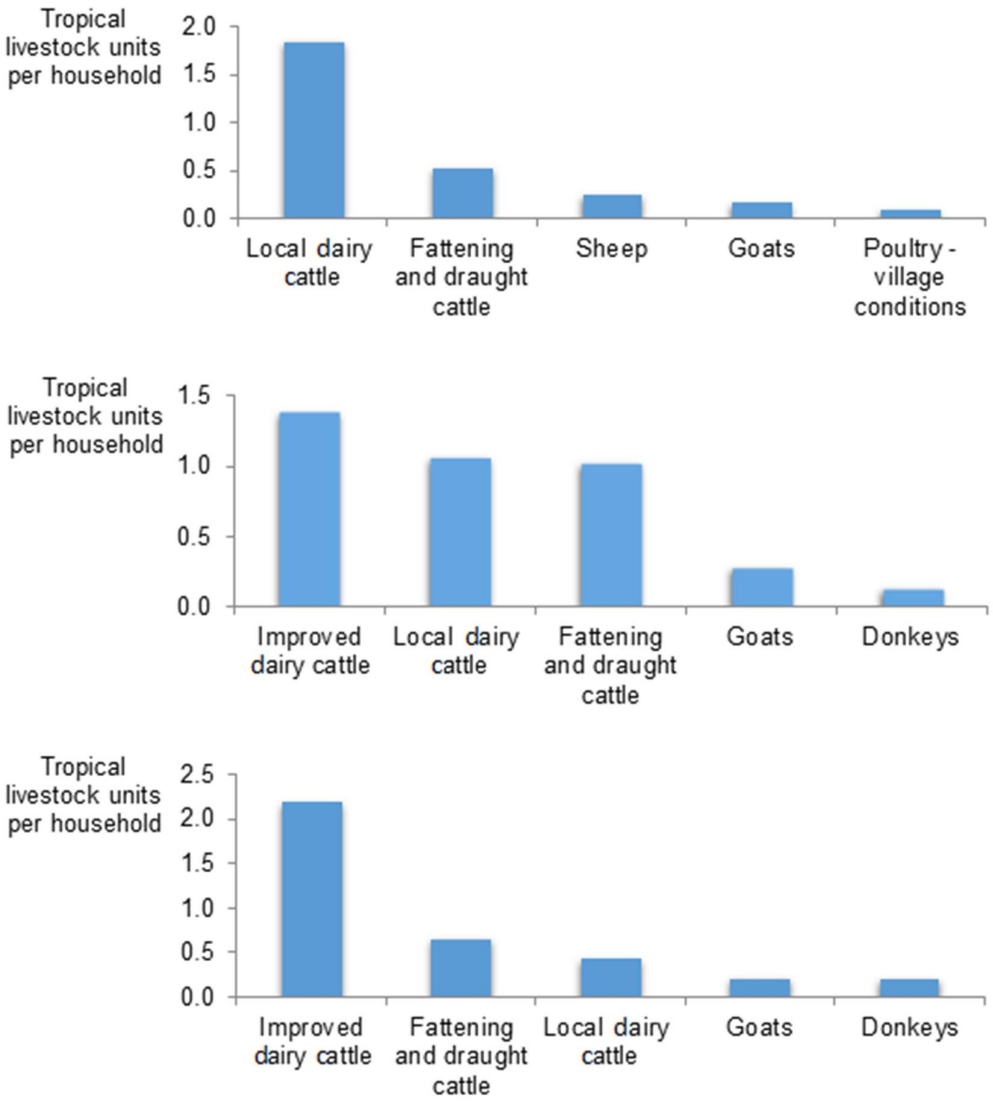


Fig. 2. Average livestock holding by category and species per household in tropical livestock units in the a) Lowlands, b) Mid-slopes, and c) Highlands of Lower Nyando, Western Kenya in October 2013.

TLU = Tropical livestock unit = 250 kg.

2.3.5 Feed availability and feeding practices

The farmers perceive that feed availability is determined by the rainfall pattern. The months of relative abundance start in March and peak in April-May then drop, but due to residual moisture in the soil feed still remains

relatively adequate. When the rains start again in August, the amount of feed rises again till December (Fig. 3a, b, and c).

The dry season of January to March is the worst time with the Lowlands being hardest hit and livestock deaths normally occur. To prevent this, some farmers in the Lowlands farm out their animals to friends in the Mid-slopes or further away to areas around Lake Victoria to keep them till the rains come. Napier grass (*Pennisetum purpureum*) is planted in the Highlands as the main supplement to pasture herbage which is the main feed. In the Mid-slopes there are many naturally-growing indigenous trees and shrubs which are used to supplement the pasture herbage such as, *Lantana camara* L., *Terminalia brownie* Fresen*, Rhus natalensis* Bernh. ex Krauss, *Tithonia spp*., *Carissa edulis* Vahl*, Grewia bicolor* Juss., *Harrisonia abyssinica* Oliv., *Aphania senegalensis* (Juss. ex Poir.) Radlk., *Thevetia peruviana* (Pers.) K. Schum., *Vepris nobilis* (Delile) Mziray, *Combretum molle* R. Br. ex G. Don, *Senna siamea* Lam., *Acacia spp*., and *Crotalaria spp*.

Further supplementation is provided by purchase, but in very few households. In the Lowlands farmers buy fish meal (64% of total households), cracked maize grains, sugarcane tops and rice stover. In the Mid-slopes the purchased supplements are sugarcane molasses (52% of total households) and commercially mixed rations while, in the Highlands it is mainly sugarcane molasses (90% of total households). Other collected feedstuffs include banana pseudo stems and leaves, sweet potato vines, and crop residues and by-products. There is usually minimal feed processing (i.e., chopping and mixing). Paddock feeds (in the Highlands) are normally chopped and added to molasses or salt lick when available. Grazing contributes about 80 – 90% of the diet livestock in the study area.

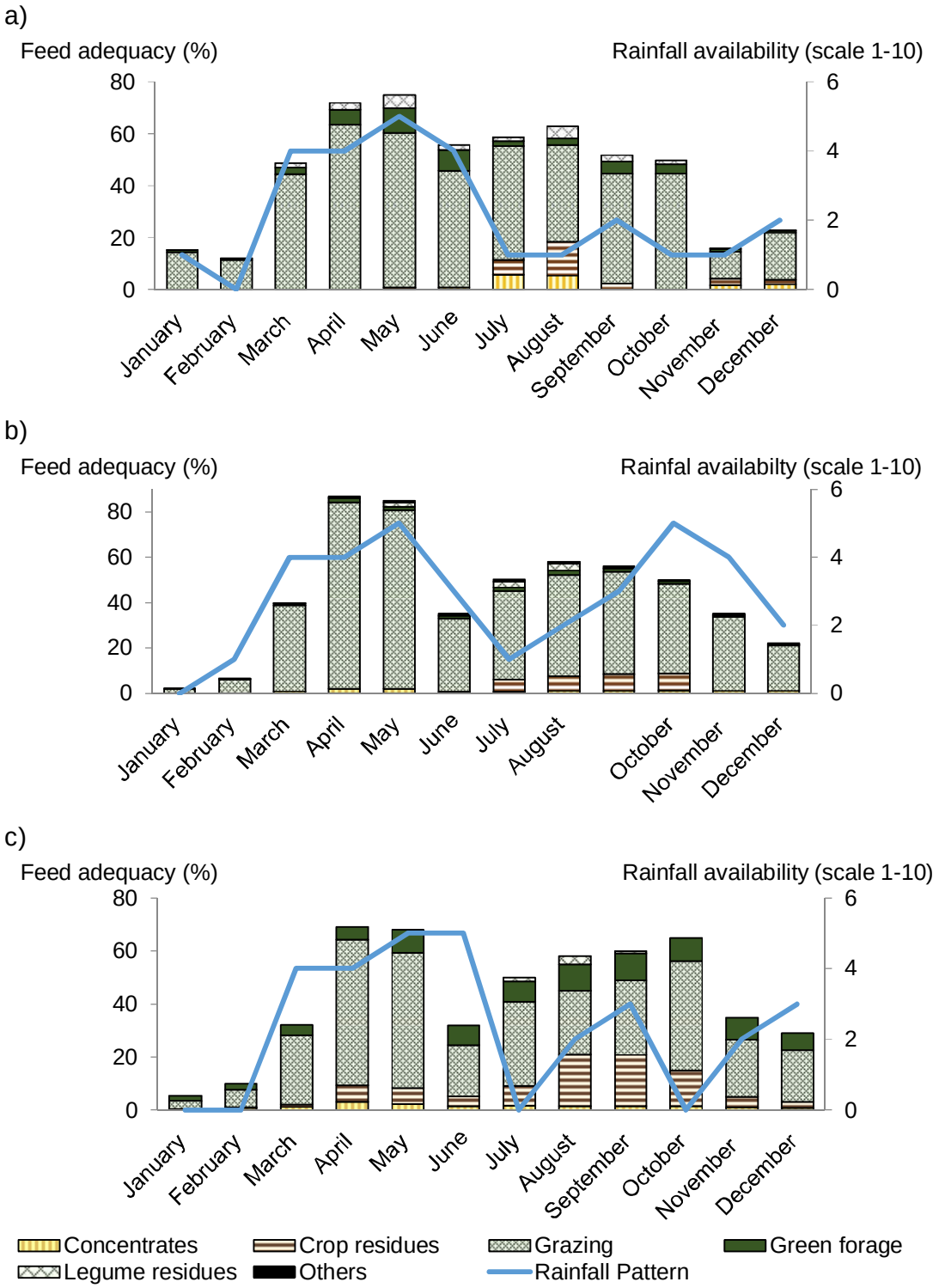


Fig. 3. Availability of feed resources (as a percentage of complete sufficiency) and rainfall pattern as perceived by farmers in the a) Lowlands, b) Mid-slopes, and c) Highlands of Lower Nyando, Western Kenya in October 2013.

*Concentrates here are mainly fish meal mixed with grains fed to chicken.

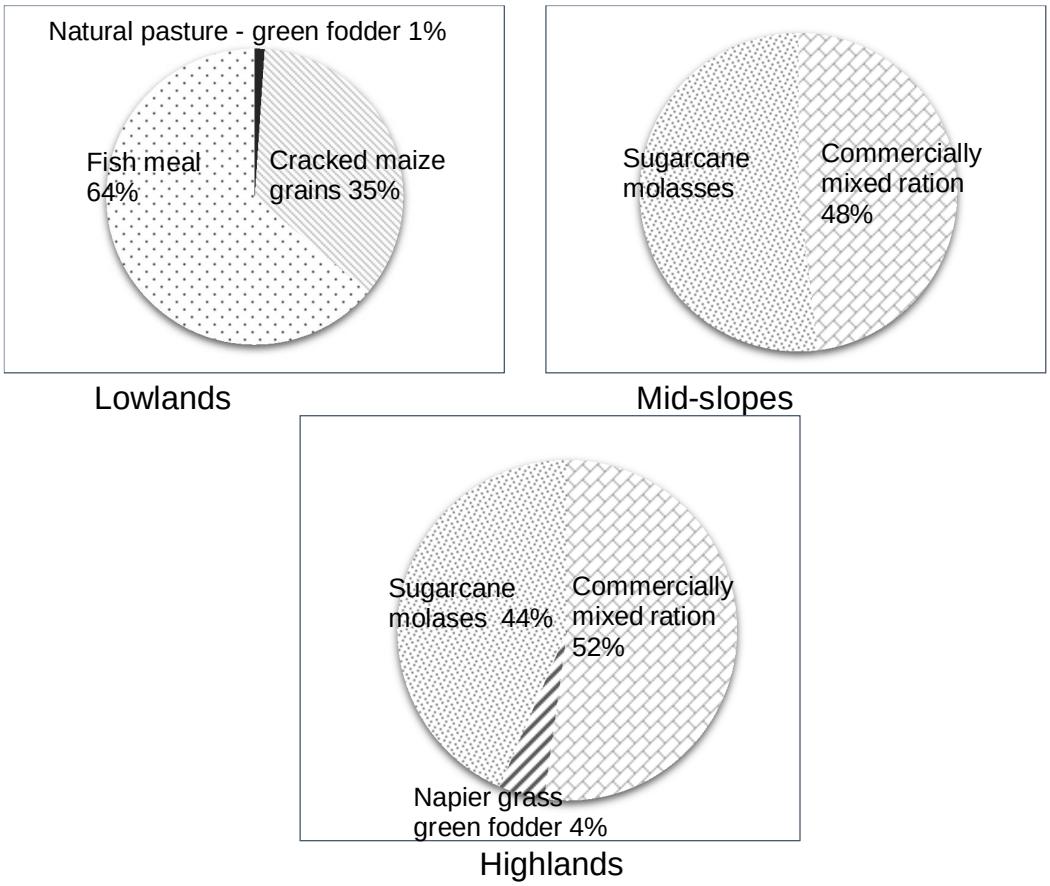


Fig. 4. Proportion of types of purchased feeds (as a percentage of the total purchased feeds) in the different zones of Lower Nyando, Western Kenya in October 2013.

Livestock in the Lowlands are usually tethered from 9 - 12 noon then herded on communal land up to 6 pm. In the Mid-slopes, they are herded in communal land from 10 am to 6 pm except in the dry season when the animals are left to feed on farms having sugarcane tops left after harvesting. Feeding in the Highlands depends on the village. In villages where land sizes are larger, animals are herded in communal land; in villages with medium-sized farms, they are tethered and fed by cut and carry while in the village with the smallest farms, they graze on paddocks and also receive cut and carry feedstuff. Chicken are generally free-range but are tethered during the planting season and when legumes are flowering so that they do not eat up the flowers.

2.3.6 Manure management

All farmers in the Lowlands collect manure; 35% of the farmers collect every 3 months while 29% of the farmers collect weekly. Over 94% of all the farmers do not separate urine from faeces, while 88% of the farmers do not mix manure with feed refusals. Manure is mainly stored in heaps (71% of the famers) or is left uncovered (88% of the farmers). The stored manure is usually (82% of the farmers) not treated in any way, while the rest turn the manure at intervals. Manure is stored before use for between 6 months to a year (53% of the farmers), and the most common method of application to the fields (76% of the farmers) is by hand sprinkling. Only 66% of the farmers in the Mid-slopes collect manure and of these, the frequency of collection is every 3 months (i.e., 41% of collectors). They neither separate urine from faeces nor mix manure with feed refusals. Most farmers (92%) store the manure in situ where it is neither covered nor actively managed. The period of storage is usually more than 3 months (58% of the farmers) and it is applied to the fields once or twice a year (42% of the farmers). All the farmers apply manure by scattering by hand in the fields. About half the farmers in the Highlands collect manure for use in other fields different from the ones the animals graze on. The manure is stored in situ and collected every 3 months or less. Urine is not separated from faeces and only 10% mix manure with feed refusals. The manure is neither covered nor actively managed during storage. Of the farmers who collect manure, 70% apply manure by scattering in the Napier grass and banana fields.

It is important to note that owing to the nature of the animal housing (above), the manure from small ruminants, calves and chicken is collected in shorter periods ranging from daily to weekly and scattered immediately onto vegetable gardens in the Lowlands and the Mid-slopes; and onto Napier grass and banana fields in the Highlands.

2.3.7 Extension services and credit facilities

Veterinary services are readily available and accessible in the Lowlands. However, the cost (2 - 15 Euros) is too high for most farmers. Farmers use bull services (to improve or cross their animals) ranging from 5 - 10 Euros per successful service depending on the perceived level of exotic gene in the bull (i.e., the more exotic the higher the price) while service with local bulls are free. Lack of cash and credit facilities was perceived as a constraint to agriculture due to lack of collateral to obtain loans in the Lowlands.

Veterinary services are neither accessible (travel of 15 - 18 km) nor affordable (at least 10 Euros per animal) for most farmers in the Mid-slopes. Most farmers use bull services which are either free or they give small tokens (e.g., chicken, milk, or sugar) for the services of improved breeds. Credit facilities are readily available although the uptake is low due to lack of confidence in the ability to meet the terms of credit. Sheep and goats are considered to be "banks" kept for short term financial security.

In the Highlands, private veterinary doctors are available at an average cost of 6 - 7 Euros per animal. Artificial insemination services are available (semen costs 10 Euros per service whether successful or not). However, farmers prefer bull service since it is cheap (small token), reliable and one ensures that the size of the calf they get can be easily birthed by the cow. Credit facilities and inputs for agricultural production are readily available.

2.3.8 Problems, issues, and opportunities as perceived by farmers

The main problems in the Lowlands were frequent cattle rustling (theft of cattle between the neighbouring Luo and Kalenjin communities), lack of cash for production, diseases, land availability, and negative cultural practices which make it difficult for young people and women to own livestock. Traditionally, only one cow kraal is allowed per home and so the elders have a lot of say over how the animals are managed (especially

disposal) since they are usually the owners of the kraal. Opportunities for tackling these problems were proposed such as liaising with the local government and police to identify cow thieves and arrest them, diversification of means of production, subsidy of veterinary services, reduction of stocking levels, adoption of more productive breeds, and sensitization of the elders to the possibility of the young people and women taking an active role in livestock production and decision-making.

In the Mid-slopes, the main problems are lack of information on proper livestock management, lack of inputs, poor availability and/or accessibility to water, lack of veterinary services, and traditional beliefs which hinder adoption of new ways of livestock production. Proposed opportunities for tackling these problems include introduction of extension services, liaising with non-governmental organizations to gain modern knowledge on livestock management through seminars and trainings, use of community-based initiatives and cooperatives to bring inputs closer to the farmers, and creation of water pans and dams or possibly drilling of boreholes.

Farmers in the Highlands identified their problems to be lack of water and money for livestock management, low feed availability, animal diseases and lack of market for produce. Opportunities mentioned include construction of dams (to harvest storm water), rain harvesting and digging of boreholes, credit facilities to improve cash for livestock farming, greater variety of feeds and the use of cultivated fodder, affordable veterinary services, construction of chilling plants, and formation of cooperative societies to help in milk preservation and marketing.

a)  b)  c) 

Fig. 5. Livestock housing a) small ruminants and calves under barns in the Highlands, b) small ruminants in roofed wooden enclosures in the Mid-slopes, and c) cattle tethered under trees in the homestead in the Mid-slopes.

a)  b)  c) 

Fig. 6. a) Wooden crutch used for milking aggressive cows in the Mid-slopes, b) A cow being tethered for milking on a short leash at the horns and the same rope used to tie hind legs together to avoid kicking during milking in an open-air wooden enclosure used to corral cattle overnight in the Lowlands, and c) manure management in the Mid-slopes by tethering animals overnight for a season on fallow crop-land before using it again for crops.

a)  b)  c) 

Fig. 7. Cattle breeds in a) Lowlands (i.e., Kavirondo zebu), b) Mid-slopes (i.e., Nandi zebu), and c) Highlands (i.e., Nandi zebu x Ayrshire) zones of Lower Nyando, Western Kenya in July 2014.

a)  b)  c) 

Fig. 8. Feeding a) on individual farm pasture plot in the Lowlands, b) on sugarcane tops in the dry season at the boundary of the Lowlands and the Mid-slopes, and c) on cut and carry Napier grass in the Highlands zones of Lower Nyando, Western Kenya between July 2014 and July 2015.

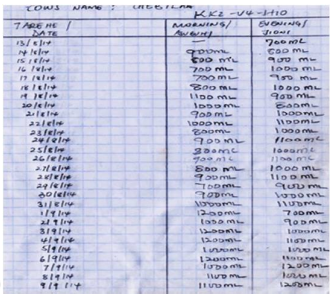
a)  b)  c) 

Fig. 9. Feed and cattle data collection a) liveweight and heart girth measurement, b) Pasture herbage using exclusion cages, and c) Farmers' milk records in Lower Nyando, Western Kenya between July 2014 and July 2015.

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3. Simple and robust algorithms to estimate liveweight in African smallholder cattle[2]

Abstract

Measurement of liveweight of stock is one of the most important production tools available to farmers – playing a role in nutrition, fertility management, health and marketing. Yet most farmers in sub-Saharan Africa do not have access to scales on which to weigh cattle. Heart girth measurements (and accompanying algorithms) have been used as a convenient and cost-effective alternative to scales, however despite a plethora of studies in the extant literature, the accuracy and sensitivity of such measures are not well described. Using three datasets from phenotypically and geographically diverse cattle, we developed and validated new algorithms with similar R^2 to extant studies but lower errors of prediction over a full range of observed weights, than simple linear regression, which was valid for measurements in an unassociated animal population in sub-Saharan Africa. Our results further show that heart girth measurements are not sufficiently sensitive to accurately assess seasonal liveweight fluctuations in cattle and thus should not be relied in situations where high precision is a critical consideration.

Key words: allometric, heart girth, prediction error, sub-Saharan Africa.

3.1 Introduction

Measurement of liveweight (LW) and LW change is ubiquitous to most aspects of ruminant livestock husbandry and management. In advanced agricultural systems, assessment of LW is indispensable in measuring

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growth, estimating intake and nutritional requirements of stock and determining their readiness for market or for joining (Sawyer et al., 1991). Measurement of LW is also requisite in the determination of more complex factors such as feed conversion efficiency and residual feed intake, which are gaining importance in advanced livestock production systems (e.g. Veerkamp 1998).

On a simpler, but equally important level, knowledge of LW is essential for safe and efficacious administration of veterinary medications and for farmers to receive an equitable price in the sale of animals. Calibrated weighing scales are considered the gold standard for determining LW, but these are rarely available to smallholder farmers in sub-Saharan Africa (SSA). Often, the only recourse that farmers have is to estimate the LW of their animals visually, but Machila et al. (2008) has demonstrated that farmers are poor judges of their animals' LW and further, that some commercially produced 'weigh bands' (e.g. CEVA Santé Animale) consistently overestimate LW of smallholder cattle, suggesting that the algorithm on which the graduations of the weigh band are based are not valid to use in such populations. Irrespective of this, heart girth circumference measurements (HG) have been consistently demonstrated across many studies to have a strong, although variable, correlation with LW (Table 1). This variability may be due to phenotypic differences between populations, but is rarely explored (e.g. Buvanendran et al., (1980)) and there has been apparently little interest in developing a more universally applicable algorithm for Zebu x cattle in SSA.

Table 1. Summary of studies (n = 9) investigating the relationship between heart girth and liveweight for *B. taurus* and *B. indicus* cattle

Country	Breed/type	Type	Class	LW (kg) range/mean	No. of animals	No. records	R^2	Regression algorithm
Tanzania[A]	E.A. shorthorn Zebu	Beef	All	106 - 409	300	-	0.88	4.55X - 409
	-	-	Male	106 - 409	195	-	0.88	4.81X - 410
		-	Female	180 - 387	105	-	0.87	6.24X - 525
Tanzania[B]	*B. taurus* x *B. indicus*	-	Cows >2 years	324.8	71	1076	0.68	4.659X - 430.84
		-	Heifers <2 years	226.9	68	1033	0.83	4.15X - 362.0
	-	-	Calves	64.3	35	424	0.88	1.6X - 81.60
Gambia[C]	N'dama	-	Males	-	1906	-	0.82	4.27X - 363.79
		-	Females	-	1038	-	0.56	3.1X - 212.48
Turkey[D]	Brown Swiss	Dairy	NA	-	44	925	0.9	4.899X - 461.05
USA[E]	Guernsey and Friesian	Dairy	Bulls	387 - 1069	50	-	0.95	21.03X - 1285.18
Ethiopia[F]	Abyssinian short-horned Zebu	Draft	Males	281 ± 37	48	1100	0.75	4.21X - 364.9
Nigeria[G]	White Fulani	-	Female	-	110	-	0.86	4.49X - 410.6
	Sukoto Gudali	-	Female	-	80	-	0.94	4.06X - 343.5
	N'dama	-	Female	-	26	-	0.96	3.75X - 320.4
S. Africa[H]	Nguni	-	All	-	725	-	0.74	0.81X + 16.58
		-	Female	268 - 470	60	-	0.9	5.13X - 504.68
Phillipines[I]	Brahman	Beef	All	268 - 660	94	-	0.94	6.55X - 738.26
		-	Male	302 - 660	34	-	0.93	6.88X - 780.42

[A]Kashoma et al. (2011); [B]Msangi et al. (1999); [C]Spencer et al. (1986); [D]Bozkurt (2006); [E]Branton and Salisbury (1946); [F]Goe et al. (2001); [G]Buvanendran et al. (1980); [H]Nesamvuni et al. (2000); and [I]Bagui and Valdez (2009).

Several studies have considered other allometric measurements (e.g. wither height, body length, body condition score), but such additional measurements have not greatly improved the relationship of LW to HG (Buvanendran et al., 1980; Bozkurt, 2006; Bagui and Valdez, 2009). Thus HG has been repeatedly demonstrated to be the most useful and robust proxy for the use of scales in the LW estimation of cattle.

Studies which explored polynomial and exponential relationships between HG and LW (Buvanendran et al., 1980; Nesamvuni et al., 2000; Francis et al., 2004), have not improved coefficients of regression by more than a few percentage points, while having added unneeded complexity to the model. Perhaps because the simplest relationship appears (based on R^2) to be as strong as the more complex equations, the relationship between HG and LW has generally been described by simple linear regression (Table 1).

Using the coefficient of determination of a regression as the criterion for goodness of fit does not provide information about variance or bias in the model, and hence, the degree to which the values predicted by the model will vary from true values. The magnitude of the prediction error (PE) will critically affect the utility of using HG measurements to estimate LW. Although PE of 20% may be acceptable for setting dosage rates for veterinary chemicals (Leach and Roberts, 1981), errors of 10% or greater are problematic when using HG measurements to assess production–related traits in individual animals that require accurate LW determination. Lesosky et al. (2012), taking a different approach - transforming the response variable while using a simple linear regression, reported PE of less than 20% with a co-efficient of determination of 0.98. This study was based on a group of phenotypically similar indigenous zebu cattle of limited weight range (mostly <100kg) and it is unclear whether such a strong relationship would be observed in a more phenotypically diverse population.

Therefore our study had four objectives:

i) To determine the strongest relationship possible between HG and LW, by considering both PE and regression coefficients , rather than regression coefficients alone;

ii) To determine the extent to which disaggregation of data into more phenotypically homogenous populations is likely to strengthen the relationship between HG and LW;

iii) To assess whether such an algorithm may be used successfully to establish LW in novel populations; and

iv) To determine the applications for which HG measurements may validly be used as an alternative to weighing scales for LW determination.

3.2 Materials and methods

3.2.1 Animal population for algorithm development

Two datasets, one each from West and East Africa were used to develop and train the HG algorithm. The East African dataset comprised smallholder (Zebu x *Bos taurus*) female crossbred dairy cattle in Siongiroi (0°55′S, 35°13′E; ~1800 m above sea level) and Meteitei (00°30′N, 35°17′E ; ~ 2000 m above sea level) districts of Rift Valley Province, and Kabras district in Western Province (00°15′10°N, 34°20′35°E: ~1500 m above sea level; (n = 439, LW: range: 36 – 618 kg, x = 264.9 kg, s.e.m. = 3.74 kg)) (Lukuyu et al., 2016). Data from cattle from West Africa were collected between November 2013 to June 2015 on 84 farms in Thiès and Diourbel regions of Senegal (n = 621, LW: range: 31 – 604 kg; x = 262.7 kg, s.e.m. = 4.06 kg) with the different breed/cross-breeds of cattle in the study sample assigned to four main breed-groups (i.e.: (i) indigenous Zebu, (ii) Zebu x Guzerat, (iii) Zebu x *B. taurus*, (iv) predominantly *B. taurus*) either on the basis of farmer recall or, where available, genotype information (Tebug et al., 2016). All animals from each study had LW assessed gravimetrically using electronic weigh scales and HG measured simultaneously.

3.2.2 Analytical Approach

The two datasets were examined both separately and in combination. These datasets were analysed and plotted using HG as the predictor variable and the measured LW as the response variable (Fig. 1). We compared the West and East African populations using analysis of covariance (ANCOVA: using the AOV function in the software page R version 3.0.3, (R Development Core Team, 2010)) on the entire population using the region (East vs West Africa) as a fixed factor and HG as a co-variant. To facilitate comparison with other studies (Table 1) we first used a simple linear regression model (SLR) to predict LW using HG (1).

$$LW = a + b(HG) \quad (1)$$

We then considered five other relationships including log-transformation and quadratic equations as methods to minimise PE, but decided on the three models that appeared to produce the strongest relationships between LW and HG. The first was a square-root transformation of LW using a simple linear regression model (SQRT-LR) (2).

$$\sqrt{LW} = a + b(HG) \quad (2)$$

The power coefficient was determined using Box-Cox function in R, using boundaries of -1 and 1 and a step of 0.001. The transformed LW was also used in a linear regression (BOXCOX-LR) (3).

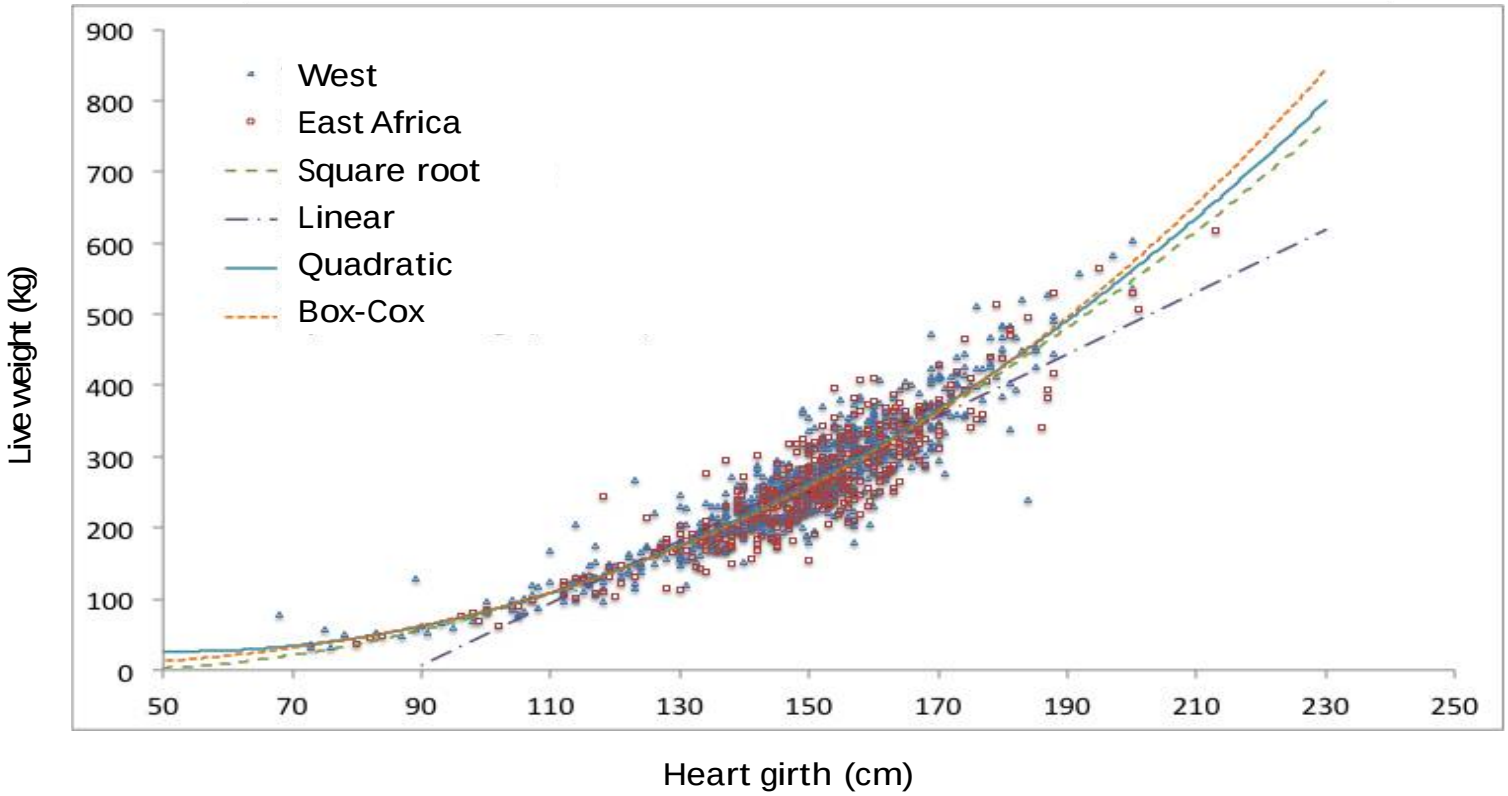
$$LW^{0.3595} = a + b(HG) \quad (3)$$

The final model examined was a polynomial equation (QUAD) (4).

$$LW = a + b(HG) + c(HG)^2 \quad (4)$$

Model goodness-of-fit was analysed using the adjusted R^2, (after back transforming the transformed response variables) and through examination of residual plots, normal probability plots and leverage plots.

Fig. 1. Cattle liveweights (kg) as a function of heart girth (cm) for two datasets, one from West Africa (Senegal) and the other from East Africa (Kenya). Line of best fit is given for (*a*) Linear, (*b*) Square-root transformation of the response variable, (*c*) Box-Cox transformation of the response variable and (*d*) Quadratic equations.



The residual plots were used to identify points with large associated residuals (possible outliers), whereas the normal probability plot was used to check linearity and normality assumptions. The leverage plots were used to detect data points with unusually high influence (Cook, 1977). Outliers noted on the diagnostic plots were investigated and either corrected when possible (i.e. simple transcription error) or removed and the resulting dataset was re-analysed. In total, only 4 of the 1064 data points were removed. In addition to R^2 we estimated PE ((ABS (measured LW – predicted LW))/measured LW) as well as the root mean squared error (RMSE). The two datasets plus the aggregated set were analysed using cross validation techniques as follows: datasets were split into two; 70% of the measurements were used to train the model (training set), whereas the other 30% were used to validate the model (validation set). The 75th, 90th and 95th percentiles for PE (i.e. what is the percent error required to capture 75%, 90% or 95% of the measurements) were calculated. The cross validation for each model (Eqns 1 - 4) and each dataset were repeated 1000 times using different splits for the cross validation each time, and descriptive statistics (x, s.d., coefficient of variation (c.v.)) were calculated for the PE 75th, 90th and 95th percentiles, model coefficients and adjusted R^2. The PE were then used in conjunction with the previous criteria given above to determine the ability of each model type to accurately predict LW from the HG measurement.

3.2.3 Model Validation

To address experimental aim (iii) we employed a further dataset derived from a mixed (Zebu and Zebu x *B. taurus*) smallholder cattle population in the Nyando Basin, Western Kenya (0°13’30’’S - 0°24’0’’S, 34°54’0’’E – 35°4’30’’E; 1200 - 1750 m above sea level n= 892, LW: range: 11.6 – 361.6 kg, x = 165.0 kg, s.e.m.: 1.45 kg; A. Onyango, pers comm.). In total 1890 measurements were used (some animals were measured 2 - 4 times) as a secondary validation set. Using the parameters estimated from each of the

models tested here and three models from other published studies, two using SLR (Msangi et al. (1999) , Kashoma et al. (2011)) and the Lesosky et al. (2012) Box-Cox transformation linear regression, we calculated the expected LW from the HG measurements. We then calculated the 75th, 90th and 95th percentiles of the PE (i.e. the percent error that contains 75%, 90% or 95% of the correct LW). Again, diagnostic plots were used to identify outliers (data points with unusually high residual values, or high leverage), which were either corrected when possible or removed. There were a total of 11 data points removed from this data set, resulting in 1879 data points being used for model validation.

As well as being useful for detecting outliers, the diagnostic plots also provide a useful visualisation of how well the model 'fits' the data. Normal probability (Q-Q) and standardized residual (residual/s.d. of residuals) plots show whether there is a systematic bias in the model, whereas the leverage plots provide an indication of the resilience of a model against outliers. Therefore, we also used these plots as a qualitative measure of each model.

3.3 Results

The datasets considered for the present study, differed from the data used in the studies of both Lukuyu et al. (2016) (LW = 102 – 433 kg) and Tebug et al. (2016). (LW = 110 – 618 kg) in that both of these used attenuated datasets in their analysis (compared with the original, or full dataset), eliminating particularly animals of low LW, which had implications in terms of linearity of the relationship between LW and HG.

3.3.1 Diagnostics

Examination of the diagnostic plots for the linear regression model (e.g. residual and standardised residual plots) revealed that at the tails of the dataset (i.e. very small or very large animals) there was a strong bias

towards positive residuals indicating a systematic underestimation of the animals' liveweight (Fig. 2*a*).

This systematic bias was not present in the SQRT-LR (Fig. 2*b*), BOXCOX-LR (Fig. 2*c*) or the QUAD models (Fig. 2*d*) suggesting that these equations more accurately reflect true measurements, particularly at the extremes of low and high weights.

Leverage plots indicate the degree to which a single data point can alter the model and therefore useful for examining the relative robustness of different models to outliers. As shown in Fig. 3, the QUAD model has points with leverage score four times greater than those in the other three models.

All four of the models had adjusted R^2 greater than 0.8, however the values of the SQRT-LR, BOXCOX-LR and QUAD models were all ~0.05 (5%) greater than the SLR (Table 2). The RMSE for the two transformed and the QUAD model were all similar and ~8% less than the SLR model (Table 2). PE for all models were similar and at the 75th percentile, but importantly, both the two transformed (SQRT-LR, BOXCOX-LR) and the QUAD model had PE of up to 9% less at the 95th percentile compared to the SLR model, in both aggregated and disaggregated datasets.

The SQRT-LR, BOXCOX-LR and QUAD models were also all significant when the dataset was disaggregated into the East and West African populations, with the adjusted R^2 values ranging between 0.797 and 0.881 and the RMSE ranging between 34.2 and 36.9 (Table 2).

Similar to the models run with the full dataset, SQRT-LR, BOXCOX-LR and QUAD models had the highest adjusted R^2 and the lowest PE (Table 2) than the SLR indicating that they again tended to fit the data more accurately, which was likely due to the poor fit of the SLR at the extremes of the LW range.

Fig. 2. Standardised residual plots for four regression model (Linear, Square-root transformation of response variable, Box-Cox transformation and quadratic equation) using cattle heart girth measurements (cm) to predict to predict liveweight (kg) for two cattle populations; one in West Africa (Senegal; n = 621) and the other in East Africa (Kenya; n = 439).

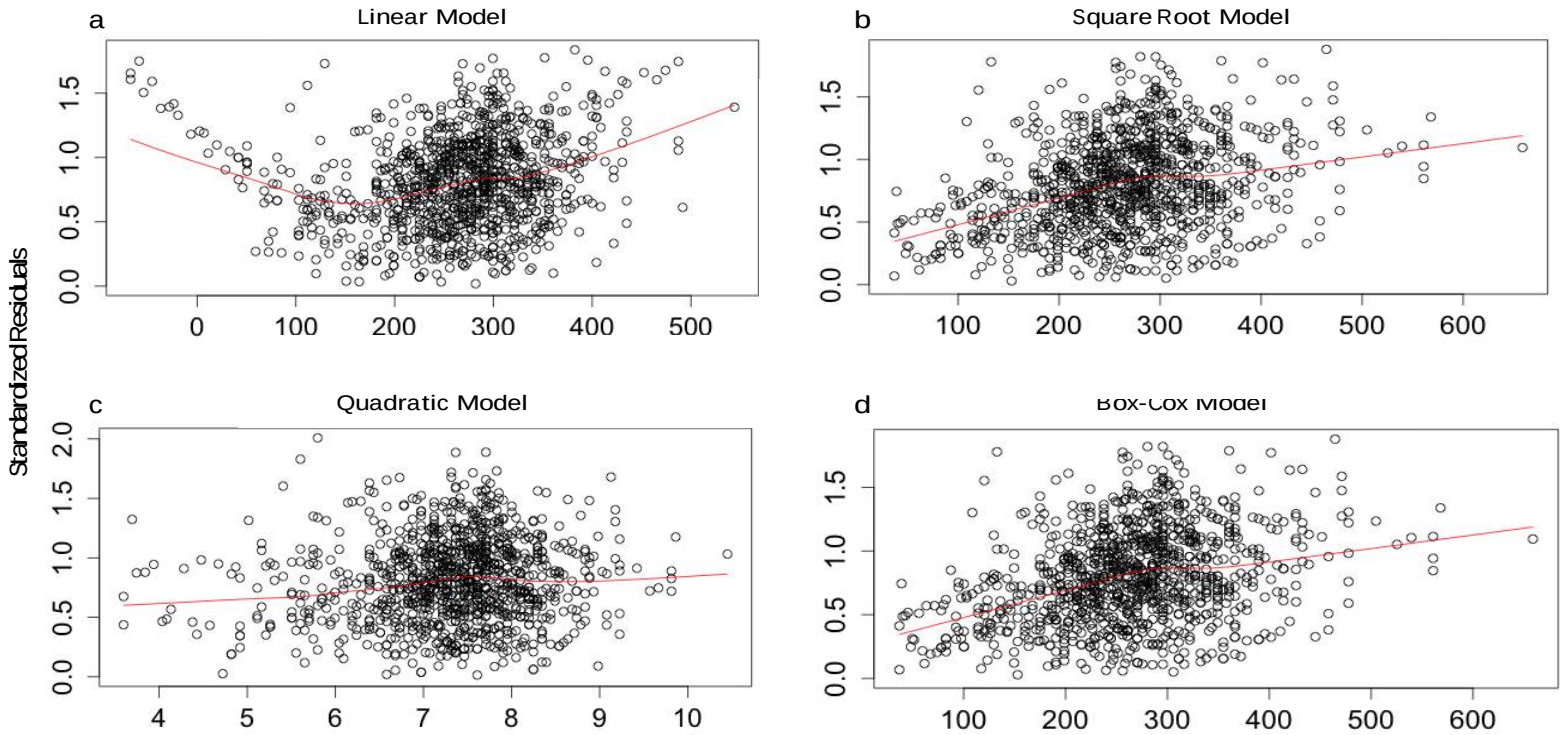
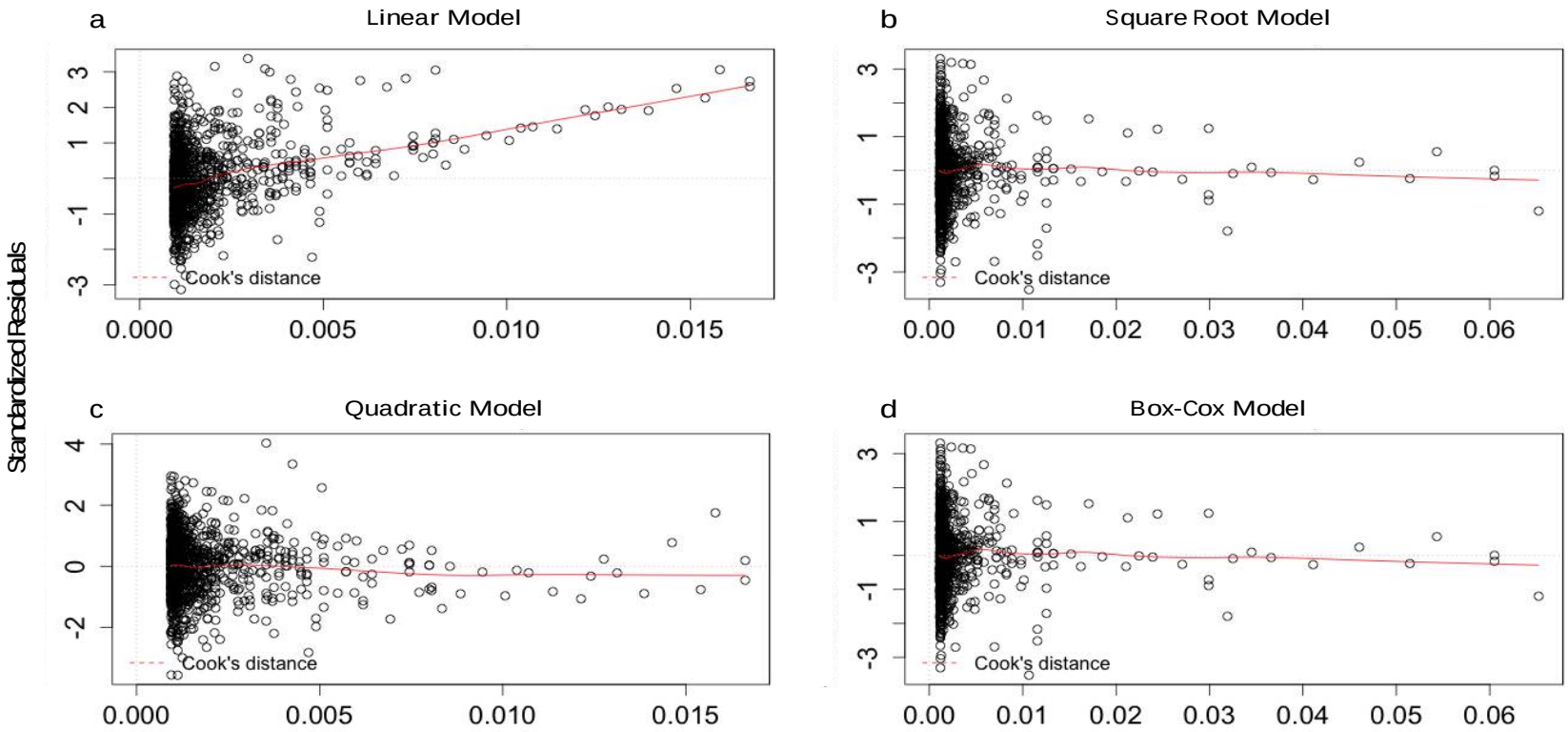


Fig. 3. Leverage plots for four regression model (Linear, Square-root transformation of response variable, Box-Cox transformation and quadratic equation) using cattle heart girth measurements (cm) to predict to predict liveweight (kg) for two cattle populations; one in West Africa (Senegal; n = 621) and the other in East Africa (Kenya; n = 439).



However, disaggregating the combined data set did not improve the model substantially, in fact, the adjusted R^2 for the East African dataset decreased compared to the full dataset (Table 2).

This was in agreement with the results of the ANCOVA, which showed that population was not a significant factor for SLR (P = 0.675), BOXCOX-LR (P = 0.706) or SQRT-LR (P = 0.886) models. This suggests that the two populations, although geographically and phenotypically divergent were similar enough to be considered a single population where LW can be effectively predicted by using the same HG algorithm(s) (refer also Fig. 1).

3.3.2 Model validation

Applying the parameters estimated from each of the models tested here and three models from other published studies using the aggregated dataset to the novel (validation) dataset produced mixed results. Applying SLR models from our own study, and simple linear models from two other published studies (Msangi et al. 1999; Kashoma et al. 2011) produced similar, moderate-adjusted R^2 (0.47-0.59), and PE of over 70% at the highest percentiles of PE (Table 3).

In comparison, the more complex models (SQRT-LR, BOXCOX-LR , QUAD) and the model of Lesosky et al. (2012), displayed high adjusted R^2 (0.91-0.92) and low PE across all percentiles (Table 3).

Table 2. Equations for estimating liveweight (LW) of cattle, showing adjusted R^2, root mean squared error (RMSE) and prediction errors at the 75th, 90th, and 95th percentiles for the tested models (Simple linear regression (SLR), Square-root transformed linear regression (SQRT-LR), Box-Cox transformed linear regression (BOXCOX-LR) and quadratic (QUAD)). All equations were significantly different from 0 ($P < 0.0001$)

Model	Algorithm	Adj. R^2	RMSE	Prediction errors[A] (Percentiles)		
				75th	90th	95th
	Aggregated Data set					
SLR	LW = -393.4 + 4.4176 * HG	0.828	38.4	± 17%	± 26%	± 37%
SQRT-LR	$\sqrt{LW}$ = -5.7123 + 0.14579 * HG	0.873	35.3	± 15%	± 22%	± 28%
BOXCOX-LR	$LW^{0.3595}$ = 0.02451 + 0.04894 * HG	0.870	35.3	± 15%	± 22%	± 28%
QUAD	LW = 73.599 - 2.291 * HG + 0.02362 * HG^2	0.856	35.2	± 15%	± 22%	± 29%
	East Africa Dataset					
SLR	LW = -397.956 + 4.4125 * HG	0.797	38.3	± 17%	± 26%	± 35%
SQRT-LR	$\sqrt{LW}$ = -5.6554 + 0.1449 * HG	0.836	36.2	± 15%	± 23%	± 29%
BOXCOX-LR	$LW^{0.3595}$ = 0.01543 + 0.04920 * HG	0.888	36.9	± 14%	± 21%	± 27%
QUAD	LW= 44.46095 - 1.82363 * HG + 0.021629 * HG^2	0.818	36.2	± 15%	± 23%	± 30%
	West Africa Dataset					
SLR	LW = -381.193 + 4.3572 * HG	0.833	38.1	± 16%	± 25%	± 35%
SQRT-LR	$\sqrt{LW}$ = -5.509777 + 0.14502 * HG	0.881	34.2	± 14%	± 21%	± 27%
BOXCOX-LR	$LW^{0.3595}$ = 0.01170 + 0.04876 * HG	0.842	35.2	± 15%	± 23%	± 29%
QUAD	LW= 113.744 - 2.87688 * HG + 0.02583 * HG^2	0.865	34.2	± 14%	± 21%	± 27%

[A]Prediction errors provided are the mean prediction errors from 1000 cross validation estimates.

Table 3. Validation of equations from the aggregated data set of West and East African cattle using an unrelated data set of cattle from the Nyando region (Western Kenya) for estimating liveweight (LW) of cattle, showing adjusted R^2, and prediction errors at the 75th, 90th and 95th percentiles for the tested models (Simple Linear regression (SLR), Square root transformed linear regression (SQRT-LR), Box-Cox transformed linear regression (BOXCOX-LR) and quadratic (QUAD)) plus a comparison with three other prediction equations from the extant literature. All equations were significantly different from 0 ($P < 0.0001$)

Model	Algorithm	Adj. R^2	Prediction errors (percentiles)		
			75th	90th	95th
SLR	LW = -393.4 + 4.4176 * HG	0.594	± 15%	± 41%	± 82%
SQRT-LR	$\sqrt{LW}$ = -5.7123 + 0.14579 * HG	0.918	± 13%	± 19%	± 24%
BOXCOX-LR	$LW^{0.3595}$ = 0.02451 + 0.04894 * HG	0.922	± 10%	± 15%	± 18%
QUAD	LW = 73.599 - 2.291 * HG + 0.02362 * HG^2	0.920	± 10%	± 15%	± 18%
(from Lesosky et al. 2012)	$LW^{0.262}$ = 0.95 + 0.022 * HG	0.913	± 12%	± 17%	± 19%
(from Kashoma et al. 2011)	LW = -409 + 4.55 * HG	0.551	± 16%	± 44%	± 87%
(from Msangi et al. 1999)	LW = -430.84 + 4.659 * HG	0.470	± 16%	± 38%	± 72%

3.4 Discussion

Algorithms using HG to predict LW in cattle have been repeatedly demonstrated to be robust, with R^2 of 0.75-0.85 and simple measures of fit, such as R^2 or RMSE, are often assumed to be a reflection of the models' predictive capacity and precision. However, the use of diagnostic plots to evaluate goodness-of-fit in models has revealed systematic biases in the use of SLR, not evident from the use of coefficients of determination as measures of fit alone. This is most apparent at the extremes of weight range (i.e. calves and mature animals), which may be why other studies examined the weight range. The calculated PE of 37% of LW under optimized conditions for the SLR suggests that the relationship between HG and LW is not a simple, linear one and that SLR equations are not particularly useful in describing the relationship between HG and LW or in the accurate estimation of LW when considering the full range of LW observed in smallholder cattle populations.

In contrast, transforming the response variable or using a quadratic equation to describe the relationship between HG and LW, both eliminates systematic bias (as indicated in diagnostic plots, see also Figs 2, 3), particularly noticeable at either extreme, and markedly improves the accuracy of LW estimates.

Intuitively, population characteristics that influence animal morphology, such as breed (type), sex, degree of maturity or body condition score, might be assumed to alter the relationship between HG and LW, and many studies have disaggregated and analysed their data by one or more of these characteristics (see Table 1 for examples). That such differences exist is clear from the different algorithms derived within single populations; however, this presents practical problems if the object is to use the algorithms so derived to estimate LW in other animals, more so if the population(s) to be assessed are different from the population the equations were derived from.

In this study, we deliberately set out to determine if a widely applicable algorithm using HG as the single dependent variable could be developed to accurately estimate LW in a novel population. Our starting point was to use two geographically separate populations that differed in breed/type and LW makeup, and we clearly showed that, despite these differences they could be considered as one population for the purpose of determining the relationship between HG and LW. Despite producing different algorithms when the populations were separated, this did not improve the strength of the relationship, or reduce the (prediction) error in any meaningful way. However, we also noted that the SLR equations developed from the datasets we used, showed lower R^2 than the values published by Lukuyu et al. (2016) and Tebug et al. (2016). We infer from this and the graphical structure of HG/LW distribution (Fig. 1), that this is a result of our equations being derived from the full range of LW and demonstrate the non-linearity of HG/LW over the full LW range.

Applying the algorithms we developed to our validation dataset highlighted two key points. First, although the validation dataset was probably reasonably similar to the (aggregated) development population, being a mixture of indigenous and crossbred cattle (but with a different LW range), applying both our SLR equation and those from two other published studies, produced such large (72 - 87%) PE as to make them inapplicable for practical purposes. In contrast, applying the more complex algorithms (SQRT-LR, BOXCOX-LR, QUAD) and the Box-Cox transformation from Lesosky et al. (2012), all produced PE of less than 25% at the highest percentile, with Box-Cox transformations and QUAD algorithm showing the lowest PE (18 - 19%) indicating that such equations may be able to be validly applied in other, novel populations. Of these, a quadratic model (QUAD) is possibly less useful given the influential effect of small subsets of the population on the equations developed and the increased complexity of

the model does not noticeably improve either the fit (R^2) or the prediction accuracy.

The reasons that the PE of the transformed equations are even lower in the validation dataset (than the development set) are difficult to define. One reason may be that the LW of the validation set occurred over a smaller range compared with the development dataset, and thus showed less variability than the development dataset. A second reason may be that measurements taken in the validation population were all made by one experienced operator and so had lower operator (random) error.

Irrespective of this, it is clear that using either a quadratic model (QUAD) or a square-root (SQTR-LR) or and Box-Cox (BOXCOX-LR) transformation (of the response variable) in a linear regression, makes the prediction of LW from HG more reliable over the full range of observed LW, considerably reducing bias and PE. Further, considering the results observed in applying those algorithms to our validation dataset it appears that the algorithms developed from this dataset may be widely applicable, at least to the types of cattle typically held by sedentary smallholder farmers, although further exploration is needed to confirm this.

There are limitations to the utility of HG in estimating LW however. PEs of ~25% (at the 95th percentile) indicate that the LW/HG relationship using non-SLR equations is sufficiently accurate to be used in veterinary applications and are much better than farmer visual-assessment estimates (Machila et al. 2008). It is important to recognize however that our improved HG-derived estimated are still not sufficiently sensitive to reliably capture relatively small changes in LW, such as those commonly observed seasonally in smallholder cattle, (observed to be in the range of 11 - 17% of LW; A. Onyango, pers. comm.) and conventional scales will continue to be required to capture data of this sort.

Conclusion

The HG measurements, although demonstrably inferior to gravimetric methods for assessing LW, have clear advantages of accessibility and ease of use. We optimized HG algorithms, significantly reducing PE associated with HG-derived estimates of LW. The improved algorithms may be used with higher confidence for animal health applications and to assist farmers in decision-making – in feed formulation, marketing, joining or other husbandry-related issues. The algorithms using a transformed response variable, (Box-Cox, or square-root transformation) or quadratic equations developed in this study, may be also be applied directly in other populations of smallholder cattle in SSA, without the need to undertake extensive testing and further development of new algorithms for each new population of interest.

Improving LW estimation (through improving the accuracy of HG-derived measurements) has the potential to improve the livelihoods of smallholders in Africa through allowing farmers to make better-informed management decisions regarding their animals. It is also clear that estimates of LW via HG measurements are limited in their accuracy, despite improvements and are not of sufficient precision to capture seasonal variations in LW that may be of interest from a research perspective or to be an equivalent alternative to well-calibrated weighing scales, where such options exists.

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4. Temporal and spatial variability in the nutritional value of pasture vegetation and supplement feedstuffs for domestic ruminants in Western Kenya[3]

ABSTRACT

Objective: Study aimed at quantifying seasonal and spatial variations in availability and nutritional quality of herbaceous vegetation on native pastures (i.e., pasture) and supplement feedstuffs for domestic ruminants to evaluate need for region- and season-specific solutions to improve ruminant feeding in Western Kenya.

Methods: Samples of pasture (n=75) and local supplement feedstuffs (n=46) for cattle, sheep, and goats were collected in 20 villages of three geographic zones (Highlands, Mid-slopes, Lowlands) in Lower Nyando, Western Kenya, over four seasons of one year. Concentrations of dry matter (DM), crude ash (CA), ether extract (EE), crude protein (CP), neutral detergent fibre (NDF), gross energy (GE), and minerals were determined. Apparent total tract organic matter digestibility (dOM) was estimated from *in vitro* gas production and fibre concentrations and/or chemical composition alone using published prediction equations.

[3] This chapter is to be submitted as:
Onyango, Alice Anyango; Dickhoefer, Uta; Rufino, Mariana Cristina; Butterbach-Bahl, Klaus; Goopy, John Patrick. (-). Temporal and spatial variability in the nutritional value of pasture vegetation and supplement feedstuffs for domestic ruminants in Western Kenya. To be submitted.

Results: Nutrient, energy, and mineral concentrations were 52 to 168 g CA, 367 to 741 g NDF, 32 to 140 g CP, 6 to 45 g EE, 14.5 to 18.8 MJ GE, 7.0 to 54.2 g potassium, 0.01 to 0.47 g sodium, 136 to 1825 mg iron, and 0.07 to 0.52 mg selenium/kg DM. The dOM was 416 to 650 g/kg organic matter but different with different methods. Nutritive value of pasture was superior to most supplement feedstuffs, but its quality strongly declined in the driest season. Highlands yielded highest pasture biomass, CP (i.e., 2.0 to 2.5 times and 1.2 to 1.3 times other zones respectively), and potassium concentrations.

Conclusions: Availability and nutritional quality of pasture and supplement feedstuffs greatly vary between seasons and geographical zones, suggesting need for season- and region-specific feeding strategies. Local supplement feedstuffs partly compensate for nutritional deficiencies. However, equations to accurately predict dOM and improved knowledge on nutritional characteristics of tropical ruminant feedstuffs are needed to enhance livestock production in this and similar environments.

Keywords: Feed evaluation; Grazing livestock; Pasture herbage; Ruminant nutrition; Seasonal variation; Tropical

4.1 INTRODUCTION

Ruminant production in sub-Saharan Africa largely depends on grazing native pastures and feeding of crop residues and agricultural by-products as dry-season supplements [1]. These crop residues and by-products tend to be rich in fibre and low in metabolizable energy (ME), crude protein (CP), and minerals, thereby limiting feed intake, diet digestibility [2], and performance of domestic ruminants.

Livestock production is an important sector in Kenyan economy where smallholder systems contribute three-quarters of total agricultural output [3]. Smallholder systems in Western Kenya have constraints in provision of sufficient quality and quantity of feedstuffs throughout the year [4]. Moreover, mineral deficiencies are common in ruminants in the Rift Valley region [5] and commercial supplements are not always affordable to smallholder livestock farmers. Climatic and edaphic factors control primary production, species composition, and nutritive value of feedstuffs for grazing livestock [6] which may result in pronounced small-scale spatial and temporal differences in the yield and nutritional value of available feed resources and thus the need for region- and season-specific solutions to improve animal nutrition and performance.

Objectives of the study were therefore to quantify seasonal and spatial variations in the availability and nutritional quality of tropical pasture herbage and supplement feedstuffs for grazing domestic ruminants in Western Kenya and to evaluate the need for local and season-specific solutions to improve livestock feeding. It was hypothesized that biomass yield (BY) and nutritive quality of the pasture vegetation grazed by animals are highly variable between seasons and geographic zones; however, local supplement feedstuffs are suitable to compensate for nutritional deficiencies in the pasture herbage and to develop region-specific solutions for improved livestock feeding and production.

4.2 MATERIALS AND METHODS

4.2.1 Study area

The study was conducted in a 100 km^2 area (00°13’ S - 00°24’ S, 34°54’ E – 35°4’ E) in Lower Nyando Basin, Western Kenya. The site was selected to

represent three distinct geographies common in the area, referred to as ‘zones’: Lowlands (0 – 12% gradient), Mid-slopes (12 – 47% gradient, steeper at the escarpment), and Highlands (> 47% gradient at escarpments, 0 – 5% at the plateau) at altitudes of 1200 - 1750 m above sea level [7]. Soils of the Lowlands are sandy-clays to silty-loamy with visible effects of soil erosion and land degradation; the Mid-slopes are clay and silty loams, while the Highlands are silty to loamy. Two-fifths of the land cover is rangelands mainly used for grazing livestock [7]. Detailed description of the area is available in [8]. Mixed crop-livestock systems are predominant. Livestock consist of cattle, sheep, goats, chicken, and donkeys. The main cattle breeds are East African shorthorn zebus and zebu x *Bos taurus* in the commercial dairy-oriented Highlands.

The climate is humid to sub-humid. The annual rainfall is 1200 – 1725 mm with a bi-modal pattern allowing for two cropping seasons a year. The four climatic seasons are long dry season (January – March), long wet season (April – June), short dry season (July – September), and short wet season (October – December). The first two climatic seasons fall in the long rainy cropping season, and the last two fall in the short rainy cropping season.

Based on results of an earlier survey conducted in the area using 200 households (IMPACTLite), 20 villages were selected (for details see [9]). Sample size of 60 households was based on a total population of 7,528 households, at 95% confidence level, 5% margin of error, and 10% variability. Proportional to size probability sampling with replacement based on clustering of the households in the IMPACTlite dataset yielded 24 farmers in the Lowlands, 18 in the Mid-slopes, and 18 in the Highlands [10].

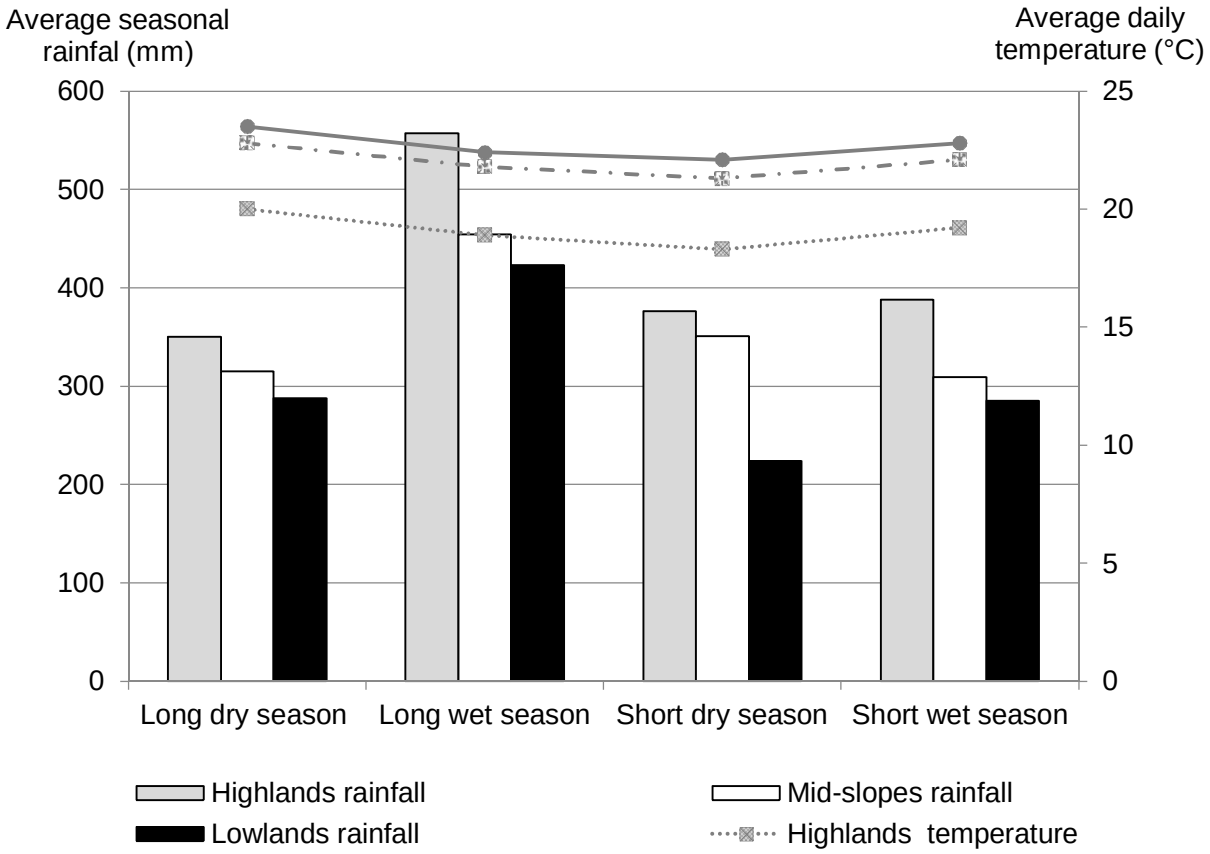

Figure 1. Mean seasonal rainfall and daily mean ambient air temperatures (1982 – 2012) for the three zones in Lower Nyando, Western Kenya. Source: Climate-data.org (http://en.climate-data.org).

4.2.2 Sample collection and processing

The herbaceous pasture vegetation is predominantly composed of grasses such as *Digitaria gazensis* Rendle, *D. ciliaris* (Retz.) Koeler, *Eragrostis superba* Peyr., *E. aspera* (Jacq.) Nees, *Hyparrhenia collina* (Pigl.) Stapf, *Cynodon dactylon* (L.) Pers., *Cappillipedium parviflorum* (R. Br.) Stapf, and *Bracharia spp.* [7]. There are a few herbaceous dicots such as *Commelina africana* L., *Portulaca olearaceae* L., *Solanum incanum* L. 1753, and *Ipomea obscura* (L.) Ker Gawl [7]. Ligneous species were not included in the pasture vegetation, because the most abundant species were also collected either as mixed browsed leaves (MBL), or individually as outlined below. Above-ground

BY of the herbaceous pasture vegetation was determined using enclosure cages to prevent livestock grazing and trampling. A wire mesh cage (0.5x0.5x0.5 m) was placed on the pasture of a randomly selected household per village, assuming the village pastures were homogenous. Hence, a total of eight cages were placed in the Lowlands, six in the Mid-slopes, and six in the Highlands. In August 2014, November 2014, February 2015, and May 2015 (i.e., coinciding with the middle of the four different seasons), the above-ground plant biomass within the cage was manually clipped at about 2.5 cm above the ground using a pair of scissors. All harvested plant material was packed into a pre-weighed paper bag, weighed (Citizen scale Model CTG6H, accuracy 0.1 g; Piscataway, New Jersey, USA), and the fresh weight recorded. Thereafter, the cage was placed back in the same location until the next sampling. A total of 75 samples of all the above-ground plant biomass material harvested were collected (i.e., 20 cages for each sampling less five tampered with by farmers or animals). Samples for each season were later pooled for all analyses on the basis of proximity of the villages to each other within the same zone (i.e., the Lowlands five samples, the Mid-slopes three samples, and the Highlands three samples) resulting in 44 pasture samples.

A total of 62 samples of supplement feedstuffs offered by farmers at the homestead (i.e., MBL, banana (*Musa ssp.*) leaves and pseudo stem, sweet potato (*Ipomoea batatas*) vines (SPV), sugarcane tops (*Saccharum officinarum*), Napier grass (*Pennisetum purpureum*), swamp reeds (*Cyperus papyrus*), maize (*Zea mays*) thinnings (MT), and rice (*Oryza sativa*) stover/husks) were collected in February 2014 (i.e., dry-season feedstuffs) and May 2015 (i.e., wet-season feedstuffs). Samples of the MBL (fed to cattle as ‘cut and carry’ during the dry season) mainly comprised leaves and twigs of *Lantana camara* L., *Terminalia brownie* Fresen*, Rhus natalensis* Bernh. ex Krauss, *Tithonia spp*., *Carissa edulis* Vahl*, Grewia bicolor* Juss., *Harrisonia*

abyssinica Oliv., *Aphania senegalensis* (Juss. ex Poir.) Radlk., *Thevetia peruviana* (Pers.) K. Schum., *Vepris nobilis* (Delile) Mziray, *Combretum molle* R. Br. ex G. Don, *Senna siamea* Lam., *Acacia spp*., *Crotalaria spp*., *Gliricidia spp*., *Grevillea spp*., and *Citrus limon* (L.) Burm. f. among others identified based on farmers' knowledge of common browsed species. At each household offering these leaves (mainly in the Mid-slopes and Lowlands), a twig of each from at least four trees or shrubs of each available species (about 30 cm long) was cut using a pair of scissors. The twigs were then cut into smaller pieces, pooled, and about 300 to 500 g of the sample were packed into a pre-weighed paper bag, weighed again (Citizen scale Model CTG6H, accuracy 0.1 g; Piscataway, New Jersey, USA), and the weight recorded. About 300 to 500 g of the leaves of *Mangifera indica* L. (MIL), and *Balanite aegyptiaca* (L.) Delile (BAL) were collected and analysed separately, because, according to farmer information and own observations, these tree species form a large part of the diets of ruminants, especially during the dry season. Banana leaves were collected following the normal practice used by farmers to harvest it (i.e., gathering the oldest green leaves). Leaves of four banana plants were cut where the leaf joins the petiole, chopped using a machete, pooled, and about 1 kg of the sample was packed into a pre-weighed paper bag, weighed again, and the weight recorded. About 20 cm length of banana pseudo stem was cut from at least four freshly cut plant stumps. These were then treated in the same way as the banana leaves. Sugarcane tops, SPV, Napier grass, swamp reeds, MT (composed of thin weak maize plants pulled out when weeding of maize farms), and rice husks/stover were sampled from heaps already on offer to the animals by first homogenizing the material and taking a representative sample. Feedstuffs were collected from all the households that used such feedstuffs and later the samples were sorted such that the same feed type collected in a geographical zone in a particular season were pooled together. Such pooling was done for all the analyses to give 46 samples, except for

apparent total tract organic matter digestibility (dOM) and ME determination where all the samples of a feed type were pooled together to give one sample per feedstuff, resulting in a total of twelve samples.

4.2.3 Chemical analyses and in vitro incubations

Samples were initially air-dried before transport and then oven-dried at 50°C to constant weight and ground to pass a 1-mm-sieve with a hammer mill (Model MF 10B, IKA Werke, Willmington, N.C., USA). Dry matter (DM) concentrations were determined by drying about 0.5 g sample in a forced-air oven at 105°C overnight. Concentrations of crude ash (CA) were determined by incineration at 550°C in a muffle furnace (Model N 11, Nabertherm, Bremen, Germany) and of ether extract (EE) by Soxhlet extraction (Tecator Soxtec System HT 1043 Extraction Unit, Foss, Tecator, Minnesota, USA). Nitrogen was analysed by Dumas combustion (Vario Max C/N Analyser, Elementar Analysensysteme GmbH, Hanau, Germany) and multiplied by 6.25 to give the CP concentration. Neutral and acid detergent fibre (NDF, ADF) concentrations were determined using an ANKOM^{200} Fibre Analyser (ANKOM Technology, Macedon, USA). Sodium sulphate was used in NDF analysis but without α-amylase [11]. Gross energy (GE) concentrations were determined by bomb calorimetry (C 7000 Isoperibolic, Janke & Kunkel IKA – Analysentechnik, Staufen, Germany). All the analyses were done in duplicate according to [12] and repeated when the standard deviation of the mean of both determinations was greater than 5% of the mean.

Cobalt, molybdenum, and selenium concentrations were determined by Inductively-Coupled Plasma-Mass spectrometry according to method 2.2.2.5 and iron, potassium, sodium, phosphorus, and sulphur concentrations by

Inductively-Coupled-Plasma-Optic-Emission spectrometry modified to pressure digestion was used according to method 2.2.2.6 [13].

In vitro incubations were done according to [14]. Rumen fluid was collected before the morning meal from two rumen-fistulated cows in late lactation fed on a diet made of (per kg; as-fed basis): maize silage (353 g), grass silage (199 g), grass hay (83 g), barley straw (15 g), a concentrate mixture (99 g) mainly composed of barley grain, maize grain, and rapeseed cake, rapeseed extract meal (51 g), and supplement water (200 g). Samples and hay standards of 200 mg were weighed in triplicate into 100 ml calibrated glass syringes. Six additional blank syringes were included in each run. Rumen fluid was mixed with a buffer solution prepared as described in [14] immediately before collecting of rumen liquor. Then, 30 ml of the inoculum was dispensed into each syringe and the initial volume recorded. Final volumes of the contents of the syringes were recorded after 24 hours. All samples were incubated for 24 hours, two times each on different days. If relative standard deviation of the results of both days was > 5%, the same sample was incubated on a third day. Mean net gas produced during fermentation of the substrate (in ml/200 mg sample DM) was calculated across the two days as the difference between the initial and the final volume of the syringe contents minus the gas production from the blank syringes corrected for day-to-day differences in the gas production from the hay standard. The dOM and ME concentrations were estimated according to [14] using the following equations:

$$dOM = 153.8 + 8.453GP + 0.595CP + 0.675CA; \quad \text{and}$$

$$ME = 2.2 + 0.1375GP + 0.0057CP + 0.0002859EE^2;$$

where dOM is the apparent total tract organic matter digestibility (g/kg organic matter (OM)), ME is the metabolizable energy concentration (MJ/kg DM), GP is the net gas production after 24 hours of incubation (ml/200 mg DM), CA is the crude ash, CP the crude protein, and EE the ether extract (all in g/kg DM).

Additionally, dOM of the pasture herbage was predicted using two equations from the literature that are based on the chemical composition of tropical grass species derived from *in vitro* estimations using [6]:

$$dOM = 139.5 + 0.83CP - 0.94\ NDF - 0.74ADF$$

(developed from tropical pasture herbage samples (n = 56) using *in vitro* rumen fluid-pepsin modified Tilley and Terry as reference methodology);

and [15]:

$$dOM = 1.22CP + 473.3$$

(developed from samples (n = 18) of six tropical grass species using *in vitro* pepsin-cellulase Tilley and Terry as reference methodology);

where dOM is the apparent total tract organic matter digestibility (g/kg OM), CP the crude protein, NDF the neutral detergent fibre, and ADF the acid detergent fibre (all in g/kg DM).

4.2.4 Statistical analyses

Statistical analysis was done using R3.2.5 (R statistical software; R Development Core Team) for descriptive statistics and one-way ANOVA. The following statistical model was used to analyse the differences in nutritional parameters between the zone and seasons:

$$Y_{ij} = \mu + S_i + s_j + Ss_{ij} + \varepsilon_{ij}\ ;$$

where Yij = response parameters; μ = overall mean; S_i = effect of the zone, i; s_j = effect of the season, j; Ss_{ij} = effect of the interaction between zone and season; and ε_{ij} = random effects.

Arithmetic means were compared using multiple comparison tests using Tukey HSD and differences declared at $p < 0.05$.

4.3 RESULTS

4.3.1 Nutritional quality and biomass yield of pasture herbage

Pasture herbage had the second highest CP concentrations (**Table 1**) and highest concentrations of phosphorus, sulphur, and molybdenum compared to the other feedstuffs analysed (**Table 2**). The ME concentrations of the pasture herbage were > 7 MJ/kg DM and the dOM was > 550 g/kg OM.

Methods used to estimate dOM yielded different results **(Figure 2**) with pronounced differences in both, absolute values and the ranking of feedstuffs according to their dOM.

Seasonal differences were observed for above-ground BY of the pasture herbage, concentrations of DM ($p < 0.05$; **Table 3**), NDF ($p < 0.01$), ADF ($p < 0.01$), and CP ($p < 0.001$), as well as dOM ($p < 0.05$). Similarly, the concentrations of potassium ($p < 0.01$, **Table 4**), phosphorus ($p < 0.001$), and sulphur ($p < 0.05$) in pasture herbage differed between seasons with lowest concentrations being observed in the long dry season.

There were significant differences between zones for BY ($p < 0.001$) and concentrations of CA, NDF, CP, and GE of the pasture herbage (for all parameters $p < 0.05$ except CP, $p < 0.01$, **Table 3**), with the Highlands having the highest BY (about 2.0 to 2.5 times the BY of the pasture herbage from the other zones) and CP concentrations (i.e., 1.2 to 1.3 times the CP of the pasture herbage from the other zones). Zonal differences were also observed in mineral concentrations for phosphorus ($p < 0.01$, **Table 4**), potassium and cobalt ($p < 0.05$), and sodium and molybdenum ($p < 0.001$). The pasture herbage in the Highlands had the highest potassium concentrations, whereas that found in Lowlands had the highest phosphorus, cobalt, sodium, and molybdenum concentrations.

Table 1. Nutrient concentrations, organic matter digestibility, and metabolizable energy concentrations of common feedstuffs fed to ruminants in Lower Nyando, Western Kenya, between February 2014 and May 2015 (Arithmetic mean ± one standard deviation)

Zone	Feedstuff	n	n*	DM	CA	NDF	ADF	CP	EE	dOM[1]	GE	ME[1]
				g/kg FM	g/kg DM					g/kg OM	MJ/kg DM	
Highlands	Napier grass	8	2	195 ± 34.8	168 ± 39.4	653 ± 19.5	376 ± 14.1	83 ± 13.1	7.0	587	14.5 ± 0.21	7.0
	Banana pseudo stem	10	2	85 ± 58.2	111 ± 24.4	655 ± 49.3	382 ± 56.4	32 ± 6.6	8.0	544	15.3 ± 0.36	7.1
	SPV	3	2	259 ± 109.0	85 ± 11.2	407 ± 31.1	278 ± 13.6	101 ± 11.0	19.0	650	16.8 ± 0.09	8.9
	Banana leaves	5	1	142 ± 26.0	159 ± 7.5	562 ± 10.1	350 ± 19.6	105 ± 18.0	45.0	416	17.2	4.3
	MT	1	1	301	137	685	372	95	16.0	576	15.1	7.1
Mid-slopes	Sugarcane tops	4	3	642 ± 373.9	52 ± 4.7	741 ± 29.4	395 ± 21.4	38 ± 6.1	6.0	430	17.2 ± 0.46	5.9
	Swamp reeds	2	1	460 ± 321.0	56 ± 7.2	714 ± 27.5	353 ± 14.2	41 ± 7.2	6.0	430	15.6	5.9
Lowlands	BAL	2	1	475 ± 118.4	66 ± 7.4	594 ± 13.3	396 ± 12.7	82 ± 8.6	8.0	425	18.5	5.5
	Rice stover	1	1	912	159	640	365	46	nd	nd	nd	nd
	Rice husks	1	1	845	45	709	371	35	nd	nd	nd	nd
	MIL	1	1	475	152	367	273	60	24.0	435	16.0	4.8
All zones	Pasture herbage	75	12	328 ± 174.1	104 ± 16.4	626 ± 33.6	321 ± 30.3	111 ± 25.7	12.0 ± 1.90	554 ± 30.0	16.6 ± 0.35	7.1 ± 0.42
	MBL	22	6	377 ± 118.6	69 ± 22.7	371 ± 39.5	255 ± 27.2	140 ± 25.9	22.0	530	18.8 ± 0.56	7.0

ADF = acid detergent fibre; BAL = *Balanite aegyptiaca* leaves; CA = crude ash; CP = crude protein; DM = dry matter; dOM = apparent total tract organic matter digestibility; EE = ether extract; FM = fresh matter; GE = gross energy; ME = metabolizable energy; MBL = mixed browsed leaves; MIL = *Mangifera indica* leaves; MT = maize thinnings; n = original number of samples; n* = number of pooled samples (samples collected in the same zone and during the same season were pooled to give one pool sample for analysis); nd = not determined; NDF = neutral detergent fibre; OM = organic matter; SPV = sweet potato vines. [1]As estimated from *in vitro* gas production and proximate nutrient concentrations using equations of [14]

Table 2. Mineral concentrations of common feedstuffs fed to ruminants collected on native pastures in Lower Nyando, Western Kenya, between February 2014 and May 2015 (Arithmetic mean ± one standard deviation)

Zone	Feedstuff	n	n*	P	K	Na	S	Fe	Co	Mo	Se
				g/kg DM				mg/kg DM			
Highlands	Napier grass	8	2	1.5 ± 0.61	42.3 ± 5.09	0.03 ± 0.01	1.1 ± 0.32	1588 ± 1796	0.4 ± 0.38	0.9 ± 0.53	0.2 ± 0.01
	Banana pseudo stem	10	2	0.6 ± 0.19	54.2 ± 4.89	0.03 ± 0.00	0.4 ± 0.06	622 ± 240	0.2 ± 0.13	1.0 ± 0.50	0.1 ± 0.05
	SPV	3	2	2.2 ± 0.99	34.1 ± 2.40	0.04 ± 0.00	1.5 ± 0.26	1142 ± 1030	0.4 ± 0.08	0.4 ± 0.31	0.1 ± 0.01
	Banana leaves	5	1	1.3	24.3	0.01	1.5	375	0.1	0.7	0.2
	MT	1	1	1.8	19.1	0.03	1.2	1825	0.7	0.4	0.1
Mid-slopes	Sugarcane tops	4	3	0.9 ± 0.17	12.3 ± 5.32	0.02 ± 0.02	0.7 ± 0.13	144 ± 50	0.1 ± 0.04	0.8 ± 0.72	0.1 ± 0.01
	Swamp reeds	2	1	1.0	11.1	0.05	1.0	282	0.1	1.8	0.1
Lowlands	BAL	2	1	0.8	17.1	0.11	2.0	255	0.1	0.1	0.2
	Rice stover	1	1	1.3	23.4	0.47	1.0	531	0.6	0.9	0.1
	Rice husks	1	1	0.9	15.9	0.02	0.8	149	0.04	0.3	0.1
	MIL	1	1	0.8	7.0	0.06	1.3	136	0.1	1.1	0.5
All zones	Pasture herbage	75	12	2.9 ± 0.85	26.5 ± 6.41	0.10 ± 0.07	2.2 ± 0.40	769 ± 362	0.3 ± 0.12	2.9 ± 1.43	0.1 ± 0.03
	MBL	22	6	1.8 ± 0.37	20.0 ± 2.28	0.03 ± 0.02	1.9 ± 0.44	297 ± 255	0.2 ± 0.11	0.9 ± 0.45	0.2 ± 0.35

BAL = *Balanite aegyptiaca* leaves; Co = cobalt; DM = dry matter; Fe = iron; K = potassium; MIL = *Mangifera indica* leaves; MBL = mixed browsed leaves; Mo = molybdenum; MT = maize thinnings; Na = sodium; P = phosphorus; Se = selenium; SPV = sweet potato vines; S = sulphur; n = original number of samples; n* = number of pooled samples (samples collected in the same zone and during the same season were pooled to give one pool sample for analysis).

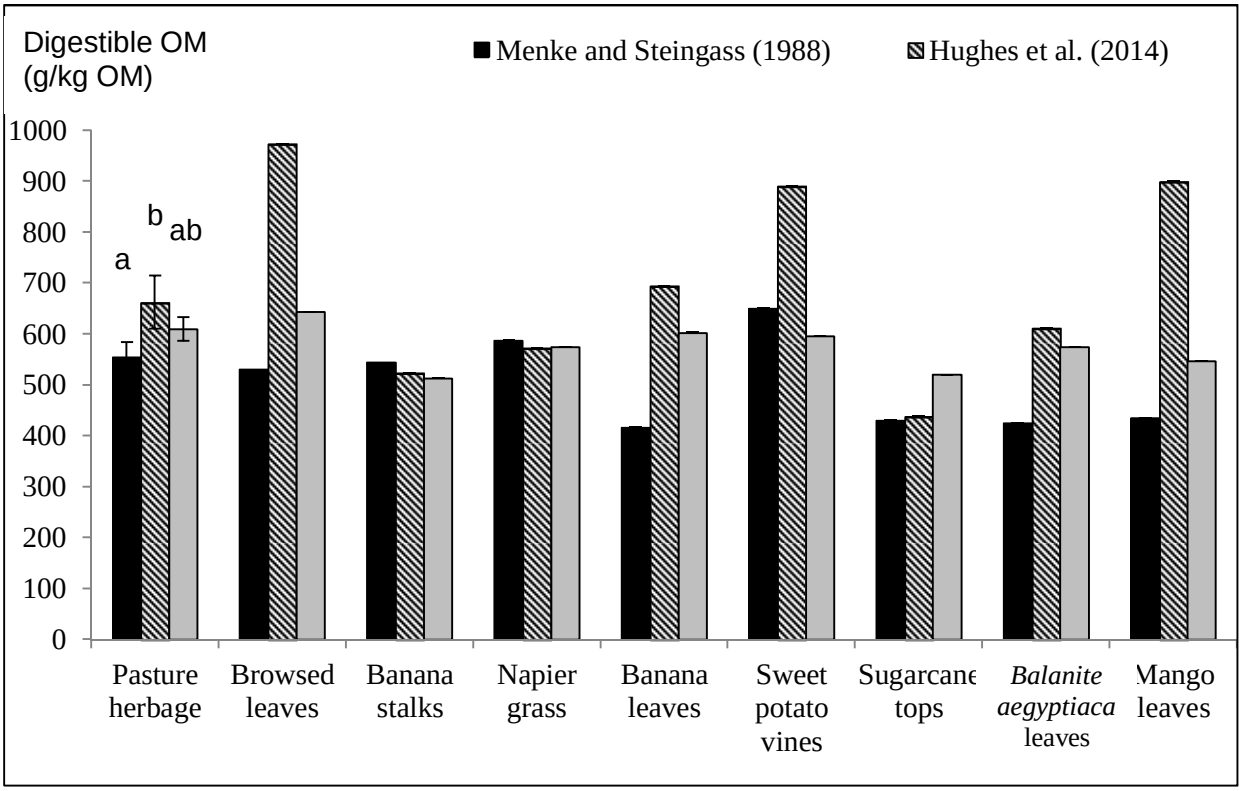

Figure 2. Comparison of apparent total tract organic matter digestibility as estimated from *in vitro* gas production [14] or proximate nutrient and fibre fraction concentrations [6,15] in feedstuffs collected (n = 12 for pasture herbage, and n = 1 each for the rest of the feedstuffs) in Lower Nyando, Western Kenya, during February 2014 and May 2015.

OM = organic matter. The error bars represent one standard deviation about the mean. Different letters on error bar imply significant differences ($p < 0.05$).

4.3.2 Availability and nutritional quality of supplement feedstuffs across zones

The MBL had the highest CP and lowest fibre concentrations compared to other supplementary feedstuffs with the exception of MIL, which had lower NDF concentrations. However, mineral concentrations in MBL were similar to other supplementary feedstuffs. There were fewer supplement feedstuffs on offer in the Mid-slopes and Lowlands than in the Highlands,

and they were of poorer nutritional quality (3.5 - 8.2 g CP/100 g DM, dOM < 430 g/kg OM, and ME < 5.9 MJ/kg DM; **Table 1**) and only available in the long dry season. The concentrations of phosphorus, potassium, iron, and cobalt (**Table 2**) were highest in supplement feedstuffs in the Highlands. However, feedstuffs in the Mid-slopes had the highest molybdenum concentrations, whereas those of the Lowlands had the highest sodium and sulphur concentrations.

Table 3. Nutritional value of the above-ground herbaceous biomass on native pastures in Lower Nyando, Western Kenya, as determined for different zones and seasons during August 2014 to May 2015 (Arithmetic mean ± one standard deviation)

Season/ Zone	n	BY	DM	CA	NDF	ADF	CP	EE	dOM[1]	GE	ME[1]
		t DM/ha	g/kg FM	g/kg DM	g/kg OM	MJ/kg DM					
Season											
Short dry	4	2.0^{ab} ± 1.03	204^{a} ± 61.4	106^{a} ± 9.9	614^{ab} ± 15.4	308^{a} ± 13.1	123^{a} ± 13.1	14^{a} ± 1.8	572^{ab} ± 8.9	16.5^{a} ± 0.23	7.3^{a} ± 0.23
Short wet	4	3.4^{bc} ± 2.99	350^{ab} ± 125.9	107^{a} ± 12.2	608^{a} ± 25.0	303^{a} ± 16.1	130^{a} ± 21.8	13^{a} ± 1.8	581^{a} ± 28.4	16.4^{a} ± 0.34	7.4^{a} ± 0.53
Long dry	4	1.4^{a} ± 0.65	546^{b} ± 154.5	95^{a} ± 23.6	634^{ab} ± 44.2	315^{a} ± 29.7	98^{b} ± 21.1	10^{a} ± 1.6	540^{ab} ± 21.6	16.8^{a} ± 0.37	7.0^{a} ± 0.17
Long wet	4	4.3^{cd} ± 1.61	211^{a} ± 42.0	108^{a} ± 15.6	647^{b} ± 31.1	360^{b} ± 20.2	95^{b} ± 27.6	12^{a} ± 1.7	523^{b} ± 15.7	16.5^{a} ± 0.46	6.7^{a} ± 0.27
SEM		0.57	72.3	6.9	9.0	9.2	4.1	1.0	4.8	0.19	0.23
p[2]		0.002	0.011	0.286	0.009	0.002	< 0.001	0.077	0.024	0.227	0.057
Zone											
Lowlands	3	1.9^{a} ± 1.20	315^{a} ± 189.0	113^{a} ± 15.7	615^{a} ± 32.9	321^{a} ± 30.2	103^{a} ± 22.8	13^{a} ± 1.4	565^{a} ± 23.2	16.3^{a} ± 0.27	7.2^{a} ± 0.35
Mid-slopes	3	2.3^{a} ± 1.24	363^{a} ± 184.3	92^{b} ± 11.9	639^{b} ± 34.3	328^{a} ± 35.2	109^{a} ± 21.5	12^{a} ± 2.5	557^{a} ± 41.3	16.9^{b} ± 0.22	7.3^{a} ± 0.51
Highlands	3	4.7^{b} ± 2.74	314^{a} ± 144.9	102^{ab} ± 11.3	632^{ab} ± 30.3	316^{a} ± 26.6	129^{b} ± 27.2	11^{a} ± 0.7	540^{a} ± 24.4	16.5^{ab} ± 0.32	6.8^{a} ± 0.34
SEM		0.52	62.6	5.9	7.8	7.9	3.6	0.9	12.8	0.17	0.20
p[2]		< 0.001	0.687	0.025	0.024	0.259	0.001	0.054	0.230	0.035	0.156

ADF = acid detergent fibre; BY = above-ground biomass yield of the pasture herbage; CA = crude ash; CP = crude protein; DM = dry matter; dOM = apparent total tract organic matter digestibility; EE = ether extract; FM = fresh matter; GE = gross energy; ME = metabolizable energy; NDF = neutral detergent fibre; OM = organic matter; n = number of pooled samples (samples collected in the same zone and during the same season were pooled to give one pool sample for analysis); SEM = standard error of mean. Superscripts in the same column with different letters denote significant differences between seasons or zones ($p < 0.05$). [1]As estimated from *in vitro* gas production and proximate nutrient concentrations using equations of [14]. [2] Season x zone interactions were not significant.

Table 4. Mineral concentrations of herbaceous vegetation collected on native pastures in Lower Nyando, Western Kenya, as determined for different zones and seasons during August 2014 to May 2015 (Arithmetic mean ± one standard deviation)

Season/ Zone	n	P	K	Na	S	Fe	Co	Mo	Se
		g/kg DM				mg/kg DM			
Season									
Short dry	4	$3.5^{a} \pm 0.49$	$28.8^{a} \pm 3.46$	$0.1^{a} \pm 0.08$	$2.5^{a} \pm 0.07$	$802^{a} \pm 198$	$0.3^{a} \pm 0.04$	$3.1^{a} \pm 1.57$	$0.1^{a} \pm 0.01$
Short wet	4	$3.5^{a} \pm 0.31$	$28.6^{a} \pm 4.36$	$0.1^{a} \pm 0.07$	$2.6^{a} \pm 0.26$	$877^{a} \pm 597$	$0.3^{a} \pm 0.16$	$3.1^{a} \pm 1.77$	$0.1^{a} \pm 0.01$
Long dry	4	$1.7^{b} \pm 0.30$	$17.8^{b} \pm 1.56$	$0.1^{a} \pm 0.11$	$1.7^{b} \pm 0.06$	$987^{a} \pm 174$	$0.4^{a} \pm 0.17$	$2.1^{a} \pm 0.86$	$0.1^{a} \pm 0.02$
Long wet	4	$2.9^{ab} \pm 0.70$	$30.9^{a} \pm 5.93$	$0.1^{a} \pm 0.06$	$2.1^{ab} \pm 0.40$	$410^{a} \pm 106$	$0.2^{a} \pm 0.10$	$3.1^{a} \pm 1.96$	$0.1^{a} \pm 0.06$
SEM		0.15	1.81	0.02	0.19	235	0.07	0.40	0.03
p^{1}		< 0.001	0.002	0.935	0.021	0.191	0.190	0.148	0.736
Zone									
Lowlands	3	$3.3^{a} \pm 0.86$	$25.7^{ab} \pm 6.15$	$0.2^{a} \pm 0.03$	$2.2^{a} \pm 0.29$	$950^{a} \pm 453$	$0.4^{a} \pm 0.12$	$4.6^{a} \pm 1.08$	$0.1^{a} \pm 0.05$
Mid-slopes	3	$2.4^{b} \pm 0.78$	$23.4^{b} \pm 4.72$	$0.1^{b} \pm 0.01$	$2.1^{a} \pm 0.53$	$550^{a} \pm 278$	$0.2^{b} \pm 0.09$	$2.4^{ab} \pm 0.21$	$0.1^{a} \pm 0.02$
Highlands	3	$3.0^{a} \pm 0.86$	$30.5^{a} \pm 7.45$	$0.1^{b} \pm 0.02$	$2.3^{a} \pm 0.46$	$807^{a} \pm 298$	$0.2^{ab} \pm 0.06$	$1.7^{b} \pm 0.27$	$0.1^{a} \pm 0.01$
SEM		0.13	1.57	0.02	0.17	203	0.06	0.35	0.02
p^{1}		0.002	0.013	< 0.001	0.538	0.244	0.034	< 0.001	0.480

Co = cobalt; DM = dry matter; Fe = iron; K = potassium; Mo = molybdenum; n = number of pooled samples (samples collected in same zone and during the same season were pooled to give one pool sample for analysis); Na = sodium; P = phosphorus; S = sulphur; Se = selenium; SEM = standard error of mean.

Superscripts in the same column with different letters denote significant differences between seasons or zones ($p < 0.05$). [1]Season x zone interactions were not significant.

4.4 DISCUSSION

4.4.1 Nutritional quality and biomass yield of pasture herbage

The nutritional quality of pasture herbage was higher than of the supplement feedstuffs in the current study and the herbaceous pasture vegetation in Tanzanian rangelands [16]. Mean CP concentration of the pasture herbage was 35% higher than that found in the rangeland vegetation of tropical highlands in Ethiopia [17], and was above the minimum threshold of 70 g/kg DM required for rumen microbial growth and activity. The NDF and ADF concentrations of the pasture herbage were 10 to 31% lower than those reported from East Africa [17,18], whereas phosphorus, sulphur, and molybdenum concentrations of pasture herbage were within the range reported in [16] and about 2 to 8 times higher than those of the supplement feedstuffs analysed in the current study. These mineral concentrations in pasture herbage were adequate for cattle requirements provided that daily feed intake is adequate [19]. Such differences in nutritional value of the herbaceous vegetation on African rangelands could be due to, amongst other factors, differences in climate, soil fertility, species composition, and stage of maturity [20].

Differences in dOM of the feedstuffs in the present study when estimated form *in vitro* gas production and proximate nutrient concentrations or from concentrations of proximate nutrient and fibre fractions could be due to differences in the chemical composition and nutrient degradability of the feedstuffs used to derive the respective equations. For instance, the extraordinarily high dOM estimates from the equation of [6] for feedstuffs with low ADF concentrations (< 280 g/kg DM) in the present compared to the pasture herbage may be related to the fact that the equation was developed in herbages rich in ADF (about 422 ± standard deviation of 39.7 g/kg DM). Values derived from the equation of [15] showed small differences in dOM

between feedstuffs, possibly because CP, which was the only independent variable of the equation, may not contribute much on its own to the overall dOM of the analysed feedstuffs. Although both equations based on concentrations of proximate nutrients or fibre fractions were derived for tropical ruminant feedstuffs, neither of them was developed based on *in vivo* data. The *in vitro* gas production equation proposed by [14] to estimate dOM of feedstuffs, has been derived from *in vivo* data of a broad range of feedstuffs which, although not tropical, covered the range of nutritional quality of the pasture herbage reported here (n = 185; *in vivo* dOM range of 293 – 800 g/kg OM). Hence, although accuracy of the dOM and ME estimates cannot be quantified here, because respective *in vivo* data is lacking, those derived from *in vitro* gas production appear to be more robust. Nevertheless, results imply that there is a need to validate or develop new equations based on *in vivo* data for estimating dOM and ME of tropical ruminant feedstuffs. Mean dOM and ME concentrations derived from *in vitro* gas production of 554 g/kg OM and 7.1 MJ/kg DM were comparable to some cultivated temperate grass hays [20], and even higher than those of the Napier grass analysed in the current study, supporting the assertion that the pasture herbage was of moderate to good quality. The relatively low nutritional quality of Napier grass in the present study may be due to the fact that farmers in the study region tend to harvest plants at a very mature stage to achieve higher BY.

4.4.2 Temporal differences in biomass yield and nutritional quality of pasture herbage

Seasonal differences in BY, concentrations of DM, NDF, ADF, and CP, and dOM were observed for the pasture vegetation, which may be related to differences in plant growth rates and stage of plant maturity. It is important to note that there were only minor differences in precipitation (CV = 3 – 17%) and

ambient temperatures (CV = 3 – 4%) between seasons (**Figure 1**) with the exception of the rainfall in long dry (driest period, 96 – 117 mm per month) and the long wet seasons (wettest period, 141 – 186 mm per month) for which also the most pronounced differences in vegetation parameters were found. Across all zones, the BY was highest in the long wet season (i.e., 1.3 – 3.0 times higher than in other seasons). However, surprisingly, concentrations of NDF and ADF were highest and CP concentrations and dOM lowest in the long wet season. That may have been, at least partly, due to rapid growth and accumulation of biomass, aided by high rainfall at the beginning of the long wet season, which was not consumed by the animals due to use of enclosure, resulting in lower quality herbage at harvest during mid-season.

Seasonal changes in mineral concentrations of the herbaceous vegetation of native tropical pastures are related to a translocation of minerals to seeds or the root system and/or a dilution process during plant growth with advancing plant maturity [21]. An adult dry non-pregnant cow in Lower Nyando has a mean liveweight of 206 kg with a mean daily gain of approximately 50 g/d. The daily ME requirements for maintenance and liveweight gain of such an animal would be approximately 35 MJ [22]. Given the ME concentrations of the pasture herbage in the long wet and long dry seasons (**Table 3**), cows would need to consume 5.4 kg DM/d and 4.9 kg DM/d of pasture during the long wet and long dry season, respectively, to meet these requirements. The DM intake would provide approximately 16 g/d and 8 g/d of phosphorus in the long wet and long dry seasons, respectively, based on the mean phosphorus concentrations in the pasture vegetation of 0.29 g and 0.17 g/100 g DM in both seasons (**Table 4**). This would exceed the daily phosphorus requirements defined by [19] of 10 g/d phosphorus in the long wet season, but is below the recommendations during the long dry season. In contrast to previous reports of mineral deficiencies in the Rift Valley of Kenya [5], concentrations of other

macro- and micro-minerals seem sufficient to meet the requirements defined by [19] of cattle at moderate to low performance levels even during the long dry season. Such evaluations based on mineral concentrations do not take into account that not all of the minerals contained in the feedstuffs are bioavailable and further studies should analyse the bioavailability of minerals from pasture herbage in tropical grasslands to evaluate its potential contribution to meeting the animals' mineral requirements. Nevertheless, results suggest a need for supplemental feeding in particular in the long dry season to prevent mineral deficiencies which may considerably reduce animal health and performance.

4.4.3 Spatial differences in biomass yield and nutritional quality of pasture herbage

Across the four seasons, the differences between zones in BY and concentrations of CA, CP, and NDF of the pasture vegetation were likely due to differences in rainfall and ambient temperature and livestock husbandry (e.g., in the Highlands cattle graze in paddocks, while in the Lowlands they are tethered or herded). For instance, the Highlands are characterized by the highest rainfall of the three zones (**Figure 1**), promoting plant growth and BY on pastures and likely increasing leaf: stem ratios in plant biomass associated with higher CP concentrations in total above-ground plant biomass [23], which may explain the higher CP concentrations in samples of the pasture vegetation in the Highlands in the current study. The N contents in the soils are 2.1 times higher in the Highlands than in the Lowlands and 1.2 times higher than in the Mid-slopes [24]. Along with the higher BY, the higher CP concentrations indicate that carrying capacity of the pastures in the Highlands may be greater than of those in the other two zones.

Pasture herbage in the Lowlands had the highest concentrations of phosphorus, sodium, iron, cobalt, and molybdenum. In contrast, the herbage in the Mid-slopes had the lowest concentrations of phosphorus, potassium, sodium, and cobalt. Site differences could possibly be due to erosion of soils with minerals in particular in the Mid-slopes leading to deposition in the Lowlands. Another reason for difference in mineral concentrations between zones may be the fact that the clay soils in the Lowlands are poorly drained. Water logging in the Lowlands may limit the availability of some minerals such as potassium whose uptake in water logged soils may be inhibited by a decrease in root cell energy caused by oxygen deficiency within the soil pore spaces [25]. Irrespective of the zonal differences in mineral concentrations, with the exception of phosphorus and sodium, mean concentrations of all minerals in the pasture herbage across all seasons were within the range or above those recommended by [19] for diets of cattle.

4.4.4 Availability and nutritional quality of supplement feedstuffs in the zones

The common supplement found in all the zones is MBL that was rich in CP likely due to the inclusion of leaves of leguminous shrub and tree species such as *Acacia spp., Sesbania spp.*, and *Calliandra spp.* in plant samples. Additionally, ADF and NDF concentrations of MBL were lower and thus dOM higher than values determined in previous studies [18]. The mineral concentrations in MBL were also higher than most of the other supplement feedstuffs analysed in the current study or published for browse leaves in the literature. For instance, the concentrations of phosphorus were marginally higher than those determined by [26] for leaves and twigs of native shrubs and trees in semi-arid, sub-tropical highland regions of Oman. The CP and selenium concentrations in MBL were much higher than in pasture herbage

across all the zones and seasons, while both had about the same dOM and ME concentrations. Assuming there were no limiting effects of anti-nutritional factors, MBL can thus be used as CP and selenium supplement to pasture herbage in all the zones. Nevertheless, further studies should be carried out on the anti-nutritional factors in MBL so as to evaluate its suitability as a supplement feedstuff.

The main supplement feedstuffs used in the Mid-slopes and the Lowlands during the long dry season, when pasture herbage is scarce, are sugarcane tops and purchased rice husks and straw. Additionally, BAL, and as a last resort, MIL are fed to ruminant livestock in the Lowlands. The availability of BAL and MIL is limited; thus, for instance, the use of MIL to supplement selenium which it has in high concentrations may not be feasible. The use of sugarcane tops and rice straw as nutrient supplement to grazing cattle is limited by their low dOM values. Hence, feed and feeding management strategies such as a physical, chemical, or biological treatment of crop residues or the strategic supplementation with purchased concentrate feedstuffs might be viable options for livestock farmers in these systems to increase feed intake and nutrient supply in domestic ruminant livestock during the dry season.

In the Highlands, a broader range of supplement feedstuffs was available. Feedstuffs such as MT are only occasionally used and thus of less relevance[27]. Banana leaves and pseudo stem and Napier grass are available all year round as supplement feedstuffs and commonly fed to dairy cattle. The CP, NDF, and ADF concentrations of Napier grass were similar to reported values [28]. Despite lower CP concentrations, Napier grass makes a good supplement in addition to grazing of pastures given that it’s dOM and ME values were higher than those of the pasture herbage. Additionally, Napier grass had higher concentrations of cobalt and selenium. Napier grass quality

could however, be even further improved by identifying optimum cutting frequency and height, and increased manure application [28]. Additionally, SPV is abundant in the Highlands at the beginning of the long dry season following its harvest after the short cropping season. The CP concentration of SPV was higher and the NDF and ADF concentrations were lower than in most supplement feedstuffs analysed in the present study, resulting in highest dOM amongst all the feedstuffs. The leaf BY of SPV has been reported to range between 0.9 t to as much as 2.8 t DM/ha in different agro-ecological zones of Kenya [29]. Moreover, the higher concentrations of CP and cobalt in SPV compared to the pasture vegetation imply that, if properly managed and conserved, SPV can be used as CP and cobalt supplement in addition to grazing the native pastures, particularly during the long dry season.

The high potassium concentrations in the supplement feedstuffs are consistent with reports of potassium abundance in other tropical feedstuffs [30], as is the case of low sodium concentrations in tropical forages due to low sodium levels in tropical soils. Generally, the iron and selenium concentrations were higher than those previously reported from East Africa [30]. The existing supplement feedstuffs in all zones had lower concentrations of phosphorus, sodium, sulphur, and molybdenum compared to the pasture vegetation. Hence, they cannot compensate for the phosphorus and sodium deficiencies noted in pasture vegetation.

The observed differences in BY and nutritional quality of the pasture vegetation between zones, and the local availability of supplement feedstuffs need zone-specific feeding strategies. The Highlands are more suitable for dairy farming than the other two zones due to high BY of the herbaceous pasture vegetation and the better nutritional quality of the supplement feedstuffs. There is however, a potential for intensification in the Mid-slopes

and the Lowlands, for example by increasing the variety of feed resources, improving forage husbandry, and processing of crop residues.

CONCLUSION

In Western Kenya, pasture herbage is of superior nutritive value than commonly available supplement feedstuffs. The highland regions are more suited to animal production due to higher herbaceous BY on native pastures and greater diversity of available supplement feedstuffs. There is need for supplemental feeding in the long dry season and locally available feedstuffs may at least partially compensate for nutritional deficiencies in the pasture vegetation. However, together with the lack of valid approaches to estimate dOM and ME of tropical ruminant feedstuffs, the spatial and temporal variability in the nutritional value of feedstuffs for domestic ruminants shows need for considerable safety margins in diet formulation and for region- and season-specific solutions to improve animal nutrition and performance.

CONFLICT OF INTEREST

We declare that there is no conflict of interest regarding the material discussed in the manuscript.

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5. A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – results for Nyando, Western Kenya[4]

Abstract

In Africa, the agricultural sector is the largest sector of the domestic economy, and livestock, are a crucial component of agriculture, accounting for ~45% of the Kenyan agricultural GDP and > 70% of African agricultural greenhouse gas (GHG) emissions. Accurate estimates of GHG emissions from livestock are required for inventory purposes and to assess the efficacy of mitigation measures, but most estimates rely on TIER I (default) IPCC protocols with major uncertainties coming from the IPCC methodology itself. Tier II estimates represent a significant improvement over the default methodology, however in less developed economies the required information is lacking or of uncertain reliability. In this study we developed an alternative methodology based on animal energy requirements derived from field measurements of live weight, live weight change, milk production and locomotion to estimate intake. Using on-farm data, we analysed feed samples to produce estimates of digestibility by season and region, then and used these data to estimate daily methane production by season, area and class of animal to produce new emission factors (EF) for annual enteric CH_4 production. Mean Dry Matter Digestibility of the feed basket was in the range of 58-64%, depending on the region and season (around 10% greater than TIER I estimates). EFs were substantially

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lower for adolescent and adult male (30.1, 35.9 versus 49 kg CH_4) and for adolescent and adult female (23.0, 28.3 versus 41 kg), but not calves (15.7 versus 16 kg) than those given for “other” cattle in IPCC (Tier I) estimates. It is stressed that this study is the first of its kind for Sub-Saharan Africa relying on animal measurements, but should not automatically be extrapolated outside of its geographic range. It does however, point out the need for further measurements, and highlights the value of using a robust methodology which does not rely on the (often invalid) assumption of *ad libitum* intake in systems where intake is known or likely to be restricted.

Key words

Enteric methane, ruminant, cattle, GHG inventory, East Africa

5.1 Introduction

In Africa, the agricultural sector is the largest sector of the domestic economy, employing between 70% and 90% of the total labour force (AGRA, 2017).

Livestock, whether based on pastoralism or as part of mixed cropping/livestock systems, are a crucial component of agriculture and it was estimated that livestock contributes to about 45% to the Kenyan agricultural gross domestic product (ICPALD, 2013). The impact of livestock on the environment in Africa is high and it is estimated that > 70% of African agricultural greenhouse gas (GHG) emissions are due to livestock production, dominated by CH_4 emissions from enteric fermentation (Tubiello et al., 2014; http://www.fao.org/faostat/en/#data/GT). Whilst an accurate picture of GHG emissions from livestock is required for inventory purposes, there is also a pressing need to ensure that estimates of livestock GHG emissions reflect the actual case both for national reporting and development and monitoring, reporting and verification (MRV) of nationally determined contributions (NDC)

on mitigation of GHG emissions from the livestock sector (Bodansky *et al.*, 2016).

There are extant studies which comprehensively model ruminant livestock emissions using a digestion and metabolism model (RUMINANT), spatially explicit data on livestock numbers and generalized assumptions on regional feed availability and digestibility (Herrero *et al.*, 2008; Thornton and Herrero, 2010; Herrero *et al.*, 2013). Other studies (Tubiello *et al.*, 2014) rely on TIER I IPCC protocols (Dong *et al.*, 2006) with major uncertainties coming from the IPCC methodology itself. One area of uncertainty is the accuracy of livestock census data used to model animal population densities and overall emissions – currently (as at 2016) FAO use 2005 data for estimating cattle populations. This of course can be addressed by the provision of more current (and accurate) census data. A more problematic area of uncertainty is the representativeness of ruminant CH_4 emission factors (EF) themselves. TIER I estimates (the most basic level) use IPCC mandated values based on a variety of published literature that report measured ruminant CH_4 emissions scaled to a year as kg CH_4 per head – studies which have almost exclusively been carried out in ruminant production systems in advanced, Western countries. These estimates are then “adjusted” for developing economy systems, on the basis of expert opinion. To date, little empirical data has been presented to corroborate or challenge these estimates for African livestock systems.

Tier II estimates represent a significant improvement over the TIER I default methodology, as country specific livestock data (on e.g.: live weight (LW), feed and activity) are used to refine EFs. Recently completed studies in South Africa (Du Toit *et al.*, 2013; Du Toit *et al.*, 2014b) and Benin (Kouazounde *et al.*, 2015) have highlighted substantial discrepancies between TIER I and TIER II emission estimates in African livestock systems.

However, there are a number of issues that occur when directly applying TIER II methodology to African smallholder livestock systems. Tier II methodology relies on estimates of enteric CH_4 production based on feed intake and diet quality, with putative intake being derived from energy expenditure estimates. Energy expenditure in turn, is based on metabolic processes (maintenance, growth, lactation, locomotion). There are (at least) two significant issues with applying this model in the context of smallholder agriculture. Firstly, the premise of estimating intake based on diet quality is grounded in the assumption of unrestricted or *ad libitum* intake. In smallholder farms, animals are typically held in kraals or bomas overnight and this practice has been demonstrated to restrict voluntary intake (Nicholson, 1987; Ayantunde *et al.*, 2008). Secondly, in estimating the Metabolizable Energy Requirement (MER) for growth, animals are assumed to grow at a steady, constant rate throughout the year. In practice ruminants on rain-fed tropical pasture will lose weight for part of the year due to feed shortage e.g. in dry seasons (Norman, 1965) and grow at higher than average rates for the balance in wet seasons with ample available feed. Because ruminants use mobilized body tissue with a higher efficiency than ingested feed (CSIRO, 2007), this has important implications for the estimation of intake throughout the year.

Considering the potential impact of the above on estimates of intake and thus enteric CH_4 emissions, we purposed to measure LW and seasonal LW flux as well as milk yield and locomotion of cattle and feed availability and its nutritional quality in a smallholder livestock system in the Nyando area of Western Kenya to allow us to provide better estimates of enteric CH_4 emissions of cattle in smallholder systems using a Tier II approach.

We hypothesized that considering seasonal changes in feed availability and nutritional quality as well as animal performance (i.e.: by the addition of in-situ measurements) would result in marked improvement in the accuracy of

calculated livestock emissions as compared to the standard IPCC Tier 1 approach.

5.2 Materials and methods

5.2.1 Study area

The study area, a 10 by 10 km^2 block in the Nyando Basin of Western Kenya (0°13'30''S - 0°24'0''S, 34°54'0''E – 35°4'30''E), was selected by the Climate Change Agriculture and Food Security (CCAFS) program of Consultative Group on International Agricultural Research (CGIAR) institutes, as a primary study site in the East African highlands (Fig. 1). The site is named Lower Nyando and has been described in detail by Verchot et al. (2008). Details on the sampling frame and region of study are available at: http://www.ccafs.cgiar.org/resources/baseline-surveys.

Briefly, a longitudinal survey was carried out in 60 households within a total of 20 villages located in the three dominant landscape positions (the Lowlands, the Slopes, and the Highlands). Proportional probability sampling based on the clusters yielded 24 farm(er)s in the Lowlands, 18 in the Slopes, and 18 in the Highlands to give a total sample of 60 households. The landscape positions were heterogeneous with regards to climate, soil type, vegetation, and livestock management, but mixed crop/livestock systems predominate. Climate is humid to sub-humid, with annual rainfall of 1200 – 1725 mm in a bi-modal pattern, allowing for two cropping seasons a year. There are four marked seasons classified as long dry season (January – March), long wet season (April – June), short dry season (July – September), and the short wet season (October – December) (Zhou *et al.*, 2007).

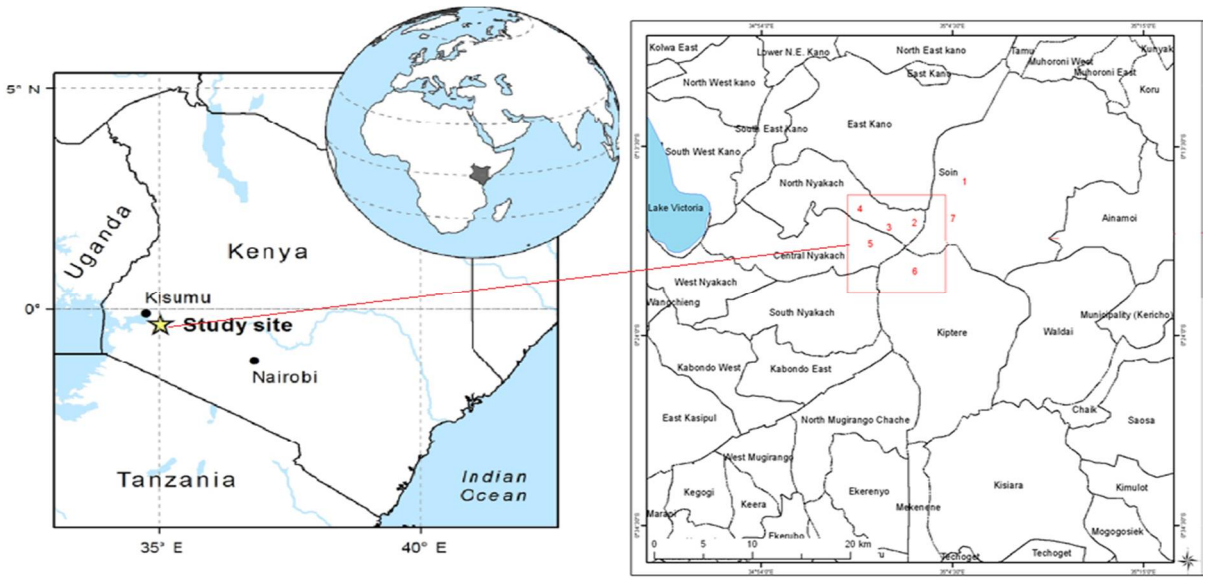

Fig. 1. Study area - Lower Nyando, Western Kenya. Left map shows country and region position. Right map shows the administrative boundaries in the study area and numbers indicate the location of villages included in the livestock emission survey.

Pastures in the Nyando region comprise mainly grasses such as *Digitaria gazensis*, *D. ciliaris, Eragrostis superba.*, *E. aspera*, *Hyparrhenia collina*, *Cynodon dactylon*, *Cappillipedium parviflorum* and *Bracharia spp.* (Verchot et al., 2008). Pasture, both in smallholder farms and communal areas tends to be subject to continuous year-round grazing.

The cattle population comprised East African shorthorn zebus and numerous indeterminate zebu x *Bos taurus* crosses. Herd size ranged from 1 to 19 cattle per smallholding.

5.2.2 Animals and animal performance data

Data was collected at approximately three month intervals from July 2014 to July 2015, to approximately coincide with the four sub-seasons observed in the study area. All cattle in each selected smallholding were identified using

individually numbered ear tags (Allflex Europe SA, Vitre) applied during the initial data collection visits. Farmers provided information on parity, pregnancy, and lactation status. Age was estimated from dentition (Torell *et al.*, 1998), while LW was determined on-farm using a portable weighing scale fitted with LED display (Model EKW, Endeavor Instrument Africa Limited, Nairobi). Heart girth was measured at each LW recording, while body condition score was assessed on a 1 to 5 scale (Edmonson *et al.*, 1989). Milk production was recorded by farmers who were supplied with a graduated plastic container (1500 ml Jug, Kenpoly Limited, Nairobi) and a notebook that was collected and collated every two months. Cattle were classified as calves (less than one year old), heifers/young males (1-2 years old), or cows/adult males (above 2 years old).

5.2.3 Feed resources - pasture and fodder yield determination

Farms were visited at the beginning of each of the two cropping seasons (Short Wet and Long Wet) to assess total farm and individual plot/field area, using a laser range finder (Truth Laser Range Finder, Bushnell Outdoor Products, USA) and land use (e.g.: crop, Napier grass, fallow).

Pasture yield was estimated using wire mesh enclosure cages (0.5 m x 0.5 m x 0.5 m) (Holechek *et al.*, 1982) to exclude grazing (one per household per village). Every three months, coinciding with the middle of the different seasons, the pasture growth was harvested from each cage with scissors ~2.5 cm above the ground. Individual samples were placed in pre-weighed paper bags and weight recorded using a digital scale (Citizen Model CTG6H, Citizen Scale Inc., USA). The cage was replaced in the same position until the next sampling. Available pasture biomass was estimated for the sampled farms in each zone by season (t dry matter (DM)/ha) by extrapolating sample mass by

area under pasture for each farm and aggregating areas for all farms in the survey, by zone.

Crop stover biomass available for fodder was determined from farmer recall of grain yield, then applying crop-specific harvest indexes for: maize (Hay and Gilbert, 2001), sorghum (Prihar and Stewart, 1991), finger millet (Reddy *et al.*, 2003), beans (Acosta Díaz *et al.*, 2008), groundnuts (Kiniry *et al.*, 2005), and green grams (Kumar *et al.*, 2013). Yields of Napier grass were estimated by multiplying the area under cultivation by published estimates for the yield of Napier under field conditions (Van Man and Wiktorsson, 2003). Yields of minor feedstuffs (e.g.: banana stems) were estimated from farmer recall regarding the amount and frequency of feeding.

5.2.4 Determination of diet quality and seasonal "feed basket"

Feed resources (i.e., pasture, crop stovers, Napier grass, etc.) were pooled by type of feed for the farms surveyed in each zone and each season and the representation of each feedstuff in the notional diet was deemed to be proportional to the availability of the different plant biomass in each zone/season. The DM, Organic Matter (OM), Crude Protein (CP), Neutral and Acid Detergent Fibre (NDF, ADF), and Ether Extract (EE) concentrations in feed samples were determined by wet chemistry and have been published elsewhere (Onyango et al., 2017). Dry matter digestibility (DMD) was estimated using the equation of Oddy *et al.* (1983):

$$\text{DMD (g/100gDM)} = 83.58 - 0.824 * \text{ADF (g/100gDM)} + 2.626 * \text{N (g/100gDM)} \quad (1)$$

Seasonal mean dry matter digestibility (SMDMD) of diets was estimated using the equation:

$$SMDMD = \sum \frac{(\text{\%diet of individual feedstuff} * \text{\%DMD of the feedstuff})}{100} \quad (2)$$

5.2.5 Estimation of cattle energy expenditure

Energy expenditure was determined for each animal for each season. Total energy expenditure was deemed to be equal to the sum of MER for Maintenance (MER_M) plus MER for Growth (MER_G) (minus for weight loss) plus MER for lactation (MER_L) plus MER for travel and ploughing/traction (MER_T and MER_P). Energy requirement for thermo-regulation was not considered, because in the area surveyed environmental conditions were such that animals should mostly have been in a thermo-neutral zone year round (Mean annual temperature:17.0 (min) - 29.4 (max) ^{0}C). Energy requirements for gestation were not specifically included, as this is only of significance with respect to energy requirements in the final 8-12 weeks of gestation and is partly captured in the dam's LW change. Calves under 3 months were treated as pre-ruminant (therefore not emitting CH_4) and the milk required for their maintenance and growth attributed to the milk production of the dam and included in the total energy expenditure for the dam. Calves over the age of three months were deemed to be weaned and on pasture. All equations for the estimation of the various components of MER have been derived from equations adopted by the CSIRO publication, "Nutrient Requirements of Domestic Ruminants" (CSIRO, 2007) (NRODR), unless otherwise stated. As typical diets for smallholders ruminants were overwhelmingly roughage based, where relevant equations pertaining specifically to forages have been used.

5.2.5.1 Estimation of energy requirements for maintenance (MER_M)

The equation for the estimation of MER_M is based on equations (1.20, 1.21 and 1.12A) in NRODR (CSIRO, 2007). The final resulting equation is:

$$MER_M(MJ/d) = K * S * M * \frac{(0.26*MLW^{0.75}*\exp^{(-0.03*A)}}{(0.02*{}^{M}/_{D}) + 0.5} \quad (3)$$

Where: K=1.3 (intermediate value between that given for B. taurus and B. indicus); S=1 for females & castrates, 1.15 for males; M=1 (0% milk in diet); MLW= mid-term LW (LW at end of season + LW beginning of season)/2 in kg); A=age (in years); DMD=Dry Matter Digestibility (g/100g); M/D=0.172*DMD - 1.707(MJ ME /kg DM) (i.e.: metabolizable energy content.

5.2.5.2 Estimation of energy requirements for growth (MER_G)

Two equations were required to account for LW change (equations 1.29 and 1.36 in NRODR (CSIRO, 2007)). Daily LW gain (/loss) was determined as:

$$LW_{change}(kg/d) = \frac{LW_{end\ of\ season}(kg) - LW_{start\ of\ season}(kg)}{\text{Number of days between measurements}} \quad (4)$$

and deemed to be constant for the whole season.

Due to adverse weather conditions during the final measurement period, it was not possible to reach farmers transporting the mobile scale. Subsequently, a final LW was estimated by the equation:

$$LW_{end\ observation\ period\ 4} = \frac{LW_{Start\ Period\ 4}\ (kg)}{LW_{End\ Period\ 2}\ (kg)} * LW_{Change\ Period\ 2}(kg/d) * 92\ (d/period) + LW_{Start\ Period\ 4} \quad (5)$$

If weight change over the observation period was positive then:

$$MER_G(MJ/d) = \frac{(LW_{change} * 0.92 * EC)}{(0.043 * M/D)} \quad (6)$$

If negative:

$$MER_{-G}(MJ/d) = \frac{(LW_{change} * 0.92 * EC)}{0.8} \quad (7)$$

Where:

EC (MJ/kg) =energy content of the tissue (which was taken as a mid-range value of 18 MJ/kg and used in all cases) (NRODR) (CSIRO, 2007);

5.2.5.3 Estimation of energy requirements for lactation (MER_L)

Daily Milk Yield (DMY) was calculated as:

$$\text{DMY (l/d)} = \frac{\text{Mean daily milk production (l)} * \text{N of days in milk}}{\text{d in season (i.e. 92)}} \quad (8)$$

Energy requirements for lactation were calculated using the equation (1.43) given in NRODR(CSIRO, 2007) as:

$$\text{MER}_\text{L} = \frac{(\text{DMY} * \text{ECM})}{\left(\left(0.02 * \frac{\text{M}}{\text{D}}\right) + 0.04\right)} \quad (9)$$

where: DMY (kg) = Eq. (8); ECM (MJ/kg) = energy content of milk (taken as 3.054 MJ/kg (CSIRO, 2007) due to a lack of data regarding constituents);

Milk consumed by pre-ruminant calves was estimated from work of Radostits and Bell (1970). It was assumed that calves grew at 50 g/day. Daily milk consumption was calculated as follows:

$$\text{Daily milk consumption (l/d)} = \text{LW}_\text{Calf}\ \text{(kg)} * 0.107 + 0.143 \quad (10)$$

5.2.5.4 Estimation of energy expenditure for locomotion (MER_T)

Energy expenditure for locomotion varies with animal husbandry practices, which were generally similar within the three studied topographic zones (Lowland, Slopes, Highlands). Estimates of daily travel were made by fitting an animal in each of three villages from each topographic zone with global positioning recorders (Allan *et al.*, 2013) for 24 h over three consecutive days. Estimates of travel for animals in each zone were derived from position data by taking the mean distance travelled by animals in a zone. Energy expenditure from travel was calculated following NRODR (CSIRO, 2007) as:

$$\text{MER}_\text{T}(\text{MJ}) = \text{DIST (km)} * \text{MLW (kg)} * 0.0026\ \left(\frac{\text{MJ}}{\text{kgLW}}/\text{km}\right) \quad (11)$$

Where: DIST = distance travelled (km); MLW = mid-term LW and 0.0026 is the energy expended (MJ/(kg LW/ km)).

Values for energy expenditure from traction or ploughing are not well characterized in the literature. Lawrence and Stibbards (1990) calculations suggest an energy expenditure for walking of 2.1 J/m/kg LW and a work efficiency for ploughing of 0.3 for Brahman cattle. Singh (1999) suggested that cattle may maintain a traction effort equivalent to 12% of their LW, at a speed of 0.6-1.0 m/s. This indicates additional energy expenditure of 0.4 J/m/kg LW. From the above it may be inferred that ploughing requires (at 0.8 m/s velocity) 0.002 MJ/h/kg LW.

Thus, energy expenditure from ploughing was calculated as:

$$\mathrm{MER_P(MJ)} = \text{Work Hours (h/d)} * \mathrm{days_{work}} * \text{MLW (kg)} * 0.002\ (\mathrm{MJ}) \tag{12}$$

Days and day length worked was based on farmer recall.

5.2.6 Calculation of emission factors (EF)

Firstly, dry matter intake (DMI) was calculated as:

$$\text{DMI (kg/d)} = \frac{\mathrm{MER_{Total}}}{\mathrm{GE*MSDMD*0.81}} \tag{13}$$

where: $\mathrm{MER_{Total}}$ = sum of all animal energy requirements (i.e. maintenance, locomotion, ploughing, lactation, etc.); GE = Gross Energy concentration of the diet (assumed to be 18.1 MJ/kg DM, a mid-range value for tissue(CSIRO, 2007)); and 0.81 was the factor to convert Metabolizable Energy to Digestible Energy (see CSIRO, 2007).

Daily Methane Production (DMP) was calculated as follows:

$$\text{DMP (g/d)} = 20.7 * \text{DMI (kg)} \tag{14}$$

using the conversion factor of Charmley *et al.* (2016). Annual CH_4 production (i.e., the EF) for each class of animal was calculated by multiplying seasonal DMP by 92 and by summing all seasons.

5.3 Results

The initial survey showed 416 cattle of all classes present in the 60 households surveyed. Given the numbers present analysis was performed for all categories of cattle. Locomotion data was not included for calves, as these generally were observed to be kept around the homestead. Cattle numbers changed by season in all three regions, due to the combined effects of informal loaning ("giving" of animals to relatives), births, deaths, commercial sales, and purchases (Table 1). When an animal was present for measurement it was considered to be "on-farm" for the whole of that season. Adult mortality was 7.0% and calf mortality 18.3% for the one year period of the survey.

LW showed little seasonal variation across the year, but there were major differences in LW between classes in a region and within classes between regions (Table 2).

The seasonal feed basket (Table 3) showed modest variations in DMD (55.9-64.1%), which may have been due to a predominant reliance on pasture in most seasons and zones.

Estimates of MER and of total daily mean metabolizable energy expenditure are given in Tables 4-8 for all the five cattle categories. Based on this information the calculated EFs ranged from 19.3 to 37.4 kg CH_4 per annum depending on location and class for adolescent and adult animals and 13.9-20.4 kg for calves < 1 year old (Table 9).

Table 1. Cattle population, by class and topographic zone, showing births, deaths, purchases sales and loans over the (12month) survey period

Topographic zone	Category	Season				Management				
		Short dry	Short wet	Long dry	Long wet	Births	Deaths	Sales	Purchases	Loans
Highlands	Males 1-2 years old	6	3	2	1	n.a.	0	5	0	0
	Males > 2 years old	11	7	7	3	n.a.	0	3	1	5
	Females 1-2 years old	3	3	3	3	n.a.	1	0	1	0
	Females > 2 years old	27	26	25	25	n.a.	2	2	2	1
	Calves	25	24	25	21	10	8	7	1	0
	Total	72	63	62	53	10	11	17	5	6
Lowlands	Males 1-2 years old	13	10	11	10	n.a.	0	5	1	0
	Males > 2 years old	22	16	18	16	n.a.	2	7	3	0
	Females 1-2 years old	11	10	7	7	n.a.	1	2	0	1
	Females > 2 years old	42	42	43	43	n.a.	1	1	3	0
	Calves	34	31	42	38	9	5	2	2	0
	Total	122	109	121	114	9	9	17	9	1
Slopes	Males 1-2 years old	15	10	6	4	n.a.	0	5	0	0
	Males > 2 years old	41	34	36	28	n.a.	1	7	8	1
	Females 1-2 years old	9	8	9	6	n.a.	0	2	2	1
	Females > 2 years old	85	70	68	56	n.a.	2	12	4	9
	Calves	72	65	53	43	5	11	18	3	2
	Total	222	187	172	137	5	14	44	17	13
Sum study region (Nyando)	Males 1-2 years old	34	23	19	15	n.a.	0	15	1	0
	Males > 2 years old	74	57	61	47	n.a.	3	17	12	6
	Females 1-2 years old	23	21	19	16	n.a.	2	4	3	2
	Females > 2 years old	154	138	136	124	n.a.	5	15	9	10
	Calves	131	120	120	102	24	24	27	6	2
	Total	416	359	355	304	24	34	78	31	20

n.a. = not applicable to category

Table 2. Seasonal mean live weights (SEM) (kg) of the five classes of cattle (females > 2 years old, 1-2 years old, males > 2 years old, males 1-year old, calves < 1 year old) from three topographic zones of the Nyando basin, Kenya.

Category/topographic zone	Short dry season	Short wet season	Long dry season	Long wet season
Females > 2 years old				
Highlands	277.2 (9.5)	272.8 (9.1)	263.6 (9.2)	256.0 (9.6)
Lowlands	180.4 (4.2)	187.6 (4.0)	186.5 (4.5)	186.9 (5.5)
Slopes	215.4 (3.7)	219.9 (4.1)	213.8 (4.5)	213.5 (5.5)
Mean	216.3 (3.8)	220.6 (3.9)	214.5 (3.9)	214.2 (4.4)
Females 1-2 years old				
Highlands	202.1 (37.1)	235.2 (30.8)	242.2 (31.9)	246.8 (32.5)
Lowlands	126.5 (8.1)	136.7 (8.9)	141.3 (13.2)	141.2 (15.0)
Slopes	140.9 (14.3)	157.2 (16.4)	160.9 (14.8)	169.5 (19.7)
Mean	143.8 (9.8)	160.9 (11.2)	168.9 (12.5)	174.1 (14.8)
Males > 2 years old				
Highlands	262.2 (9.1)	259.7 (15.4)	245.9 (20.2)	222.6 (5.9)
Lowlands	196.0 (5.7)	205.6 (7.9)	188.5 (9.0)	179.3 (9.2)
Slopes	216.1 (7.2)	226.4 (7.8)	214.9 (7.2)	218.1 (8.6)
Mean	216.9 (5.1)	224.2 (5.8)	209.4 (5.8)	204.1 (6.5)
Males 1- 2 years old				
Highlands	197.1 (33.4)	194.3 (28.1)	169.9 (8.5)	158.7 (n.a.)
Lowlands	116.1 (9.5)	126.6 (12.4)	130.5 (9.1)	140.6 (9.1)
Slopes	138.8 (8.5)	153.8 (12.6)	147.4 (13.5)	163.5 (15.2)
Mean	140.5 (9.1)	147.3 (9.4)	140.0 (7.2)	149.0 (7.6)
Calves < 1 year old				
Highlands	83.4 (8.7)	90.1 (11.4)	85.6 (11.8)	90.8 (13.8)
Lowlands	48.5 (4.1)	58.4 (4.1)	69.2 (3.9)	74.7 (4.5)
Slopes	64.4 (4.6)	73.8 (5.4)	76.6 (5.5)	83.6 (6.2)
Mean	63.4 (3.3)	72.6 (4.0)	76.0 (3.7)	81.6 (4.1)

n.a. = not applicable to category

Table 3. Composition of seasonal diets and their dry matter digestibility in the three topographic zones of the Nyando basin, Kenya.

Topographic zone	Feedstuff	Short dry season		Short wet season		Long dry season		Long wet season	
		% diet	% DMD	% diet	% DMD	% diet	% DMD	% diet	% DMD
Highlands	Pasture	72.1	64.5	78.2	64.2	83.4	63.5	83.4	59.6
	Banana stems	1.3	54.9	1.3	48.0	1.3	57.4	1.3	48.0
	Napier Grass	14.3	55.5	14.3	56.4	14.3	55.5	14.3	56.4
	Banana leaves	1.0	60.8	1.0	60.8	1.0	60.8	1.0	60.8
	Sweet potato vines	1.9	66.2	0.5	63.7	n.f.	n.f.	n.a.	n.a.
	Maize stover[a]	9.4	55.9	4.7	55.9	n.a.	n.a.	n.a.	n.a.
	Average DMD		59.6		58.2		59.3		56.2
Lowlands	Pasture	93.9	62.4	98.6	64.0	34.7	61.7	100.0	57.7
	Tree leaves[b]	n.f.	n.f.	n.f.	n.f.	55.6	59.3	n.f.	n.f.
	Sugarcane tops	n.f.	n.f.	n.f.	n.f.	9.0	52.9	n.f.	n.f.
	Maize stover[a]	6.1	55.9	1.4	55.9	0.7	55.9	n.a.	n.a.
	Average DMD		59.2		60.0		57.5		57.7
Slopes	Pasture	100.0	63.8	100.0	64.1	90.7	59.9	100.0	56.8
	Sugarcane tops	n.f.	n.f.	n.f.	n.f.	9.3	51.9	n.f.	n.f.
	Average DMD		63.8		64.1		55.9		56.8

DMD = dry matter digestibility; n.a. = not available; n.f. = available, not fed;
[a] Crop residues were predominantly maize stover.
[b] *Balanite aegyptiaca* & *Mangifera indica* ssp.

Table 4. Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of female cattle > 2 years old, for maintenance (MER_M), growth (MER_G), milk production (MER_L), locomotion (MER_T) and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short Dry Season					Short Wet Season					Long Dry Season					Long Wet Season				
	MER_M	MER_G	MER_L	MER_T	Total	MER_M	MER_G	MER_L	MER_T	Total	MER_M	MER_G	MER_L	MER_T	Total	MER_M	MER_G	MER_L	MER_T	Total
Highlands																				
1st Quartile	26.7	- 4.9	0.0	0.9	31.3	25.9	- 5.3	0.0	0.9	27.6	26.2	- 6.4	0.0	0.9	25.3	25.6	- 3.7	0.0	0.8	24.6
Mean	28.8	-1.5	15.7	1.0	44.0	28.9	0.9	8.3	1.0	39.7	28.1	- 2.1	8.4	1.0	35.4	27.9	2.1	2.6	1.0	33.6
3rd Quartile	31.6	2.7	20.6	1.2	48.5	31.3	4.7	11.0	1.1	46.2	31.1	- 0.5	13.1	1.1	37.5	31.1	8.6	0.0	1.1	37.9
Lowlands																				
1st Quartile	20.2	- 0.1	0.0	1.2	25.4	20.7	- 0.3	0.0	1.3	27.8	20.4	- 6.3	0.0	0.6	17.7	20.3	- 0.3	0.0	0.6	21.4
Mean	21.6	4.8	7.7	1.4	35.4	22.2	6.1	4.0	1.4	32.9	22.5	- 3.8	1.9	0.7	21.3	22.4	6.0	0.4	0.7	29.5
3rd Quartile	23.2	8.8	11.2	1.5	43.0	23.9	11.3	7.9	1.6	39.7	24.2	- 0.7	3.6	0.8	24.9	24.6	11.8	0.0	0.8	36.2
Slopes																				
1st Quartile	21.8	- 0.5	0.0	1.4	23.7	21.9	- 3.1	0.0	1.5	26.7	22.2	- 1.8	0.0	0.7	23.2	21.5	- 3.4	0.0	0.7	19.8
Mean	23.6	3.4	7.0	1.6	35.6	23.9	0.1	8.4	1.6	34.2	24.5	3.1	1.2	0.8	29.6	24.2	- 0.2	1.1	0.8	26.0
3rd Quartile	25.4	8.5	10.5	1.8	41.8	26.0	2.7	19.2	1.8	43.4	26.7	6.7	0.0	0.9	34.6	26.7	2.8	0.0	0.9	31.0
All Nyando																				
1st Quartile	21.5	- 1.6	0.0	1.2	25.4	21.9	- 2.5	0.0	1.2	27.1	21.7	- 4.4	0.0	0.7	20.4	21.5	- 2.5	0.0	0.7	21.3
Mean	24.0	2.9	8.7	1.4	37.0	24.4	2.1	7.0	1.4	34.9	24.6	- 0.2	2.9	0.8	28.1	24.5	2.3	1.2	0.8	28.8
3rd Quartile	26.1	8.0	12.0	1.7	43.7	26.3	5.5	11.1	1.7	41.3	26.9	2.1	2.8	0.9	33.9	27.0	6.4	0.0	0.9	34.9

Table 5. Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of female cattle 1-2 years old, for maintenance (MER_M), growth (MER_G), locomotion (MER_T) and total energy expenditure (total) from three topographic regions of the Nyando basin, Kenya.

	Short dry season				**Short wet season**				**Long dry season**				**Long wet season**			
	MER_M	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**
Highlands																
1st Quartile	21.4	8.7	0.6	30.7	25.7	4.6	0.7	31.1	26.1	- 1.8	0.8	27.5	26.8	5.4	0.8	33.1
Mean	23.9	13.6	0.7	38.2	27.9	7.1	0.8	35.9	28.4	0.3	0.9	29.5	29.4	7.8	0.9	38.1
3rd Quartile	28.6	20.4	0.9	49.9	31.7	10.7	1.0	43.4	32.3	2.0	1.0	31.5	33.4	10.9	1.0	45.4
Lowlands																
1st Quartile	15.9	3.3	0.8	21.8	16.9	2.5	0.5	19.9	17.1	- 4.2	0.4	13.0	16.4	2.5	0.4	18.9
Mean	17.5	5.4	0.9	23.7	18.3	4.3	0.9	23.5	18.7	- 3.4	0.5	15.8	18.5	4.6	0.5	23.6
3rd Quartile	18.7	6.8	1.0	25.3	19.4	5.8	1.1	26.3	20.6	- 2.8	0.6	18.5	20.6	6.6	0.6	28.2
Slopes																
1st Quartile	15.5	0.8	0.8	19.0	16.8	2.0	0.9	24.8	17.7	0.0	0.4	19.0	19.0	4.2	0.5	22.4
Mean	18.9	3.4	1.1	23.4	20.5	6.5	1.2	28.2	21.8	1.9	0.6	24.4	22.6	8.4	0.5	27.1
3rd Quartile	22.5	6.0	1.3	29.9	24.7	9.5	1.5	32.0	25.5	3.6	0.7	27.3	26.2	11.2	0.7	36.8
All Nyando																
1st Quartile	15.9	2.6	0.8	21.4	17.3	2.4	0.8	22.2	17.7	- 3.1	0.4	17.2	18.3	2.6	0.5	21.5
Mean	19.3	6.5	0.9	26.8	21.2	5.6	0.9	27.7	22.2	- 0.6	0.6	22.2	22.6	6.5	0.6	28.5
3rd Quartile	22.0	7.8	1.0	29.9	24.8	9.4	1.1	31.7	26.1	1.6	0.8	27.5	27.5	10.8	0.8	36.1

Table 6. Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of male cattle > 2 years old, for maintenance (MER_M), growth (MER_G), locomotion (MER_T) and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season				**Short wet season**				**Long dry season**				**Long wet season**			
	MER_M	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**
Highlands																
1st Quartile	40.4	- 2.0	0.9	37.8	41.0	- 0.3	0.9	41.8	38.7	- 0.2	1.1	38.8	37.6	- 2.4	0.8	36.1
Mean	43.2	- 1.8	1.3	42.7	43.6	0.7	1.0	45.3	42.3	- 0.5	1.4	42.0	38.4	- 1.7	0.8	37.6
3rd Quartile	47.1	0.0	1.5	48.3	47.6	1.2	1.1	50.3	47.5	0.0	1.7	45.7	39.5	- 1.3	0.8	38.9
Lowlands																
1st Quartile	33.7	0.0	1.5	35.5	35.7	- 2.4	1.5	34.0	34.4	- 5.7	1.8	28.2	32.7	- 3.8	1.3	29.8
Mean	34.9	7.4	1.7	44.0	36.6	2.5	1.6	40.6	35.3	- 4.7	2.0	31.5	34.0	1.8	1.4	37.2
3rd Quartile	37.1	17.1	2.1	52.3	39.0	10.0	1.8	48.5	38.5	- 1.0	2.4	34.2	36.9	9.0	1.5	45.1
Slopes																
1st Quartile	33.8	0.0	1.5	37.1	34.4	- 0.6	1.5	35.8	35.9	- 3.1	1.9	35.8	36.2	- 0.5	1.4	36.9
Mean	37.2	5.4	1.8	44.4	38.3	2.7	1.7	41.6	38.5	- 0.6	2.4	40.3	38.6	0.6	1.6	40.9
3rd Quartile	40.9	10.5	2.1	48.9	41.5	5.9	1.9	46.1	41.8	0.5	2.9	44.1	41.9	0.8	1.8	45.9
All Nyando																
1st Quartile	34.0	0.0	1.4	36.9	35.8	- 0.7	1.4	36.0	35.3	- 4.2	1.7	33.2	33.8	- 1.7	1.2	34.3
Mean	37.6	4.8	1.7	44.0	38.7	2.4	1.6	41.9	38.1	- 1.8	2.1	37.6	37.0	0.8	1.5	39.2
3rd Quartile	40.7	8.9	2.1	49.2	41.3	5.7	1.8	48.1	41.5	0.0	2.6	42.3	40.0	2.0	1.7	44.0

Table 7. Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of male cattle 1-2 years old, for maintenance (MER_M), growth (MER_G), locomotion (MER_T) and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season				**Short wet season**				**Long dry season**				**Long Wet Season**			
	MER_M	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**	**MER_M**	**MER_G**	**MER_T**	**Total**
Highlands																
1st Quartile	32.2	0.0	0.7	34.6	33.9	1.8	0.6	40.5	33.5	- 1.2	0.8	33.9	32.9	3.5	0.6	37.0
Mean	37.2	0.8	0.9	38.9	37.6	4.0	0.7	42.3	34.3	0.7	1.0	36.0	32.9	3.5	0.6	37.0
3rd Quartile	45.8	0.0	1.0	46.9	39.8	6.0	0.8	44.8	35.0	2.7	1.1	38.2	32.9	3.5	0.6	37.0
Lowlands																
1st Quartile	20.1	0.0	0.6	28.8	23.9	1.7	0.8	28.6	25.2	- 2.3	0.8	23.9	27.1	0.5	0.9	31.4
Mean	25.2	7.3	0.9	33.4	27.4	4.8	1.0	33.2	28.0	- 0.2	1.2	28.3	29.2	4.4	1.0	34.7
3rd Quartile	28.0	9.0	1.1	34.3	29.0	6.8	1.1	34.9	29.5	0.4	1.1	29.3	30.1	6.7	1.1	39.0
Slopes																
1st Quartile	25.4	0.0	1.0	27.6	27.0	0.5	0.7	24.1	27.2	0.3	1.0	30.3	31.4	- 0.1	1.1	32.4
Mean	28.1	7.6	1.1	36.8	30.4	4.5	0.9	27.8	30.6	3.2	1.2	34.2	32.9	0.5	1.2	34.5
3rd Quartile	31.1	12.2	1.3	41.2	34.0	6.5	1.3	39.7	32.7	5.2	1.2	38.9	34.6	0.6	1.3	36.5
All Nyando																
1st Quartile	24.8	0.0	0.8	28.8	25.1	1.6	0.7	28.8	25.6	- 1.3	0.8	27.1	28.6	0.2	0.8	33.1
Mean	29.0	5.8	1.0	35.9	30.3	4.5	0.9	32.6	29.6	0.7	1.1	30.9	30.6	3.2	1.0	35.0
3rd Quartile	32.5	9.0	1.2	41.0	34.2	6.6	1.1	40.3	33.0	2.1	1.1	35.3	32.9	4.2	1.1	38.2

Table 8. Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of calves < 1 year old, for maintenance (MER_M), growth (MER_G), and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season			**Short wet season**			**Long dry season**			**Long wet season**		
	MER_M	**MER_G**	**Total**	**MER_M**	**MER_G**	**Total**	**MER_M**	**MER_G**	**Total**	**MER_M**	**MER_G**	**Total**
Highlands												
1st Quartile	9.53	0.00	13.13	9.05	2.25	9.11	8.14	0.00	8.29	8.89	2.93	11.12
Mean	16.20	6.30	22.26	17.48	7.00	23.17	16.76	2.02	18.78	17.79	7.33	25.12
3rd Quartile	22.35	10.72	31.29	25.94	10.40	34.19	25.83	3.89	25.89	24.84	10.43	36.81
Lowlands												
1st Quartile	8.00	0.00	12.46	10.11	3.49	14.52	12.30	- 0.80	12.47	14.30	1.85	16.74
Mean	11.15	5.17	16.31	12.90	6.23	19.13	14.86	1.17	16.03	15.72	6.19	21.91
3rd Quartile	13.96	8.67	19.50	14.68	8.63	24.24	17.26	3.24	21.29	19.40	9.41	27.05
Slopes												
1st Quartile	8.38	0.00	9.34	9.09	1.66	12.62	11.24	1.07	13.99	12.73	2.81	17.23
Mean	13.30	4.99	18.29	14.74	4.06	18.74	15.96	4.96	20.93	17.04	5.16	22.20
3rd Quartile	17.25	9.12	24.32	19.31	5.75	23.96	20.24	7.22	26.68	20.38	7.08	28.29
All Nyando												
1st Quartile	8.49	0.00	10.57	9.56	2.15	12.73	11.00	0.00	12.41	11.64	2.77	16.74
Mean	13.31	5.28	18.57	14.80	5.24	19.77	15.84	3.11	18.93	16.80	5.99	22.79
3rd Quartile	17.39	9.10	24.05	19.31	7.73	25.00	19.80	5.76	25.06	20.74	8.75	28.47

Table 9. Mean live weight (kg) and emission factors (CH_4 kg/animal/annum) for the five classes of cattle in the three topographic zones of the Nyando basin, Kenya.

	Females > 2 years old		**Females 1-2 years old**		**Males > 2 years old**		**Males 1-2 years old**		**Calves < 1 year old**	
Topographic zones	**Live weight (kg)**	**Emission factors (CH_4 kg/yr)**	**Live weight (kg)**	**Emission factors (CH_4 kg/yr)**	**Live weight (kg)**	**Emission factors (CH_4 kg/yr)**	**Live weight (kg)**	**Emission factors (CH_4 kg/yr)**	**Live weight (kg)**	**Emission factors (CH_4 kg/yr)**
Highlands	267.3	34.1	220.6	31.7	249.2	37.4	180.0	34.5	87.5	18.1
Lowlands	185.0	26.7	128.4	19.3	196.0	34.1	129.1	28.9	62.7	13.9
Slopes	215.7	27.1	157.1	23.5	219.5	36.6	139.5	27.8	74.6	16.1
Mean	216.3	28.3	154.6	23.0	216.0	35.9	143.5	30.1	73.4	15.7

5.4 Discussion

The mean EFs derived from the present study are substantially lower for adolescent and adult male (30.1, 35.9 versus 49 kg CH_4) and for adolescent and adult female (23.0, 28.3 versus 41 kg), but not calves (15.7 versus 16 kg) than those given for "other" African cattle in IPCC (Tier I) estimates (Dong *et al.*, 2006). This was surprising given that MER_M (which is directly proportional to LW) was the predominant energy demand in our calculations and the mean LW of females in our study was similar to the "typical" female weight for African cattle used in Tier I. However, male animals were ~25% lighter than the male LW used in the IPCC information (Table 10A.2). Because the approach to develop TIER II EFs here is basically the same as the approach given by the IPCC, that is to say:

CH_4 = Energy intake* Y_m ("methane conversion factor"),

it follows that either the calculation of energy intake or Y_m or both must vary substantially from the IPCC approach.

The alternative equation for methane production rate (MPR- CH_4 g/d) developed by Charmley *et al.* (2016) and equivalent to the equation used in this study, at 6.3% of gross energy intake (GEI) is in close agreement with the IPCC default estimate of 6.5%. Thus, it seems reasonable to conclude that the major differences in EFs between our method and that of IPCC TIER I occur due to markedly different estimates of voluntary intake. IPCC methodology explicitly assumes that intake is *ad libitum* and bases estimates of intake on diet digestibility and some categorical assumptions on energy expenditure. As stated earlier, the assumption of *ad libitum* intake is frequently violated for African smallholder livestock, due to restrictive husbandry practices including being held in bomas overnight without access to feed or water or the tethering or grazing reduced sward heights during day time (Njarui *et al.*, 2016). We

deliberately set out to avoid reliance on the assumption of *ad libitum* intake as we based our estimates on energy expenditure. In our study estimates of energy expenditure were based on repeated animal measurements and using this, combined with knowledge of feed resources available, to estimate intake. This has resulted in lower estimates of GEI and hence, EFs that are considerably lower than Tier 1 estimates. Our study also suggests that animal intakes were well below *ad libitum*, evidenced partly by the frequently observed seasonal LW losses.

The EFs reported in this study were much less than the 76.4 kg and 71.8 kg for dairy and beef cattle, respectively, reported by Du Toit *et al.* (2014) for livestock systems in South Africa. This might be expected given the LW of these cattle being approximately three times that of the cattle in our study (and that voluntary intake would have been commensurately larger). Kouazounde *et al.* (2015) reported an average EF of 39 kg for cattle from Benin, although this varied considerably according to breed and body size. By comparison, Swamy and Bhattacharya (2006) have reported EFs of 21-23 kg CH_4 for cattle in India in a similar LW range (175-300 kg) to the present study – although a lower Y_m (4.83-6.0%) appears to have been used.

The DM digestibility's of the individual diet components (Table 3, with further details in Onyango *et al*., 2017) were in agreement with those calculated by Shem *et al.* (1995) for typical livestock feeds used by smallholders in northern Tanzania. Our estimates of the average digestibility of the seasonal food basket for smallholder cattle are somewhat greater than the default digestibility (55%) in IPCC estimates, but this does not account for the disparity in EFs between the two systems. The importance of crop residues in the diets of smallholder livestock has been stressed (McDowell, 1988), but this may in some cases be overemphasized – in our study we found that in nearly all locations and seasons, available pasture was (see Table 3) the most important

feed resource. The limitations to the precision of our estimates of pasture biomass and quality through the use of exclusion cages are in principal clear, yet difficult to assess in terms of their practical implications (if any). On the one hand, the rapid senescence of tropical grasses after reaching maturity has been clearly demonstrated (Wilson and Mannetje, 1978), implying that our sampling interval may result in the over or under estimation of DMD of pasture for some parts of the year. Another consideration is that constant grazing, whilst potentially increasing DMD, will lead to impaired plant growth and lower production of biomass (Troughton, 1957). Ultimately this must be seen as a potential limitation of the pasture assessment, along with the number and area, of samples to estimate pasture growth, indicating that further work is required. However, other estimates – in particular of the availability of crop stovers and Napier grass were made with a high degree of confidence, because precise areas under cultivation were measured and not subject to such complications as communal grazing. The limited quantities of stovers and Napier grass available for consumption also indicate that animals must derive a large proportion of their energy requirements by feeding on pasture and thus we believe our feed basket composition to be substantially correct.

Surprisingly, there were no clear seasonal trends in the nutritional value (i.e.: digestibility) of pasture, most likely because the samples as harvested showed the effects of early - mature stages of growth and the climatic effects of more than a single season. Similarly, there were no uniform changes in cattle's' LW by landscape position or season, which was also not expected – LW losses for some individuals occurred in all landscape positions in all seasons. The reasons for this are difficult to discern, in part this was probably due to limitations in the sampling protocol – a full month was required to measure the LW of all cattle in the study area, so that while animals were measured from the very start of the season, some would not be weighed until mid-season.

Local weather conditions and individual husbandry decisions most likely also played a role in the observed variability in cattle LW flux and highlight the overall heterogeneity of smallholder farming systems.

Despite the absence of uniform trend(s), it is clear that most animals were in energy deficit for part of the year and mobilizing body reserves to meet energy requirements. Taking account of these losses was an important factor in assessing intakes and ultimately DMP. An important limitation in assessing MER_G was a lack of knowledge of the tissue composition of the LW gain, which can vary from 8.5-29 MJ/kg (CSIRO, 2007). Algorithms based on breed type and growth stage exist to estimate composition (Corbett *et al.*, 1987), but such data was not available for the population studied, so a mid-range value was employed, with unknown error. Milk composition was not measured in this study; however, such knowledge would produce better estimates of the energy expended during lactation and improve the precision of intake estimation in lactating animals. A significant feature of rain-fed systems is the variability in biomass production due to variance in rainfall. In this study we examined animal production over one full year only, whereas Herd *et al.* (2015) have suggested that up to five years data is required to sufficiently capture the variability in rain-fed pasture systems to provide reliable estimates of ruminant GHG emissions.

Conclusions

In this study, we avoided the need to rely on the assumption of *ad libitum* intake by deriving energy expenditure from production parameters, which allowed us to produce more reliable estimates of intake, and ultimately CH_4 production by smallholder cattle. Based on this new approach, which is appropriate for smallholder livestock systems, we calculated EFs up to 40%

less than existing TIER I estimates. Nevertheless, it needs to be stressed our study is the first of its kind for Sub-Saharan Africa relying on animal measurements, which should not automatically be extrapolated outside of its geographic range. It does however, point out the need for further measurements, and highlights the value of using a robust methodology which does not rely on the (often invalid) assumption of *ad libitum* intake in systems where intake is known or likely to be restricted.

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6. Estimation of enteric methane emission factors and intensities in smallholder cattle systems in Western Kenya[5]

Abstract

Demand for animal-based food products is fuelled by a growing and richer global human population. Ruminant production systems in sub-Saharan Africa (SSA) need to meet this demand through enhanced efficiencies and not increased stocking which increase enteric methane (CH_4) emissions. Farm system optimization and policy interventions require accurate reporting of emissions. Data on SSA emissions are scarce, outdated, highly uncertain, and non-specific to prevailing systems. Tier 2 methodology, based on area-specific feed and cattle characterization, would improve accuracy, lower uncertainties, improve data reliability for decision-making, and guide mitigation policy by relating productivity to emissions. Study objectives were to i) use Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology to estimate enteric CH_4 emission factors (EF) and associated emissions; ii) estimate emission intensities (EI); and iii) derive uncertainties accompanying estimated EFs in cattle systems of Western Kenya. Cattle and feedstuffs characterization was done in twenty villages in three geographic zones in Western Kenya over four seasons of one year. The cattle were disaggregated by age and production stages. Feedstuffs and seasonal diets offered to cattle were established and samples collected from all the households. The samples were analysed for dry matter (DM), crude ash (CA), crude protein (CP), and gross energy (GE). Apparent total tract digestibility of organic matter (dOM)

[5] This chapter is not published but the publication format has been applied in keeping with the format of the rest of the chapters some of which have been published or ready for submission.

was estimated using *in vitro* gas production. Estimation of CH_4 emissions was done using IPCC Tier 2 methodology. Uncertainty analysis was done using coefficients of variation (CV) method. The uncertainties were combined using IPCC method of propagation of errors. The EIs, in carbon dioxide equivalent (CO_2eq.) using a global warming potential of CH_4 of 25 times that of CO_2 over a 100-year time horizon (IPCC, 2007), were calculated from the total annual emission divided by the total annual production. Tier 1 methodology under-estimated EFs of young, pregnant, and lactating cattle but over-estimated EFs of dry non-pregnant and adult male cattle. Estimation of intensities should consider multi-functionality of cattle for valid decisions on possible mitigation measures. The intensities reveal a large potential for mitigation of emissions. Uncertainties associated with Tier 2 methodology were lower than those of Tier 1. Milk production records, liveweight (LW), and diet digestibility require more accurate determination because they contributed most to uncertainty.

Key words: Emission factors, emission intensity, uncertainty

Abbreviations: CA, crude ash; CM, consumable meat; CP, crude protein; DE, digestible energy expressed as a percentage of gross energy; DM, dry matter; DMI, dry matter intake; dOM, apparent total tract organic matter digestibility; EF, emission factor; GE, gross energy; GEI, gross energy intake; GHG, greenhouse gas; GP is the net gas production after 24 hours of incubation; HG, heart girth; IPCC, Intergovernmental Panel on Climate Change; LW, liveweight; LWG, liveweight gain; OM, organic matter; REG, ratio of net energy in diet available for growth to digestible energy consumed; REM, ratio of net energy in diet available for maintenance to digestible energy consumed, Y_m, methane conversion factor of the feed.

6.1 Introduction

Demand for animal products has been on the increase fueled by increasing global human population (United Nations, 2001) and change in dietary patterns towards preference for animal-based food products (Popkin, 2009). The consumption of animal protein has increased (United Nations, 2006) with increasing urbanization, literacy levels (UNESCO, 2016), and personal disposable incomes (Lakner and Milanovic, 2015). Increased livestock production, especially in ruminant production systems, to match this demand must be from improved efficiencies and not increased livestock numbers which would increase release of enteric methane (CH_4). The CH_4 is both a waste of feed energy (Johnson and Johnson, 1995) and a greenhouse gas causing climate change (IPCC, 2007). It is important that accurate reporting of CH_4 emissions in ruminant production systems is done to form a basis for farm system optimization and policy interventions.

Many countries in the developing world are generating little or no data on emissions (Du Toit et al., 2013b). Data on sub-Saharan Africa (SSA) emissions are scarce. When such data exist, they are based on global default Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factors (EF) (IPCC, 2006a) because the SSA countries do not have their own EFs. These default IPCC Tier 1 EF values are not specific to the prevalent production systems in different regions and do not account for possible differences in CH_4 emissions between different cattle (i.e., with respect to breeds and physiological states) or for differences in feed intake levels and diet compositions. Secondly, Tier 1 EFs are accompanied by large uncertainties due to their lack of region-specificity (Dong et al., 2006). It is considered good practice by IPCC to report emission inventory with its associated uncertainties because the level of uncertainty provides information

on the reliability of the estimate in drawing conclusions and making decisions (Dong et al., 2006; Frey et al., 2006). A more refined method with lower uncertainties for estimating emissions is to develop own Tier 2 EFs based on area-specific feed and cattle characterization (Dong et al., 2006). Kenya, for instance, carried out only one greenhouse gases (GHG) inventory, in 2005, based on animal population data from 1994 (over 10 years old) and used Tier 1 EFs (NEMA, 2005) accompanied by ±50% uncertainty (Dong et al., 2006). This information is outdated and likely does not reflect the current state due to possible changes in herd compositions and sizes, feed quality, and breed composition. Emission intensity (EI) plays an important role in guiding mitigation policy by assigning typical CH_4 emissions to products (i.e., emissions per unit product), and seeking ways to optimize productivity so as to rationalize the emissions accompanying the production processes.

Objectives of the present study were therefore to i) use IPCC Tier 2 methodology to estimate enteric CH_4 EF and associated emissions; ii) estimate the EIs; and iii) derive the uncertainties accompanying the estimated EFs in cattle systems of Western Kenya.

6.2 Materials and methods

6.2.1 Study site

The study was done in a 100 km^2 Lower Nyando block in Western Kenya, East Africa (0°13’30’’S - 0°24’0’’S, 34°54’0’’E - 35°4’30’’E). The area was part of Climate Change Agriculture and Food Security (CCAFS) sentinel sites detailed in Sijmons et al. (2013) and Förch et al. (2014). The site was selected to represent three distinct geographies common to the area which were also heterogeneous with regards to livestock management, i.e., the Lowlands (0 - 12% gradient in slopes), the Mid-slopes (12 - 47% gradient, steeper at the

escarpment), and the Highlands (> 47% gradient at escarpments, 0 - 5% at the plateau) with altitudes ranging from 1200 m to 1750 m above sea level (Verchot et al., 2008; Rufino et al., 2016). More details on the study site is available in (Sijmons et al., 2013). The climate is humid to sub-humid with bi-modal rainfall pattern (i.e., long and short rains). The rainfall is about 1200 - 1750 mm per annum, mean annual temperature being 17.0 ^{o}C (minimum) and 29.4 ^{o}C (maximum). There are four seasons, i.e., long dry season (January - March), long wet season (April - June), short dry season (July - September), and short wet season (October - December) (Zhou et al., 2007). Farmers are smallholders practicing mixed crop-livestock agriculture. About two-fifths of the land cover is rangelands that are mainly used for grazing livestock (Verchot *et al*. 2008). The livestock kept are cattle, sheep, goats, chicken, and donkeys. The dominant livestock species in the Highlands are cattle, in the Mid-slopes cattle and goats, and in the Lowlands a mixture of the three groups of ruminant species: cattle, sheep, and goats (Ojango et al., 2016). The study focused on cattle systems in the area with important cattle breeds being East African shorthorn zebus: Kavirondo zebus in the Lowlands, Nandi zebus in the Mid-slopes, and zebu x *Bos taurus* crossbreeds in the more commercial dairy-oriented Highlands.

A longitudinal survey was carried out in 60 households in 20 villages (i.e., 24 households in eight villages in the Lowlands, 18 households in six villages each in the Mid-slopes, and in the Highlands) were selected based on results of the IMPACTLite survey conducted earlier in the area (Rufino et al., 2013; Silvestri et al., 2014; Förch et al., 2014). More details on the sampling frame are available in Förch et al. (2014) and sample size determination is detailed in chapter 4.

6.2.2 Cattle and diet data collection

Data was collected as detailed in Goopy et al. (submitted). Briefly, farm visits were conducted every three months, between July 2014 and July 2015, to coincide with the four climatic seasons in the study area. All cattle in the study were identified by numbered ear tags (Allflex Europe SA, Vitre) applied at the initial visit and subsequently for new additions at the first encounter. The age of the cattle was estimated using dentition (Torell et al., 1998). Farmers gave information on number of hours worked by draught males, parity, pregnancy, and lactation status of the adult females. Liveweight (LW) was determined at every visit using a 600 kg - 3 tonne capacity, portable weighing scale (1.0 m x 1.0 m x 1.5 m Animal Weighing Scale, Endevour Instrument Africa Limited, Nairobi, Kenya) fitted with a display indicator (Model EKW, accuracy 0.2 kg, Endevour Instrument Africa Limited, Nairobi, Kenya). Heart girth circumference (HG) was measured every time LW was recorded and body condition scored on a 1 - 5 scale according to (Edmonson et al., 1989). Milk records were kept by farmers who used graduated plastic containers (1500 ml Jug, Kenpoly Limited, Nairobi) and a notebook. These records were collected from the farmers and collated every two months.

At the beginning of each cropping season (i.e., long wet and short wet seasons), total area of the farms and plots was assessed using a laser range finder (Truth Laser Range Finder, Bushnell Outdoor Products, USA) and the different land uses per plot recorded. Pasture yield was estimated according to chapter 4. Farmers in the study provided information on the other feedstuffs they fed their cattle in addition to grazing the natural pasture vegetation during each of the four seasons. The biomass yield of maize crop residues was estimated based on farmer information on grain yield and crop harvest index (Hay and Gilbert, 2001) and Napier grass biomass yield was based on Nyambati et al. (2010). Biomass of other feedstuffs used i.e., banana pseudo

stems, sweet potato vines, and sugarcane were estimated from farmer information on the amount and frequency of feeding. All the feedstuffs on offer were pooled by type of feed, geographical zone (hereafter referred to as “zone”), and season. Proportion of each feedstuff in the seasonal diet was assumed to be proportional to biomass availability of each feedstuff in the zone or season.

Samples of pasture herbage and all the feedstuffs fed to cattle in the study area were collected from all the households every season, as detailed in chapter 4. The samples were analysed in duplicate for dry matter (DM) by placing about 0.5 g of the samples in a forced-air oven at 105°C overnight followed by crude ash (CA) analysis by incineration in a muffle furnace at 550°C (Model N 11, Nabertherm, Bremen, Germany) for 4 hours both methods according to Naumann and Bassler (2007). Crude protein (CP) concentration was determined by Dumas combustion (Vario Max C/N Analyser, Elementar Analysensysteme GmbH, Hanau, Germany) for Nitrogen concentrations multiplied by 6.25. The apparent total tract digestibility of organic matter (dOM) was estimated from gas production during *in vitro* incubation of the feed samples for 24 hours (Menke and Steingass, 1988; chapter 4) run in triplicate twice, each time on a different day. The gross energy (GE) was analysed using bomb calorimetry (C 7000 Isoperibolic, Janke & Kunkel IKA – Analysentechnik, Staufen, Germany). Analyses were repeated in case the relative standard deviation of the duplicate or triplicate determinations was less than 5% of the mean values.

Mean dOM and GE concentrations of the diets offered to cattle during different seasons was obtained by using the equation:

$$\text{Diet dOM (g/100 g OM)} = \Sigma\ [(x_i * \text{dOM of the feedstuff}_i)/100] \qquad (1)$$

where OM is the organic matter; x is the dry matter proportion of the feedstuff, i, in the diet of cattle (in %).

The mean seasonal diet dOM values calculated above were then used for subsequent calculations for emission factors (Table 1).

6.2.3 Estimation of enteric methane emissions and emission intensities

Estimation of GHG emissions was based on Tier 2 methodology of IPCC Guidelines for National Greenhouse Gas Inventories (Dong et al., 2006). Briefly, the cattle were categorized as young stock (< 1 year old), adult males (> 1 year old), and adult females (> 1 year old). The adult females category was further differentiated into to the following sub-categories: dry non-pregnant, pregnant, and lactating cows. Net energy requirements for each individual animal were calculated from their average LW, liveweight gain (LWG), number of hours worked, if pregnant, and the average milk yield and milk fat content in case of lactating cows using the equations and coefficients presented in Table 2.

Table 1. Proportion of individual feedstuffs in the total diets and apparent total tract organic matter digestibility of the feedstuffs (N = 24) offered to cattle in Lower Nyando, Western Kenya, during different seasons between August 2014 and May 2015.

Zone	Feedstuff	Short dry season		Short wet season		Long dry season		Long wet season	
		Proportion in diet (% as fed)	dOM g/ 100 g OM	Proportion in diet (% as fed)	dOM g/ 100 g OM	Proportion in diet (% as fed)	dOM g/ 100 g OM	Proportion diet (% as fed)	dOM g/ 100 g OM
Lowlands	Pasture	93.9	57.2	98.6	59.2	34.7	55.9	100.0	53.6
	Tree leaves[ɣ]	0.0	0.0	0.0	0.0	55.6	42.5	0.0	0.0
	Sugarcane tops	0.0	0.0	0.0	0.0	9.0	43.0	0.0	0.0
	Maize stover*	6.1	52.7	1.4	52.7	0.7	52.7	0.0	0.0
	Average dOM		**56.7**		**59.0**		**46.0**		**53.6**
Mid-slopes	Pasture	100.0	58.1	100.0	60.2	90.7	51.6	100.0	52.8
	Sugarcane tops	0.0	0.0	0.0	0.0	9.3	43.0	0.0	0.0
	Average dOM		**58.1**		**60.2**		**50.3**		**52.8**
Highlands	Pasture	72.1	56.3	78.2	54.9	83.4	54.4	83.4	50.6
	Banana stems	1.3	54.4	1.3	54.4	1.3	54.4	1.3	54.4
	Napier Grass	14.3	58.7	14.3	58.7	14.3	58.7	14.3	58.7
	Banana leaves	1.0	41.6	1.0	41.6	1.0	41.6	1.0	41.6
	Sweet potato vines	1.9	65.0	0.5	65.0	0.0	0.0	0.0	0.0
	Maize stover*	9.4	52.7	4.7	52.7	0.0	0.0	0.0	0.0
	Average dOM		**55.9**		**55.5**		**54.7**		**51.3**

*dOM of maize stover from Methu et al. (2001); dOM = apparent total tract organic matter digestibility as estimated from proximate composition and gas production during *in vitro* incubation (Menke and Steingass, 1988) using the following equation: dOM (g/100 g OM) = 15.38 + 0.8453 • gas produced + 0.0595 • crude protein + 0.0675 • crude ash; OM = organic matter. For details see text.

[ɣ]*Balanite aegyptiaca* and *Mangifera indica* leaves.

Average dOM (g/100 g OM) = Σ [(x_i * dOM of the feedstuff$_i$)/100]; where x is the dry matter proportion of the feedstuff, i, in the diet of cattle (in %).

Table 2. IPCC equations and coefficients used in calculation of net energy requirement in this study.

NE requirement MJ day^{-1}	**Equation**	**Category**	**Coefficient**
Maintenance	Coefficient * (kg LW)$^{0.75}$ (MJ day^{-1} kg^{-1})	Non-lactating cows	0.322
		Lactating cows	0.386
		Bulls	0.370
Activity	Coefficient * NE_m	Grazing large areas	0.360
Growth	22.02 * ((LW/Coefficient *MW)$^{0.75}$) * (LWG)$^{1.097}$	Growing females	0.8
		Growing bulls	1.2
Lactation	Milk * ((1.47 + (0.40 * Fat))	Lactating cows	-
Work	0.10 * NE_m * Hours	Draught bulls	-
Pregnancy	Coefficient * NE_m	Pregnant cows	0.1

From Dong et al. (2006).
Fat = average fat content of the milk (4%, w/w); Hours = average number of hours worked (hours/day); LW = average liveweight of cattle in the population (kg); LWG = average daily LW gain (kg/day); Milk = average milk production (kg/day; converted from litres by assuming a density of 1.03 kg/l at 25°C, 1 atmosphere pressure); MW = average mature LW of an adult female in moderate body condition (kg) which was 179.1 kg in the Lowlands, 219.3 kg in the Mid-slopes, and 280.9 kg in the Highlands; NE = net energy; NEm = net energy requirements for maintenance (MJ day^{-1}).

The total daily net energy requirements of animals of each category were then used to estimate the daily gross energy intake per animal by summing the net energy requirements and dividing by the ratio of energy in the diet available for various functions to digestible energy consumed in the diet:

$$\text{Gross energy intake (GEI), MJ day}^{-1} = \{[(NE_m + NE_a + NE_l + NE_w + NE_p)/REM](NE_g/REG)\} / (DE/100) \quad (2)$$

where, NE_m, MJ day^{-1} = net energy required for maintenance;

NE_a, MJ day^{-1} = net energy required for activity (grazing large areas);

NE_l, MJ day^{-1} = net energy required for lactation;

NE_w, MJ day^{-1} = net energy required for work;

NE_p, MJ day^{-1} = net energy required for pregnancy;

NE_g, MJ day^{-1} = net energy required for growth; negative for negative LWG

REM = ratio of net energy available in the diet for maintenance to digestible energy consumed = $[1.123 - (4.092*10^{-3} * DE) + 1.126*10^{-5} * (DE)^2] - (25.4/DE)]$; (3)

REG = ratio of net energy available in diet available for growth to digestible energy consumed = $[1.164 - (5.160*10^{-3} * DE) + [1.308 *10^{-5} * (DE)^2] - (37.4/DE)]$; (4)

DE, % of gross energy = digestible energy.

The gross energy intake per animal was then converted to the EF by multiplying with the CH_4 conversion factor and dividing by energy content of CH_4 as shown:

EF, kg CH_4 $head^{-1}$ $year^{-1}$ = $[GEI * (Y_m/100) * 365] / 55.65$ (5)

where, GEI, MJ day^{-1} = gross energy intake;

Y_m, % of gross energy = CH_4 conversion factor of the feed assumed to be 6.5%; and 55.65 is the energy content of CH_4 in MJ kg^{-1} CH_4 (Dong et al., 2006).

The category EF was obtained from the average of the individual animal EF. Using the category EF and the number of cattle in the category gives the CH_4 emission per category. The total overall CH_4 emission is obtained by summing all the category CH_4 emissions as shown:

The annual emissions per cattle category per zone, E (kg CH_4 $year^{-1}$)

= Category EF *the number of cattle in the respective cattle category (6)

Total emissions for all cattle categories per zone, kg CH_4 $year^{-1}$ = Σ E (7)

Tier 1, Tier 2, and simplified Tier 2 are methods used by IPCC to estimate enteric EFs (Dong et al., 2006). Tier 1 methodology of IPCC uses default values on typical cattle performance data of cattle in Africa (Table 3) not

considering the prevailing specific production levels, physiological states, or feed characteristics. Tier 2 methodology is outlined above.

Table 3. Cattle and feed characterization parameters used in enteric methane emission factors using default IPCC Tier 1 and Tier 2 methodology for cattle in Lower Nyando, Western Kenya between August 2014 and May 2015.

IPCC Method	Category	LW (kg)	LWG (kg day^{-1})	Milk (kg day^{-1})	Work (hr day^{-1})	DE (% GE)	GE (MJ kg^{-1} DM)	Y_m (% GE)
Tier 1 †	Young	75	0.10	0.0	0.00	60.0	18.45	6.5
	Adult males	275	0.00	0.0	1.37	55.0	18.45	6.5
	Mature females	200	0.00	0.3	0.00	55.0	18.45	6.5
Tier 2 ɣ	Young	100	0.12	0.0	0.00	54.7*	16.56	6.5
	Adult males	215	0.02	0.0	1.54	54.7*	16.56	6.5
	Mature females	216	-0.01	1.6§	0.00	54.7*	16.56	6.5

†From Dong et al. (2006); ɣbothoriginal and simplified Tier 2 methods; *apparent total tract organic matter digestibility of feed.
DE = digestibility of feed (% of gross energy); GE = gross energy; hr = hours; LW = liveweight; LWG = liveweight gain; Y_m = methane (CH_4) conversion factor (percent of gross energy in feed converted to CH_4); §the milk fat content used in calculating the net energy for lactation was 5.9% w/w for the Lowlands and the Mid-slopes, and 4.4% for the Highlands based on milk fat content in Nandi County, Kenya with similar agro-ecological zones (P. Wanjugu, personal communication).

Simplified Tier 2 methodology employs cattle LW and estimated dietary net energy concentration (NE_{ma}) or, for the case of mature dairy cattle, digestible energy as a percentage of GE of the feed. Prediction equations are used to estimate dry matter intake (DMI) which is then converted to GEI by multiplying it with the GE concentration of the feeds (Dong et al., 2006). The GEI is then used to derive the EF for the cattle category using equation (5) above.

DMI for young, kg day^{-1} = $LW^{0.75} * [(0.2444 * NE_{ma} - 0.0111 * NE_{ma}^2 - 0.472)/NE_{ma}]$ (8)

DMI for adult males, kg day^{-1} = $LW^{0.75} * (0.0119 * NE_{ma}^2 + 0.1938)/NE_{ma}]$ (9)

DMI for adult females, kg day^{-1} = {[(5.4 * LW)/100]/[(100 - DE)/100]} (10)

where, LW, kg = liveweight; and

NE_{ma}, MJ kg^{-1} DM = (REM * GE * DE) / 100; with (11)

REM = ratio of digestible energy available for maintenance to digestible energy consumed;

GE (MJ kg^{-1} DM) = gross energy of the feed; and

DE (% of feed GE) = digestible energy.

The GEI (MJ day$^{-1)}$ was calculated by multiplying DMI by the GE concentration in the cattle diets. Subsequently, EF (in kg CH_4 head^{-1} year^{-1}) was calculated based on equation (5).

In chapter 4 we discussed two equations to predict digestibility of feeds, Matlebyane et al. (2009) and Hughes et al. (2014) equations. These equations were used in place of dOM as estimated from *in vitro* gas production (Menke and Steingass. 1988) to estimate digestibility of feeds based on seasonal diets shown in Table 1. The estimated weighted mean digestibility (i.e., 59.6% for Matlebyane et al. (2009) equation, and 65.4% for Hughes et al. (2014) equation) values were then employed in Tier 2 methodology holding all the other parameters constant as in Table 3.

Goopy et al. (2017) proposed three algorithms for LW estimation using HG measurement of which two most promising for use by smallholders in SSA are Box and Cox (1964) (BOXCOX-LR) and square root transformation of LW using linear regression (SQRT-LR). The LW in IPCC Tier 2 methodology was varied using these two algorithms to test the effect of the algorithms on the EF of the cattle. All the input parameters for EF estimation were the same as for Tier 2 methodology except LW. The arithmetic mean ± standard deviation of HG was 102 ± 23.0 cm for young cattle, 139 ± 9.3 cm for adult males, and 139 ± 10.9 cm for adult females.

Tier 2 methodology of IPCC specifies that a range of 6.5 ± 1% of GE of the feed is converted to CH_4. Here, both the lower (i.e., 5.5%) and upper (i.e., 7.5%) limits were tested in the calculations to find out how much they differed from the default value (i.e., 6.5%) for low digestible tropical feeds in African rangelands. The fat content of the milk (g/100 g milk) used in the equation for net energy for lactation was varied using 3.5 g/100 g milk which is the level of fat found in most Kenyan commercially packaged full fat pasteurized milk brands; and 7.0 g/100 g milk, which was the highest milk fat content of East African zebu breeds/strains in Rege et al. (2001) as other parameters were kept constant. The resulting EF were then compared to the Tier 2 value based on milk fat content of 5.9 g/100 g milk for the Lowlands and the Mid-slopes, and 4.4 g/100 g milk for the Highlands. These values were those measured in Nandi County, Kenya for similar agro-ecological zones as those in this study (P. Wanjugu, personal communication).

The EI of milk and meat production were calculated from the total annual emission per zone divided by the annual milk and meat production per zone as follows:

Milk EI, kg CH_4 kg^{-1} milk = (Σ E) / annual milk production (12)

Meat EI, kg CH_4 kg^{-1} CM = (Σ E) / (CM * annual cattle sales) (13)

where, CM is the consumable meat of the cattle calculated as

CM (kg) = LW at sale * 52% dressing percentage * 69% consumable meat percentage (Rewe et al., 2006) (14)

The EI was converted into carbon dioxide equivalent (CO_2eq.) by multiplying the intensities in kg CH_4 kg^{-1} product with the global warming potential of CH_4 of 25 times that of CO_2 over a 100-year time horizon (IPCC, 2007).

6.2.4 Uncertainty analysis

Robustness of the results from Tier 2 method used to derive the EFs as well as identification of critical areas to concentrate on during data collection was determined using uncertainty analysis. Uncertainty is a pointer as to the quality of process of estimating EF, and shows the reliability of the results to guide further discussions and decisions based on the EFs. Uncertainty analysis was done on all cattle and feed characterization data (i.e., LW, daily milk production, number of hours worked, and digestibility and GE of the feedstuffs) of 388 cattle used as input parameter to the Tier 2 method across all seasons and zones and emission factors. This was done according to Kelliher et al. (2007).

Uncertainty of the input parameter i in an animal category across the four seasons,

$$U_i = SEM_i / Mean_i \quad (15)$$

where, SEM_i = standard error of the mean of variable i in the category

= (standard deviation /$\sqrt{n}$);

n = number of observations in the category per season;

i = input parameter

The SEM for the input parameters was calculated from individual animal data in a category (regardless of the zone) per season. This resulted in an uncertainty value of the parameter per season. The seasonal uncertainties were then combined using rule B of propagation of errors (Frey et al., 2006; Kelliher et al., 2007) given that the standard error of the mean of the parameters was less than 30% of the mean and assuming none of the variables were correlated.

$$U_{total} = [\sqrt{(U_1^2 + U_2^2 + \ldots + U_n^2)}] \quad (16)$$

where, U_{total} = uncertainty in the product of the parameters; and

U_i = uncertainty of the parameter i.

Contribution of each variable to cumulative uncertainty was then calculated as:

$$U_i (\%) = (U_i / U_{total}) * 100. \quad (17)$$

6.2.5 Statistical analyses

Number of observations per season varied as animals moved in and out of the study households (i.e., through births, deaths, sales, and gifts). A total of 417 animals were observed, however only animals that were in a household for two consecutive seasons (to allow for observation of LWG) were considered in the calculation of EF and accompanying uncertainties, thus the number of working observations reduced to 388. The calculations (i.e., GEI and CH_4 emission in one year) were first done for each individual animal per season (i.e., N = 388). The animals were then aggregated into categories per zone (i.e., n = 15) and the annual EF of the category calculated by averaging the seasonal EFs per zone. Emissions were then calculated per zone by multiplying the annual EF with the total working number of animals (i.e., those observed at least two consecutive seasons) in the zone. Each zone was then considered as a single enterprise for production parameters (i.e., daily milk production, lactation days per season, LW of sold animals), emissions, and EIs (i.e., n = 3).

Descriptive statistics and one-way ANOVA was done using R 3.2.5 (R Development Core Team, 2016). The following statistical model was used to analyse the differences in disaggregated production parameters (i.e., daily milk production, lactation days per season, and LW of sold animals), and EFs per animal category between the zones:

$$Yi = \mu + Si + \varepsilon i;$$

where Yi = response production parameters; μ = overall mean; Si = effect of the zone, i; and εi = random effects.

$$Yj = \mu + Sj + \varepsilon j$$

where Yj = response emission factor; μ = overall mean; Sj = effect of the methodology, j; and εj = random effects.

Arithmetic means were compared using multiple comparison tests using Tukey HSD and differences declared at $P<0.05$.

6.3 Results and discussion

6.3.1 Cattle populations, performance and diet characterization

Cattle populations (heads household^{-1}) were numerically largest in the Mid-slopes ($P<0.05$, Fig. 1a) for all the cattle categories, and smallest in the Highlands, except for lactating cows whose proportion in the total cattle population was highest in the Highlands. Cattle numbers and production in the zones differ depending on their level of intensification. Mid-slopes has the most extensive system while the Highlands have the most intensive system with a greater emphasis on milk production. Average daily milk yield of cows in the Highlands without including the milk fed to the calves (i.e., 3.3 kg equivalent to 3.4 l cow^{-1}, Table 4) is lower than reported for dairy systems in Central Kenya (14.6 l cow^{-1}; in Rufino et al. (2009), despite similarities in agro-ecological conditions which predispose the Highlands to high production, showing that there is a great potential for increasing production and thus animal performance in the Highlands which would reduce EIs from the zone.

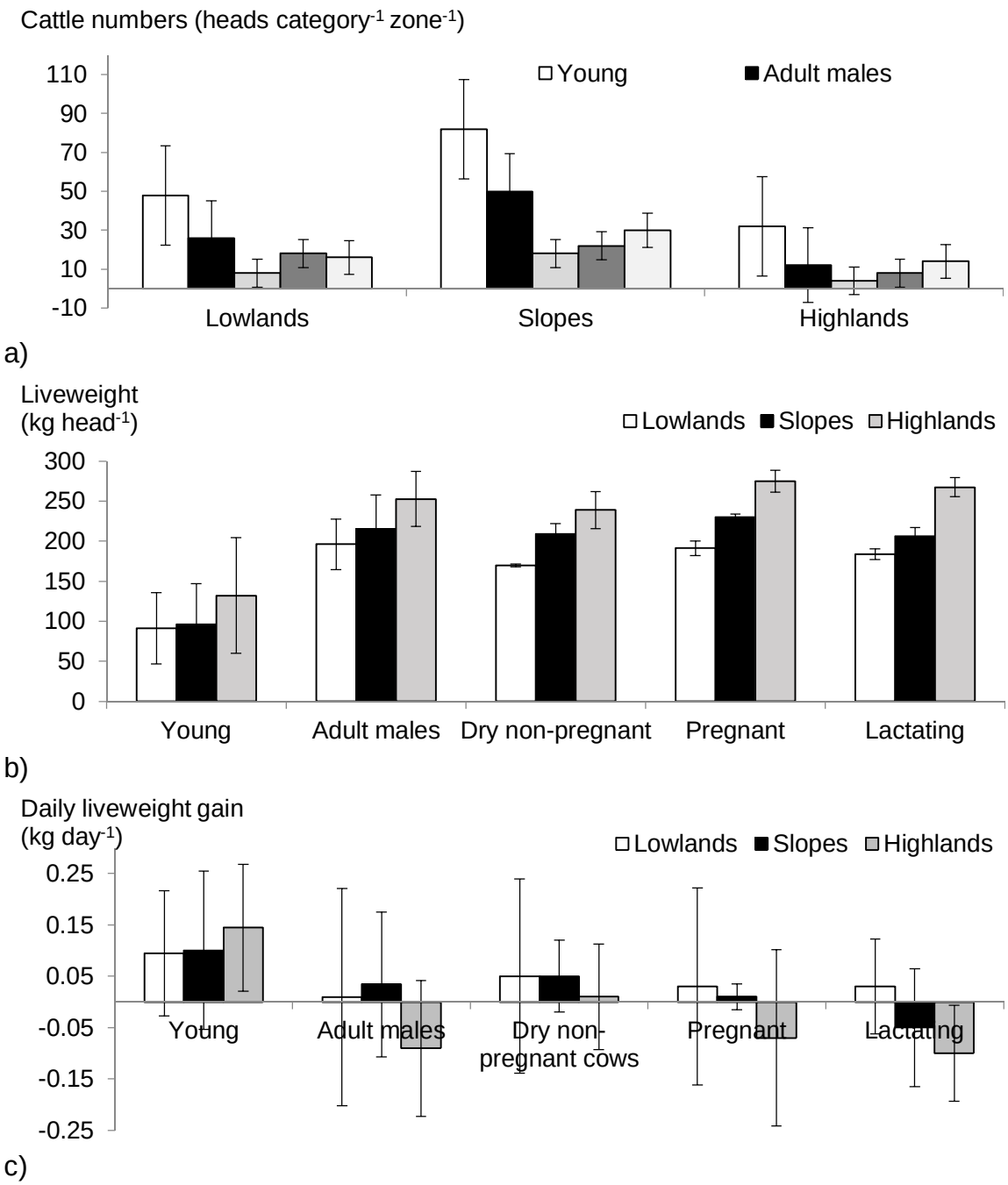

Fig. 1. a) Herd composition, b) liveweight, and c) daily liveweight gain of cattle (arithmetic mean ± standard deviation) across the seasons in the zones of Lower Nyando, Western Kenya, between August 2014 and May 2015.

Category: young (< 1 year old); adult males, dry non-pregnant, pregnant, and lactating (> 1 year old). Number of observations across seasons is equal to the cattle numbers per category per zone in a); No significant differences between zones P = 0.117 in a); P = 0.167 in b); and P = 0.332 in c).

Cattle herds mainly comprised young, followed by adult males, and adult cows. Proportions of young stock in cattle herds were likely high due to the high rates of mortality at 18.3% of all the calves (Goopy et al., 2018). This mortality requires that farmers keep a large number of calves for replacement. In the same line, about 35% of adult females are older than six years and thus past optimum productive age. Hence, there appears to be a high potential to increase overall herd performance and thus to reduce EIs by, for instance, reducing calf mortality and a greater selection of animals to reduce the proportion of non- or low-producing animals in the herd.

Farmers in the Mid-slopes kept large numbers of adult males for draught power to plough the lands due to relatively low labour availability compared to the other zones (Tsegaye et al., 2008; Jayne and Muyanga, 2012). The herd numbers and structures highlight the multiple purposes of livestock husbandry in such smallholder farming systems.

Cattle in the Highlands had, numerically, the highest and those of the Lowlands the lowest average LW (kg head^{-1}) for all the categories. In the same line, net LWG of young cattle was numerically highest ($P<0.05$, Fig. 1c) and daily milk production (kg cow^{-1}) significantly highest ($P<0.01$, Table 4) in the Highlands. Generally, farmers in the Highlands were observed to primarily keep the expensive, more productive crossbred cows that tend to have higher LW and genetic potential (Rege et al., 2001) as compared to the local zebu cattle which are commonly kept in the other two zones. Moreover, the superior nutritional quality and availability of feedstuffs to animals in the Highlands (see Table 1 and chapter 4) may explain their higher LW and performance as compared to cattle in the Mid-slopes and Lowlands. Instead, farmers in the Mid-slopes sold more animals as compared to those in the Highlands and Lowlands (heads year^{-1} and kg CM year^{-1}).

Table 4. Milk and meat production in 60 households in the zones of Lower Nyando, Western Kenya (arithmetic mean ± one standard deviation, number of observations in parentheses) between August 2014 and May 2015.

Parameter / Zone	**Lowlands**	**Mid-slopes**	**Highlands**	**P-value**
Daily milk production[§] (kg cow^{-1})	0.8^{a} ± 0.47 (16)	1.2^{a} ± 0.40 (30)	3.3^{b} ± 1.30 (14)	0.007
Lactation duration (days per season^{-1})	60^{a} ± 54.1 (16)	74^{a} ± 64.4 (30)	92^{a} ± 13.1 (14)	0.712
Liveweight of sold cattle (kg head^{-1})	151.4^{a} ± 57.35 (18)	155.9^{a} ± 72.24 (49)	181.9^{a} ± 91.79 (19)	0.365
Milk produced (kg year^{-1} zone^{-1})	3,072	10,656	16,863	na
Meat sold (kg year^{-1} zone^{-1})	978	2,741	1,240	na

[§]Milk production less the milk used by suckling calves; Liveweight is convert to consumable meat using a dressing percentage of 52% of slaughter weight and consumable meat percentage of 69% of dressed weight (Rewe et al., 2006). Different superscripts in a row denote significant differences (P<0.05).

The LWG in the present study (i.e., ± 0.1 kg day^{-1}) was generally low but similar to those of Brahman crossbreds in Vietnam on low quality diet (Quang et al., 2015) and more than five times lower than those found in grazing Friesians in New Zealand (Lassey et al., 1997) and two to five times lower than cattle grazing native pasture in dry tropics and subtropics of Australia (Shaw & Mannetje (1970) and McCown et al. (1986) cited in Rao et al. (2015)).

These differences are possibly due to differences in genetic potential of the cattle for feed conversion and quality of feedstuffs on offer. There were large variations in daily LWG in all zones and categories. This is possibly due to large differences in individual management decisions regarding the genetics of livestock holding, feeding, and general husbandry. There is a possibility of season x zone interactions in daily LWG. The effect of these interactions could have been that a zone such as the Lowlands, which has a scarcity of feed resources all year round, showed lower LWG variations because seasonal effects have less impact on LWG as compared the Highlands that have distinct seasons of plenty and scarcity of feed resources. Overall, a positive daily LWG was observed for young and dry non-pregnant cows (composed mainly of still growing heifers) in all zones which is likely related to the higher growth potential of the growing cattle as compared to the mature cattle. Adult males, pregnant, and lactating cows (i.e., the productive cattle) in the Highlands showed a daily LW loss, as did lactating cows in the Mid-slopes. Energy and protein requirements of the productive animals are higher than of those of the other categories and were apparently not met, particularly during the long dry season, resulting in a mobilization of their body reserves (chapter 4). Hence, there is need for strategic differentiated feeding of individual or small groups of cattle in a herd according to their performance level and nutritional requirements in order to achieve higher production levels and to avoid excessive LW losses during periods of feed scarcity (Dickhoefer et al., 2011). Negative LWG of

cows in the Highlands is possibly due to poor nutrition which is not commensurate to high maintenance and production energy requirements of the large physical frame of crossbreed cows. This results in short lactating periods where the animals quickly dry and start gaining weight again due to reduced energy requirements (i.e., no more energy for lactation required). This has adverse effect on productivity because the animals rarely reach their genetic potential. There is need to improve feed resources in tandem with improving genetic potential of cattle since higher producing cattle tend to be more feed-intensive.

Pasture is the main feedstuff with the exception of the long dry season in Lowlands and Mid-slopes due to unavailability and in Highlands, in short dry and short wet seasons, due to availability of alternative feedstuffs (Table 1). Diet digestibility is subject to seasonal and zonal variability resulting nutritional deficiencies (chapter 4). The implication of this variability in quality and quantity of feedstuffs is that enteric CH_4 emissions are likely not to be uniform or similar and thus results from one agro-ecological zone may be of limited inferential use to another zone.

6.3.2 Emission factors and emission intensity

The Tier 2 EF ranged between 20 - 29 kg CH_4 head^{-1} year^{-1} for the young; 34 - 48 kg CH_4 head^{-1} year^{-1} for dry non-lactating; 36 - 45 kg CH_4 head^{-1} year^{-1} for pregnant; 40 - 50 kg CH_4 head^{-1} year^{-1} for adult males; and 50 - 63 kg CH_4 head^{-1} year^{-1} for lactating cows (Table 5). The EF estimated according to Tier 2 methodology greatly depend on the animal and feed characteristics used as input parameters (Dong et al., 2006). Hence, with the exception of the adult males, Tier 2 EF in the present study were similar to those estimated for cattle herds in India, also composed of zebu breeds of similar LW and milk production, and with diets of comparable digestibility (Swamy and Bhattacharya, 2006).

Table 5. Emission factors (kg CH_4 head^{-1} year^{-1}) of various cattle categories in the geographical zones of Lower Nyando, Western Kenya, as estimated from data collected during August 2014 and May 2015 (arithmetic mean ± standard deviation, number of observations in parentheses).

Zone / Category	**Young**	**Adult male**	**Dry non-pregnant**	**Pregnant**	**Lactating**
Lowlands	20.2[a] ± 7.61 (48)	39.9[a] ± 18.26 (26)	34.4[a] ± 14.52 (8)	38.9[a] ± 25.12 (18)	50.5[a] ± 17.46 (16)
Mid-slopes	23.4[a] ± 10.66 (82)	45.7[ab] ± 13.79 (50)	40.4[a] ± 18.86 (18)	45.7[a] ± 24.97 (20)	50.0[a] ± 19.38 (30)
Highlands	29.1[b] ± 12.26 (32)	50.0[b] ± 11.29 (12)	48.2[a] ± 21.09 (4)	36.8[a] ± 33.81 (8)	62.7[b] ± 27.95 (14)
Overall	23.7 ± 10.68	44.1 ± 15.65	39.1 ± 18.65	42.2 ± 25.55	53.2 ± 21.90
P-value	< 0.001	0.023	0.181	0.182	0.001

Category emission factor = [estimated category gross energy intake * Methane (CH_4) conversion factor (Y_m) * 365] / 55.65. Y_m was assumed to be 6.5% (Dong et al., 2006), 365 days in a year, and the energy content of CH_4 is 55.65 MJ/kg).

Category: young (< 1 year old); adult males; dry non-pregnant cows; pregnant cows; and lactating cows (all > 1 year old).

Moreover, Tier 2 EF for the young and female categories in the present study were also similar to those of Borgou cattle in Benin with similar LW and offered diets of similar composition and digestibility (Kouazounde et al., 2014). The EFs here were similar to those in Asia for other non-dairy cattle (Yamaji et al., 2003 cited in Fu and Yu (2010)) but lower than those in China for the same type of cattle (Zhou et al., 2007; Dong et al., 2004) and South African cattle in all systems from dairy on concentrate diet to pasture-based communal systems (Du Toit et al., 2013a). The differences in EFs can be attributed to differences in diet digestibility and LWs of cattle with the larger breeds having high maintenance requirements resulting in greater feed intake and thus higher emissions. The highest EF (kg of CH_4 head^{-1} year^{-1}) were determined for cattle in the Highlands for the young ($P<0.001$), adult male ($P<0.05$), and lactating cows ($P<0.01$) as compared to the Lowlands and the Mid-slopes (Table 5). The higher EF in the Highlands is possibly a result of higher average LW of the crossbred cattle and their higher milk yields, both resulting in higher energy requirements and thus higher estimated feed intake levels as compared to the other zones, which in turn increases CH_4 emission estimates (Yan et al., 2009). Tier 1 EF by IPCC were lower than the Tier 2 EF for young cattle ($P<0.001$) and lactating cows ($P<0.001$) across the zones (Table 6), but were higher than the Tier 2 EF for adult males ($P<0.001$).

The average LW of the young cattle used for the Tier 2 method was much higher than that assumed for Tier 1 estimates (Table 3) possibly leading to different EFs of the young. Moreover, average milk yields used for Tier 2 estimates in this study were about three to ten times higher than those assumed for Tier 1 estimates by IPCC (Table 3) which may explain the different EFs of the lactating cows. This reiterates the need for the more specific and representative Tier 2 as opposed to the generalized Tier 1.

Table 6. Emission factors for cattle as estimated by different models and by Tier 2 using different methods for estimating digestibility and liveweight, levels of methane conversion factor, and milk fat content in Lower Nyando, Western Kenya, between August 2014 and May 2015 (arithmetic mean ± one standard deviation).

Criteria	Method	Young	Adult males	Dry non-pregnant cows	Pregnant cows	Lactating cows
n		162	88	30	48	60
Models	Tier 1	16.0^{a}	49.0^{a}	$41.0d^{a}$	41.0^{a}	41.0^{a}
	Tier 2	23.7^{b} ± 10.68	44.1^{b} ± 15.65	39.1^{a} ± 18.65	42.2^{a} ± 25.55	53.2^{b} ± 21.90
	Simplified Tier 2	16.6^{a} ± 6.51	34.7^{c} ± 8.37	31.7^{b} ± 8.25	38.6^{a} ± 7.86	36.6^{c} ± 7.71
	P value	<0.001	<0.001	<0.001	0.084	0.000
Digestibility methods	Menke & Steingass	23.7^{a} ± 10.68	44.1^{a} ± 15.65	39.1^{a} ± 18.65	42.2^{a} ± 25.55	53.2^{a} ± 21.90
	Matlebyane	20.2^{b} ± 8.75	38.6^{b} ± 12.70	34.2^{b} ± 14. 40	38.1^{ab} ± 19.70	46.8^{b} ± 16.76
	Hughes	17.9^{c} ± 7.99	34.3^{c} ± 11.35	30.5^{b} ± 12.97	34.2^{b} ± 17.03	42.3^{c} ± 15.12
	P value	<0.001	<0.001	<0.001	0.002	0.000
LW methods	Measured LW	23.7^{a} ± 10.68	44.1^{a} ± 15.65	39.1^{a} ± 18.65	42.2^{a} ± 25.55	53.2^{a} ± 21.90
	BOXCOX LW	19.8^{b} ± 10.26	33.6^{b} ± 11.56	37.4^{a} ± 14.72	34.2^{a} ± 17.03	47.2^{a} ± 27.49
	SQRTLR LW	16.4^{c} ± 10.46	34.7^{b} ± 12.90	36.3^{a} ± 16.03	37.6^{a} ± 19.93	48.3^{a} ± 27.35
	P value	<0.001	<0.001	0.911	0.138	0.046
Y_m levels	Y_m 6.5%	23.7^{a} ± 10.68	44.1^{a} ± 15.65	39.1^{a} ± 18.65	42.2^{a} ± 25.55	53.2^{a} ± 21.90
	Y_m 5.5%	20.0^{b} ± 9.04	37.3^{b} ± 13.25	33.1^{b} ± 15.78	35.7^{b} ± 21.62	45.0^{b} ± 18.53
	Y_m 7.5%	27.3^{c} ± 12.32	50.9^{c} ± 18.06	45.2^{c} ± 21.52	48.7^{c} ± 29.48	61.4^{c} ± 25.27
	P value	<0.001	<0.001	<0.001	0.000	0.000
Milk fat content	4.4% and 5.9%	na	na	na	na	53.2^{a} ± 21.90
	3.5%	na	na	na	na	51.3^{a} ± 21.15
	7.0%	na	na	na	na	55.8^{a} ± 21.70
	P value	na	na	na	na	0.082

BOXCOX LW = emission factor (EF) estimated using LW from Box and Cox (1964) equation ($LW^{0.3595}$ = a + b(HG); HG = heart girth (cm); Hughes = EF estimated using DE derived from Hughes et al. (2014) equation; LW = liveweight; Matlebyane = EF estimated using DE derived using Matlebyane et al. (2009) equation; na = not applicable; SQRTLR LW = EF estimated using LW derived from square root transformation of LW using linear regression ($\sqrt{LW}$ = a + b(HG); Tier 1 = IPCC default EF for cattle grazing large areas in Africa; Tier 2 = EF estimated using measured LW, digestibility estimated from Hohenheim gas production method and Menke and Steingass (1988) equation, and milk fat of 5.9 g/100 g for Lowlands and Mid-slopes zones, and 4.4 g/100g for Highlands zone using IPCC Tier 2 methodology; Y_m 5.5% and Y_m 7.5% = EF estimated using methane (CH_4) conversion factor of 5.5% and 7.5% of gross energy in feeds converted to CH_4 respectively. Different letters in a column denote significant differences between the methods.

Overall, the meat EI was higher (i.e., 56 to 100 kg CO_2 eq. kg^{-1} meat) than the milk EI (i.e., 4 to 32 kg CO_2 eq. kg^{-1} milk) in all the zones (Fig. 2). The EIs of meat and milk were numerically highest in the Lowlands (but not statistically different, P>0.05) and lowest in the Highlands which is related to low production of cattle in the Lowlands, in terms of both, milk and cattle sales. The milk EIs in the Highlands were higher than those found by Weiler et al. (2014) for cattle systems in the Nandi county of Kenya, an area with generally similar management practices.

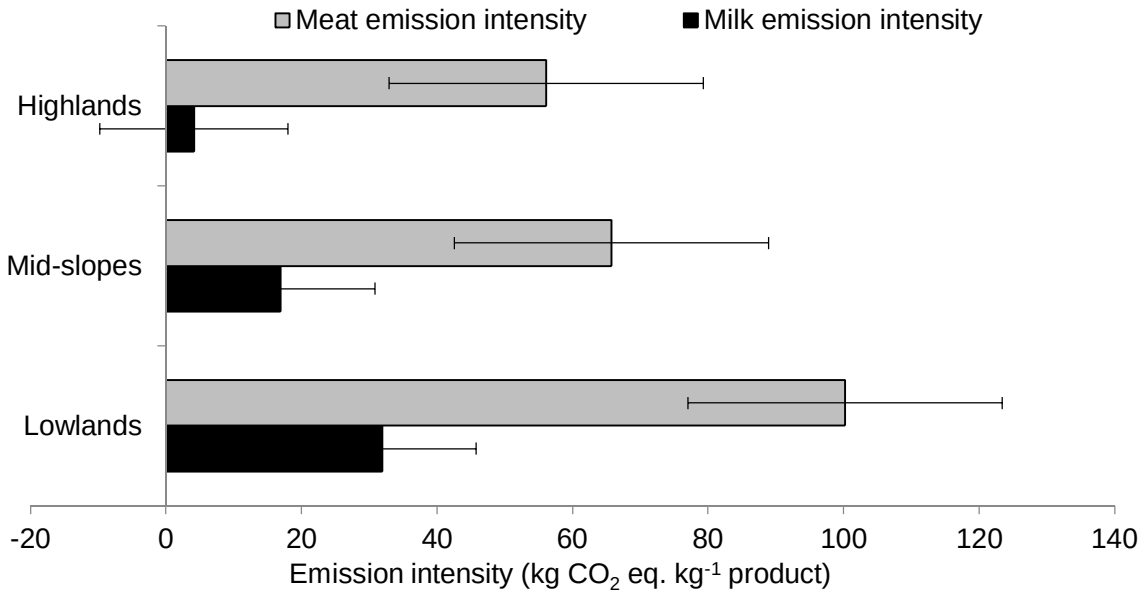

Fig. 2: Methane emission intensities (kg CO_2 eq. kg^{-1} product) of cattle in different zones (N = 3, bars denote one standard deviation about the mean of zones) of Lower Nyando, Western Kenya, as estimated from data collected during August 2014 and May 2015.

Global warming potential of methane is 25 (IPCC, 2007). There were no significant zonal differences (P = 0.692).

This is probably because the present study did not account for milk suckled by the calves as well as the multiple roles cattle play during life cycle assessment as was done in the Nandi county study. Moreover, these intensities were high

and typical of a previous report that smallholder systems in SSA have high EIs (Herrero et al., 2013) due to low quality and scarcity of feeds as well as low cattle productive potential.

The EIs of meat and milk were much higher as compared to those from high producing, intensive large-scale faming systems; for example, meat intensity from Sweden of 17 kg CO_2 eq. kg^{-1} meat (Cederberg and Darelius (2000) cited in de Vries and de Boer, 2010) and milk intensity of 0.93 kg CO_2 eq. kg^{-1} milk in New Zealand (Basset-Mens et al., 2009), and 1.0 – 1.3 kg CO_2 eq. kg^{-1} milk in Germany (Haas et al. (2001) cited in de Vries and de Boer, 2010). Hence, improving productive and reproductive performance of cattle through, for instance, improved nutrition, breeding management, and health care, could contribute to considerably reduce EIs of meat and milk produced in these systems. Nevertheless, it is important to note that livestock in African smallholder systems are kept for both, meat and milk production, and also supply multiple non-marketable services to farm households such as financial security, wealth status, and insurance.

Accounting for these diverse functions by relating CH_4 emissions to total outputs from livestock would greatly reduce the EI values and likely make them more comparable to those of intensive, specialized systems in which milk and/or meat are the sole outputs of livestock farming.

However, reduction of intensities with increased production is not guaranteed and depend on yield partition between milk and meat produced in a system because emissions from different products are accompanied by different efficiencies in the source system (Flysjö et al., 2012). There is need to consider both systems producing multiple marketable products (Flysjö et al., 2012) and multi-functionality of cattle beyond marketable products (Weiler et al., 2014) in order to come up with holistic viable mitigation options.

6.3.3 Uncertainty analysis

Uncertainty analysis was done on all the data from cattle and diet characterization except milk fat content which was not measured in the present study. The analysis only focused on cattle and feed characterization, and EF as required by IPCC Good Practice Guidance (Dong et al., 2006). At 95% confidence interval, the uncertainty associated with Tier 2 EFs presented here was ±43% of the mean EF per cattle category. This uncertainty in EF is within the range of uncertainty related to IPCC Tier 1 EFs of ±30 to ±50% of mean EF (Dong et al., 2006), but is much higher than the uncertainties reported by Karimi-Zindashty et al. (2012) of EF for cattle in Canada of -19 to +24% and by Monni et al. (2007) for cattle of all categories in Finland of -22 to +39% of the mean EF. The differences in the uncertainties between the present study and these other studies may be due to differences in methodology used to derive them (Zhu et al., 2016). For instance, we used CV method (Kelliher et al., 2007) and combined the uncertainties using propagation of errors (Frey et al., 2006). Instead, Dong et al. (2006), Karimi-Zindashty et al. (2012), and Monni et al. (2007) used the upper and lower bounds of the 95% confidence interval of the mean EF (i.e., two times the standard deviation in normal distribution). There is need for uniform methodology for calculating uncertainty to allow for comparison of uncertainty values obtained from different studies especially from similar systems. Additionally, differences may be due to relatively uniform cattle management in developed countries across large areas minimizing uncertainties due to less variation in cattle and feed characteristics. For example, use of commercial concentrates of standardized rations for specific cattle category of the same breed results in about uniform LW, LWG, and milk production. The IPCC Tier 1 EFs cover large spatial scale i.e., continental-scale. Variability in parameters from one place to another within the continent is probably large because of

different management systems leading to higher uncertainties as compared to our study which covers a small geographic area. Moreover, agricultural subsidies in some countries such as Austria are tied to animal husbandry statistics which greatly reduces uncertainty due to independent and consistent verification (Winiwarter and Rypdal, 2001). The implications of higher uncertainty in smallholder systems as compared to uncertainties in large-scale systems of the developed countries is that there is more confidence in decisions made based on emission values obtained in the developed countries than from smallholder systems.

Contribution of individual variables to cumulative uncertainty is presented in Fig. 3. Uncertainty in milk records was highest (i.e., CV range of 0.06 - 0.15, lowest in the Mid-slopes and highest in the Lowlands) amongst the feed and cattle characteristics used as input variables in calculation of EFs by IPCC Tier 2 which may at least partly be due to inaccuracies in recording caused by illiteracy or the lack of motivation of farmers to keep records resulting from weak market structures, and other labour demands i.e., other farm work, and in some cases large stocking numbers, competing for their time and attention. Indeed, farmers in the Lowlands (i.e., Kisumu) had marginally lower literacy levels than those in the other zones (i.e., Kericho) (Ojango et al., 2016).

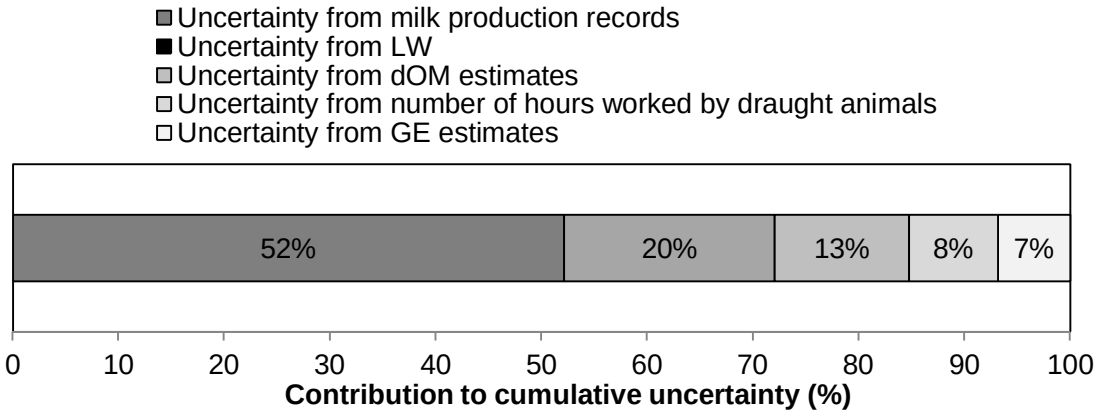

Fig. 3. The contribution of individual cattle and feed characterization parameters to the overall uncertainty of emission factors of cattle in Lower Nyando, Western Kenya, between August 2014 and May 2015.

dOM = apparent organic matter digestibility of the feedstuffs (g/100 g organic matter, OM); GE = gross energy content of the feedstuffs (MJ/kg DM); LW = liveweight (kg); Milk production in kg year^{-1} zone^{-1}; Number of hours worked by draught animal in hours day^{-1}.

Uncertainty in average LW of cattle of different categories ranged from a CV of 0.02 – 0.04. Uncertainties related to the LW of young and dry non-pregnant cows were higher than of any adult cattle category whose LW is relatively stable due to maturity. Uncertainty in estimates of dietary GE concentrations was rather small and consistent at a CV of 0.01. In contrast, the uncertainty in average dOM of the animals diets ranged from a CV of 0.01 to 0.04 and was highest in the dry season, likely due to the fact that a broader diversity of feedstuffs of varying digestibility is used in this season to cope with the nutritional stress. The uncertainties in GE and dOM were based on diet estimates and not individual feedstuffs, which was the form in which they were used as inputs in the IPCC Tier 2 model for estimating EF. As such, they may have systematic errors that may have been propagated in the course of estimating dietary composition. Uncertainties in the number of hours worked by draught animals were a CV of 0.03 for the long rainy season and 0.02 for the short rainy season. It was observed that all farmers, in the present study, with draught bulls mainly used them during the long rainy season, which was

the main cropping period, whereas in the short rainy season, some farmers left their land fallow and thus used the animals less for draught power. The large number of animals involved in the main cropping season may account for the higher uncertainty in the number of hours worked due to involvement of more farmers hence more variations in decisions regarding, say, work duration. Overall, farmer reports on number of hours worked by draught animals in these systems are highly inaccurate. Farmers do not keep records on how long the animals work each day which greatly varies from day-to-day depending on factors such as human and animal strength and motivation, condition of the field to be ploughed, level of feeding of the animal, and other commitments of the farmer on a particular day as noted from direct observation during the study.

The level of data aggregation influences the uncertainty in EF estimates. Zonal, seasonal, or household aggregation would decrease variations in the dataset. However, such aggregation can result in propagation of errors and hence, evaluation of uncertainty in the present study was done on primary disaggregated data. Indeed, while disaggregation can reduce uncertainties and improve precision of EFs (Basset-Mens et al., 2009), the same may increase uncertainty in individual feed and cattle characteristics data (Milne et al., 2014) leading to overall high uncertainties. All parameters analysed, except Y_m at 7.5% of dietary GE intake, resulted in significantly lower Tier 2 EF ($P<0.001$, Table 6). The differences in estimated EF from different models, digestibility estimation methods, LW estimation methods, and Y_m levels is likely due to use of compromise methods which are non-specific to smallholder systems in SSA and shows how critical it is to use actual measurements were possible. Where actual measurements are not possible, tools to improve estimation of feed and cattle characteristics must be developed. The tools include, inter alia, accurate prediction methods to estimate diet digestibility of

tropical feedstuffs based on *in vivo* data, representative and accurate LW prediction algorithms, and EF calculation models which are as representative as possible of cattle and feed characteristics as well as management practices of SSA smallholders. Milk fat content had the least effect on EF and as such, literature values may suffice without having to mobilize resources towards its accurate determination.

Conclusion

Farmers should stock herds at their optimum production levels to avoid keeping non-productive heads which increase EIs. There is need to improve feed resources in tandem with improving genetic potential of cattle since higher producing cattle tend to be more feed-intensive. Differentiated feeding of cattle in a herd depending on their level of performance is recommended to avoid excessive LW losses and increase production. Crossbred cattle with higher LW and milk yields had higher EFs but lower EIs due their high production levels. The IPCC Tier 1 method under- or over-estimates Tier 2 EFs of different cattle categories possibly due to differences in cattle characterization between the two models. The meat and milk EI were high and typical of SSA smallholder systems characterized by low quantity and quality of feedstuffs, and low productive potential of cattle. The EIs should consider the multi-functionality of cattle in these systems for valid conclusions on possible mitigation measures. Uncertainty of the estimated Tier 2 EFs was lower than those in Tier 1 which cover large spatial scale with probably higher variability in parameters. Uncertainties in this study were larger than in developed countries possibly due to non-uniform cattle management and differences in methods of calculating uncertainties. Milk production records, LW, and diet digestibility should be more accurate hence more resource allocation during inventory compilation because they contribute most to

uncertainty. Decision on the appropriate level of aggregation is important to reduce uncertainties and improve precision of EFs. There is need for actual measurements and where not possible, tools such as accurate prediction methods for digestibility of tropical feedstuffs based on *in vivo* data, representative and accurate LW prediction algorithms, and EF calculation models representative of cattle and feed characteristics as well as management practices of SSA smallholders must be developed. Literature values for milk fat content may suffice since it had the least effect on EF.

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7. General discussion

7.1 Constraints in cattle and feed characterization

Tier 2 methodology by Intergovernmental Panel on Climate Change (IPCC) for estimating emission factors (EF) requires characterization of cattle and feedstuffs. One way of characterizing cattle is by their liveweight (LW). As highlighted in chapter 3, LW is important for measuring growth, formulating feed rations, administering veterinary drugs, market pricing, determining readiness for breeding and work, and calculating expended energy for estimating methane (CH_4) emissions. Chapter 6 shows that actual LW is the second most important contributor to EF uncertainty. Actual LW measurements using calibrated weighing scales are ideal but scales are rarely available in tropical smallholder (SH) systems. Even if scales were to be provided, difficult terrain and lack of proper road infrastructure would minimize access to farmers. The SH system is made up of many farmers making individual management decisions. This does not allow for uniform and/or controlled breeding (Orodho, 2006) to raise livestock cohorts which could be periodically weighed instead of the need for continuous weighing in inaccessible places. In addition, record-keeping of such measurements, as well as other production and breeding activities, is a challenge due to factors such as adult illiteracy, i.e., about 20% of the household heads in Lower Nyando (Ojango et al., 2016). Labour pressure places demands on farmers' time especially in the Highlands where the system is more intensive (Verchot et al., 2008). Lack of motivation due to weak market structures in the Mid-slopes and the Lowlands (chapter 2, Weiler et al., 2014) also hinder keeping of records. A convenient compromise system for estimating LW has been the use of weight bands to measure the heart girth (HG) of cattle from which their weight may be estimated (Lesosky et al., 2012). However, algorithms on which these bands are designed may not be applicable to all cattle breeds across Africa and as such may under- or over-estimate the actual LW. Hence, in chapter 3, alternative equations which can be used to estimate the LW of zebu cattle in East Africa with

greater accuracy are proposed. Precautions were taken to ensure the actual LW measured was as accurate as possible. For instance, measurements were done early in the morning before animals were fed or watered (i.e., there was a 12- to 15-hour interval between the last feeding and measurement) to minimize the effect of gut fill on the accuracy of the estimated LW. The same weighing scale (calibrated before every measurement) and operators were also used throughout the study. Although the estimated LW from the algorithms developed were of lower accuracy than actual measurements (i.e., up to actual LW ± standard deviation of 35 kg) especially in determining seasonal LW variations in adult male cattle and overall LW changes in the young cattle, the estimates were robust across a variety of SH cattle populations in Africa, more accurate than those found in the literature for the same populations, and met the minimum threshold for some applications such as administration of veterinary drugs i.e., below an error of 20% (Lesosky et al., 2012). For instance, the equation derived from using Box and Cox (1964) transformation of LW (i.e., BOXCOX-LR equation) had 95% of the estimates falling between ±18% of the actual LW, whereas 75% of the estimates were within ±10% of actual LW. This level of accuracy coupled with conversion of this equation into weighing bands is sufficient to provide information that can be used by farmers to make decisions on feeding, marketing, breeding, and readiness for draught service. Insensitivity of the algorithms to seasonal LW changes (i.e., up to a standard deviation of ±17 kg for adult males and ±12 kg for young cattle) is possibly due to disparities in feeding by farmers especially in the dry season which can cause large differences, for instance, in gut fill, which can make up to 15% of LW (NRC, 2001). This may be due to use of diverse supplement feeds with differing qualities and digestibility fed in different quantities. Variability in LW within the categories is less pronounced in the other seasons when pasture is the primary feedstuff and the overall feeding is more or less consistent among the households. Additionally, in chapter 6, the estimated LW from the

algorithms gave significantly lower EF than the actual LW ($P<0.05$) for the young, adult male, and lactating cows categories. This is possibly due to lower estimated LW gains/losses resulting from insensitivity of the algorithms to LW fluctuations likely to be found in these three categories, i.e., the young are in a stage of active growth while the adult males and lactating cows experience LW fluctuations due to uncompensated energy requirements for work and milk synthesis respectively. For those categories where the accuracy is low, use of calibrated scales and a quest for more sensitive algorithms for African SH cattle are recommended to improve robustness, to be applicable to phenotypically diverse cattle populations, and reliability of the derived EF for decision making purposes.

The use of one pasture exclosure cage (0.5 m x 0.5 m x 0.5 m) per village to determine pasture quantity and quality (chapter 4) was possibly not sufficient to give a representative sample to reliably estimate the standing plant biomass quantity and quality. It was assumed that the pasture herbage within a village was homogeneous which may not be the case. However, a statistical analysis of the pasture herbage samples later showed that except for crude ash concentrations, there were no significant differences in nutrient concentrations within the zones. Given that villages make a zone, there were no differences between the villages and possibly within villages in a given zone, supporting our assumption of homogeneity. The plant biomass collected within the immobile cages may be different from that outside the cages due to variations in plant growth rates and nutritional quality of forage caused by selective feeding behaviour of domestic ruminants and variations in regenerative potential of swards at continuous grazing (Sheath and Macfarlane, 1990). For instance, it has been shown that grazing ruminants have the ability to select herbage of two to three times higher phosphorus concentrations when oesophageal fistula samples are compared to hand-plucked samples (Engels (1981) cited in Underwood and Suttle, 1999). However, selective grazing behaviour is more important in seasons when there is adequate vegetation (i.e., half a

year) while in the lean seasons almost the entire sward is cleared, in which case the effect of selectivity is cancelled (Kerridge et al., 1990). Similarly, cattle graze swards to different heights depending on seasonal availability of pasture i.e., higher during plenty and lower to the ground in dry seasons and not necessarily one inch above the ground as was sampled here. This is because bite depth as a proportion of sward tiller height is relatively constant (Barrett et al., 2001). However, bite volume is also dependent on the sward bulk density (Mcgilloway et al., 1999) and hence, the grazed height will depend on the available pasture biomass as well as the stocking density. In the same line, only the pasture herbage was monitored and sampled more than once, ignoring the ligneous vegetation which also contributes to diets of domestic ruminants. This was however remedied by sampling tree leaves and shrubs separately (i.e., mixed browsed leaves) in the dry season when they are mostly used as cut and carry feeds. In any case, since the pasture herbage was of superior nutritive quality, selective grazing behaviour may have led to animals avoiding the mixed browsed leaves in the wet seasons eliminating the need for sampling the browse species every season. These feedstuffs are also probably of lower relevance to cattle who are mainly grazers. There may be a need to increase the sampling frequency from every three months at the middle of each of the four seasons as was done in the present study in order to sufficiently capture the seasonal changes in both biomass yield and nutritional quality of the vegetation resulting from rapid growth and changes in vegetation under the prevailing tropical climatic conditions (McDonald et al., 2010). Future similar studies should address these shortcomings by, ideally, the use of more exclosure cages within an area to capture any heterogeneity, the use of oesophageally fistulated animals in experimental conditions, mimicking as closely as possible the sward heights grazed by animals, moving cages around the pasture field, and sampling of all types of vegetation in a pasture. These measures would deepen our understanding of such pastures and enable us to draw more precise

conclusions regarding their use. As a result, farmers could be better advised as to the best pasture husbandry practices which would ensure higher production thereby reducing the greenhouse gas (GHG) emission intensities.

Digestibility and metabolizable energy (ME) concentrations of feeds are important in the estimation of enteric CH_4 emissions, as well as, in feed evaluation and diet formulation. The reference methods for the determination of apparent total tract digestibility (dOM) or ME concentrations in animal diets are *in vivo* experiments which are however, expensive, laborious, and may raise animal welfare concerns. Alternative, indirect methods have been developed in the past decades that are based on or validated by data derived from *in vivo* trials. These alternative methods include for instance, use of allometric equations to estimate diet digestibility or ME content from concentrations of crude nutrients and/or fiber fractions as well as the gas production during *in vitro* fermentation. However, while there are numerous robust algorithms available for temperate feedstuffs, there are only very few published prediction equations for digestibility and ME values based on chemical composition and no specific equation based on *in vitro* gas production for tropical feedstuffs. In this study, the gas production method by Menke and Steingass (1988) was used to estimate the dOM and ME concentrations of the herbaceous pasture vegetation and supplement feedstuffs (chapter 4). Menke and Steingass (1988) related results from *in vivo* trials to chemical parameters (i.e., crude protein (CP), crude ash, ether extract concentrations), and gas produced from *in vitro* digestion with rumen liquor of temperate feedstuffs of varying qualities. Additionally, we estimated the dOM of pasture herbage using other equations which were developed for grasses; one developed for temperate grasses (Stergiadis et al., 2015b) and two equations developed for tropical grasses (Hughes et al., 2014; Matlebyane et al., 2009) and the results were compared (Fig. 1 left-hand side).

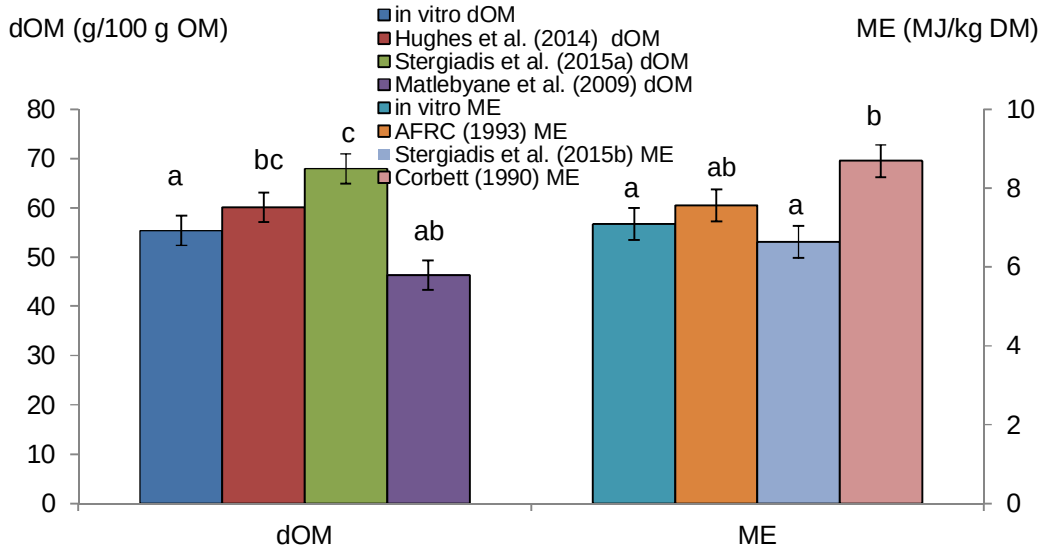

Fig. 1. Comparison of apparent organic matter digestibility (dOM) and metabolisable energy (ME) as estimated from *in vitro* gas production or some published prediction equations of herbaceous pasture vegetation (arithmetic mean ± one standard deviation (bars); n = 24) in Lower Nyando, Western Kenya.

DM = dry matter; OM = organic matter; different letters above bars show significant differences declared at P<0.05 using Tukey HSD.

The two equations for tropical feedstuffs yielded similar dOM values to each other. This is possibly because the feedstuffs from which the equations were derived originate from similar climatic conditions as the pasture herbage in the present study and probably have the same photosynthetic pathways (e.g., both had C4 grasses in pasture herbage). However, the dOM values derived using Menke and Steingass (1988) equation (based on data from temperate feedstuffs, i.e., hay, grass-cobs, straw, grass, grass silage, maize silage) and Matlebyane et al. (2009) equation (based on data from six tropical grasses) gave similar values, probably because the quality range of feedstuffs used to derive the Menke and Steingass (1988) equation was wider and probably covered the quality range for grasses used to derive the Matlebyane et al. (2009) equation. Similarly, the dOM values from Hughes et al. (2014) equation (based on data from two tropical grasses) were similar to those of (Stergiadis et al., 2015b) equation (based

on data from temperate fresh-cut perennial ryegrass swards) possibly because the acid detergent fibre (ADF) values of grasses used to derive the Hughes et al. (2014) equation were low and similar to ADF values characteristic of temperate grasses.

Fig. 1 right-hand side shows the comparison of ME values of pasture herbage estimated by gas method; Stergiadis et al. (2015a) equation derived using temperate grasses; AFRC (1993) equation most commonly used equation in the tropics (Mero and Udén, 1998; Mupangwa et al., 2000); and Corbett (1990) equation derived from tropical grasses in Australia. As expected, the Corbett (1990) equation (based on tropical grasses) gave different ME values from the equations based on data from temperate feedstuffs. The ME value estimated by the AFRC (1993) equation was similar to the ME values estimated by all the equations here. This is probably because the AFRC (1993) equation is derived from a wide variety of feedstuffs with wide range in quality therefore able to predict both the relatively high-quality temperate feedstuffs as well as the low-quality tropical feedstuffs.

This shows the versatility of the AFRC (1993) equation for use with both, tropical and temperate feedstuffs, and supports its common use (Matizha et al., 1997; Pozdíšek et al., 2003; Melaku et al., 2004; Rufino et al., 2009; Ricci et al., 2013; Salehi et al., 2014). However, this does not necessarily mean that AFRC (1993) is more accurate but simply that it is based on many feedstuffs with widely varying MEs and therefore more likely to cover the ME of a tropical feed falling within its range than other equations based on few feedstuffs of very extreme MEs. Though the accuracy of the *in vitro* gas production method used here for the test feedstuffs cannot be corroborated due to lack of *in vivo* data for the same feedstuffs, the estimates derived from it seem reasonable. This is because the prediction equation was derived from *in vitro* experiments and chemical composition of feedstuffs validated by data from *in vivo* trials. Additionally, the equation

covered many roughages (i.e., n = 185) which though from temperate zones, had, in many cases, a nutritional quality typical of that of tropical feedstuffs (i.e., dOM 29 – 80 g/100 g dry matter, DM). Moreover, these estimates are in close agreement with the default digestibility values proposed by IPCC for tropical feedstuffs in Africa showing that the estimates we derived are quite robust. However, there is need for accurate *in vivo* derived and/or validated equations for tropical feedstuffs.

In chapter 6, we estimated EFs using digestibility as estimated by different equations. All the estimated EFs were significantly different ($P<0.001$). The fact that different methods of estimating digestibility and ME value give such varied results shows that accurate determination or estimation of digestibility and ME values must be done, if the decisions based on EFs derived from them are to be sound.

7.2 IPCC Tier 2 model methodology

One of the main aims of the thesis was to determine area-specific EFs to enable more accurate reporting of enteric CH_4 emissions from cattle systems which is, by far, one of the main sources of greenhouse gas emissions in Kenya (NEMA, 2005). Herd size and structure determination could confound the results of such a study, if the scale of measurement were not well defined. Definition of livestock ownership raises gender and youth issues. The Luo tribe in the Lowlands, for instance, has a tradition allowing only one kraal per homestead despite the number of separate households within the homestead. The homestead head, usually the patriarch, considers all the animals within the kraal his own and must be consulted on any decisions regarding livestock. This meant that homesteads where polygamy was practiced (i.e., 17% of the households in the Lowlands equivalent to 7% of all the households surveyed) and/or had youth owning livestock (i.e., 25% of the households in the Lowlands equal to 10% of all the households surveyed) could be mistakenly counted as one

household while in actual fact they could be many. This has implications and exposes the weakness of the household as a unit of measurement during later upscaling or extrapolation of research findings. Additionally, there is a practice of loaning of cattle, especially draught cattle during the ploughing season, and also a form of transhumance where livestock are sent off to friends or relatives during the dry season to cushion against loss of animals due to inadequate feedstuffs depending on the severity of the drought. Both these customs mean that enteric emissions from the unit of measurement, whether household or village (chosen usually due to convenience in sampling), are not uniform throughout the year. Livestock survey or census done once a year may not cover these seasonal variations and as such may under- or over-estimate the number of animals. It is therefore important to carry out longitudinal surveys, as was done in this study, which capture seasonal changes in herd sizes and structure. Herd sizes and structure are important in the estimation of CH_4 emissions, because estimates of emissions for a certain region are a product of EF and the number of cattle kept therein. Likewise, when scaling up the contribution of SH cattle emissions in Kenya, the number of livestock in SH systems as a proportion of total livestock holding is calculated based on the herd size and structure found in a study.

The Tier 2 IPCC model provides criteria for classifying livestock into categories and sub-categories. For instance, the model defines growing cattle (young) as pre-weaning calves, replacement dairy heifers, post-weaning fattening cattle and feedlot-fed cattle on more than 90% concentrates. However, unlike for growing lambs whose upper age limit is set to one year, IPCC does not specify the age-limit for the category “young” cattle. Although this is understandable given the wide range of breeds with different ages for attaining maturity, the age threshold for the “young” category should be estimated for different regions or at least specified in order to allow comparison of EF. Alternatively, a cut-off LW may be useful. When working out EFs in the present study (chapters 5 and 6),

the upper age limit of young cattle was set to one year. However, when comparing this IPCC Tier 2 EF with IPCC Tier 1 default values, there is ambiguity as to whether the differences in these EFs are at least partly a result of differences in cattle classification. Ambiguity in classification may also occur due to cattle belonging to more than one category. For instance, cows who are in-calf while at the same time are lactating may result in double counting (i.e., under pregnant cows, then as lactating cows). In order to avoid this, it may be necessary to work out annual gross energy intakes (GEI) for individual cattle (as opposed to category GEI) before classifying them into categories as was done in this study or probably use median which is a more robust measure than mean of the test parameter.

Most equations predicting conversion of GEI by ruminants into CH_4 energy (i.e., estimating CH_4 conversion factors (Y_m)) have been derived from experiments using temperate feedstuffs and cattle breeds found in temperate regions (e.g., Johnson and Ward, 1996). These equations may not be appropriate for cattle breeds found in tropical conditions and feeding on tropical diets. For example, IPCC suggests that on average, a range of 5.5 - 7.5% Y_m in cattle grazing low-quality pastures, or feeding on low-quality crop residues and by-products while Kurihara et al. (1999) found values of up to 11% for tropical grasses. In chapter 6, change in Y_m to 5.5% (i.e., lower bound) and to 7.5% (i.e., upper bound) resulted in an EF that was ±15% of the EF derived using the standard Y_m of 6.5%. The feedstuffs used in this study were of highly varying nutritional quality (chapter 4), i.e., from the very low-quality sugarcane to above average quality (i.e., CP > 7 g/100 g DM, dOM > 55 g/100 g DM, and ME > 7 MJ/kg DM) pasture herbage and sweet potato vines. Indeed, chapter 4 revealed that pasture herbage was of superior quality to most supplement feedstuffs, contrary to popular belief among the farmers that feeding cultivated exotic fodder and commercial concentrates they can ill afford (Lukuyu et al., 2009; chapter 2) are the best ways to improve the nutrition of their flock as opposed to

targeted management aimed at optimizing the existing pastures. Due to high variability in feedstuff quality, it seems realistic to use a Y_m value of 6.5% as opposed to the upper and lower bound values. The high variability of estimated EF to differences in Y_m shows, however, the need to have region-specific Y_m values based on local feedstuffs. This would greatly improve accuracy of the estimated EF and thereby increase confidence in decisions made by stakeholders based on such estimations. For instance, the government can use low EF estimates with low uncertainties to bargain for better terms in the carbon trading market and also use low EFs to minimize emissions and thus increase the capacity for trade. Policy makers are also able to put in place appropriate interventions such as those needed to mitigate and/or adapt to climate change.

The IPCC Tier 2 methodology (Dong et al., 2006) is based on the level of feed intake that must be achieved to meet the energy requirements of cattle for maintenance, production and other purposes and the energy concentration in their diet. Such estimates of feed intake do not take into account whether the animals actually have access to the calculated feed mass or whether they have the biological capacity to ingest the required amount of feed. For this reason, there are criteria put in place by IPCC in order to confirm how realistic the estimated feed intake is. Firstly, the estimated dry matter intake (DMI) should be within a range of 2 - 3% of cattle LW. Secondly, a simplified way to estimate DMI still based on the cattle LW and dietary net energy concentration (NE_{ma}) (i.e., NE_{ma} = ratio of net energy available in the diet for maintenance to digestible energy consumed * gross energy of the feed * digestible energy as a percentage of gross energy/100) should also be within 2% of cattle LW. Further, the IPCC gives a range of NE_{ma} for low-quality diets which should be between 3.5 and 5.5 MJ/kg DM. In this study, the DMI of cattle of the different categories was estimated by dividing required GEI by the average gross energy concentration of the diets (see chapter 6). Our estimated DMI by IPCC Tier 2 was within 2 - 3% of cattle LW, by simplified NE_{ma} method was 2% of

cattle LW, and the NE_{ma} value was within the recommended range for low-quality diets. Indeed, this shows that the assumptions made by IPCC regarding feed quality as well as the methods used in chapter 4 to estimate feed quality are in close agreement. This implies that the methods used in the present study can be used to estimate IPCC Tier 2 EF of cattle in similar conditions and for future studies in the area. This however, does not negate the need for region-specific feed quality information recommended earlier as evidenced by the variability of EF to changes in methods used to estimate the digestibility of the feeds (chapter 6).

Different estimation procedures, as shown in chapter 5 and 6, have a role to play in estimated EFs. Though the bases are the same (i.e., using cattle and feed characterisation), the EFs in chapter 5 were much lower than those in chapter 6. This is possibly because the working in chapter 5 avoided the implicit assumption of *ad libitum* feed intake by IPCC methodology used in chapter 6. Use of alternative EF estimation methods, bearing in mind the fact that animals in sub-Saharan Africa (SSA) SH systems rarely have *ad libitum* access to feedstuff, is important in the quest for region-specific EFs.

Challenges in milk sample collection, preservation, and transport to laboratory as well as the low number of laboratories available to do good quality milk analysis hindered milk analysis in the present study. However, as shown in chapter 6, use of 3.5 g/100g or 7.0 g/100g of milk fat content did not lead to significant differences in EFs. It is also important to note that milk pricing in the study area does not depend on protein or fat content and neither is the value chain properly developed to produce processed milk products. This means that deployment of resources to milk analysis when collecting data for estimating IPCC Tier 2 EF in a similar study under similar production systems may be unnecessary, because the impact of the additional information obtained is minimal. This however, may not be the case in systems where milk production is high and substantial energy intake

by the cows goes towards fulfilling increased requirements for milk synthesis and maintenance.

7.3 Sustainable intensification options through improved feeding and pasture management

Chapter 4 characterizes the feed resource base in the study area, highlighting the importance of the pasture vegetation for cattle feeding (also chapter 5 table 3 and chapter 6 table 1). The cattle systems in the Lowlands and the Mid-slopes rely on unregulated grazing on communal pastures in the village in addition to household grazing plots set aside by farmers for use by their own animals. These household plots serve the animals for one to two hours daily out of the average nine hours set aside for grazing. There is need, in future studies, to redefine the spatial scale of study from household to village level in order to accurately explore the collective use and management of pasture and other feed resources (Rufino, 2008). Additionally, there is no active pasture management due to a perception that the existing native pasture vegetation is sustainable and that not much can be done to improve it. Quantity and quality of pasture entirely depends on the physical environment, save for the animal droppings during grazing which serves as a way of nutrient cycling. However, communal land for grazing is declining, because land is increasingly owed by individuals (Migot-Adholla et al., 1994) and/or is progressively being converted to crop land (Olang and Njoka, 1987). Farm sizes per household described in chapter 2 and cattle ownership per household in chapter 6 gives an approximate stocking density of 13 - 17 heads per hectare in the Lowlands, 2 - 6 heads per hectare in Mid-slopes, and 5 - 13 heads per hectare in the Highlands. This stocking density may not be sustainable under the current conditions. Hence, in the mid to long term, grazing and pasture management strategies will be needed to compensate for the decline in pasture area and to maintain or even increase the contribution of pasture

vegetation to nutrient and energy supply to local cattle herds by improving the nutritional quality and biomass yields of forage on pastures (Angassa and Oba, 2010; Thornton and Herrero, 2010).

As compared to the pasture vegetation, the contribution of crop residues and agricultural by-products to cattle feeding in the study area is minor which might be at least partly due to the fact that the Lowlands and the Mid-slopes, in particular, are not prime crop production areas and crop yields are low (Sijmons et al., 2013). Added to this, no crop residue conservation is practiced. The animals are left to graze in the crop fields after harvest leading to sub-optimal usage of crop residues as feedstuffs. In the Lowlands, the rice and sugarcane residues used as livestock feed in the dry season are purchased from neighbouring areas. Similarly, rice straw and husks are sourced from irrigated farms nearby at 200 Kenya shillings (1.7 Euros, at about 1 Euro = 117 Kenya shillings in 2014, http://www.centralbank.go.ke/rates/forex-exchange rates) per bale (about 30 kg DM) inclusive of transport using motorcycles. Sugarcane tops are from the Mid-slopes (5 - 10 km away) purchased as well for 200 Kenya shillings per bale (about 20 kg DM). These prices may seem to farmers as much cheaper than the high quality commercial concentrates that are sold at 2,000 Kenya shillings (about 17 Euros) per bag (70 kg as fed basis, equal to 63 kg DM) (prices gotten from local retailers in markets in the study area). Nevertheless, nutritional quality of these crop residues and by-products is low so that they are still quite costly after all. For instance, the commercial concentrates cost 1.67 Euros per kg of CP based on a CP concentration of 16 g/100 g DM (Lukuyu et al., 2012), sugarcane tops cost 2.13 Euros per kg of CP, and rice stover 1.50 – 1.80 Euros per kg of CP (based on CP concentrations in chapter 4). A strategic supplementation of animals with small amounts of concentrate feeds might be more effective in increasing animal performance and thus more profitable (Dickhoefer, 2009). Moreover, collection of sugarcane tops increases labour demands for the

women who are in many cases already strained from other chores (Weiler, 2013). Many farmers are unable to raise sufficient money to buy commercial concentrates which are usually sold in bulk. Moreover, lack of forage for all animals in the dry season (chapter 4) does not allow farmers to focus on supplementing only the animals that may be most efficient in using the additional energy and nutrients provided by the supplement feed. Hence, supplemental feeding strategies using locally available feedstuffs are needed to improve the animals' productive and reproductive performance. The cost and benefits of these feeding strategies along with their implications for labour demand are required to determine the economic value of current practices as compared to the use of commercial concentrates to supplement animals (Lukuyu et al., 2012).

As is the case with pasture management, especially in the Mid-slopes and the Lowlands, there is no active effort to improve feed resource base of other feedstuffs supplementing pasture. This lack of motivation to actively manage feed resource base may be at least partially due to weak market infrastructure for animal products in the zones (Weiler et al., 2014) and low cattle productivity, as well as a lack of knowledge of improved nutrition and feed management (Randolph et al., 2007). Lack of knowledge of nutritive quality of the available supplement feedstuffs may hinder their recognition and use as viable alternatives. For instance, sweet potato vines have not been adequately utilized because the farmers are not aware of its high nutritive value. Hence, there is still a strong need for agricultural extension work and for farmers to be trained on feed management practices such as those involved in increasing area under fodder crops, planting, weeding, fertilization, harvesting intervals, and processing and conservation of feed resources as well as the use of commercial concentrate and mineral-vitamin mixtures to optimize the feeding and hence production in these systems while minimizing emission intensities per unit product.

7.4 Contribution of smallholder cattle farming to methane emissions

The total livestock population in Kenya was based on 2009 national livestock census (KNBS, 2010). The animals were divided between various production systems according to the proportional composition of the ruminant production systems in Kenya (as determined by Peeler and Moore (1997) and cited in Orodho (2006)) in the various systems. The small-scale ruminant systems in Kenya are divided into dual dairy-meat production, i.e., 41.4% of the total cattle population in Kenya, and dairy production, i.e., 19.5% of the total cattle population in Kenya (Orodho, 2006). The former is typical of the Lowlands and the Mid-slopes zones and the latter is typical of the Highlands zone in the present study. The cattle in these two production systems were put into categories based on the herd composition in the present study (chapter 6, Fig. 1). Emissions were then calculated using IPCC Tier 2 EF (chapter 6, Table 5) and the cattle numbers per category per system. These emissions were then summed and converted from CH_4 emissions to carbon dioxide equivalents (CO_2eq) (Table 1) assuming the global warming potential of CH_4 to be 25 that of CO_2 over a 100-year time horizon (Forster et al., 2007).

Table 1. Contribution of enteric methane emissions from smallholder cattle systems in Kenya to total agricultural GHG emissions in Kenya.

	Small-scale dairy-meat production			Small-scale dairy production		
Category	Herd composition* (% of total heads**)	Population (million heads)	Emissions (CH_4 in Gg year^{-1})	Herd composition* (% of total heads**)	Population (million heads)	Emissions (CH_4 in Gg year^{-1})
Young (< 1 year old)	45	3.3	71.9	50	1.7	49.5
Adult males	16	1.2	51.4	11	0.4	20.0
Dry non-pregnant cows	9	0.6	22.4	6	0.2	9.6
Pregnant cows	14	1.0	42.3	12	0.4	14.7
Lactating cows	16	1.2	60.3	21	0.7	43.9
Total	100	7.3	248.3	100	3.4	137.7
Total cattle emissions (CO_2eq in Gg year^{-1})	9651.5					
Smallholder cattle emissions (% agricultural CH_4 emissions*** in Kenya)	44					
Smallholder cattle emissions (CO_2eq as % of total agricultural emissions*** in Kenya)	26					

Gg = Gig grams = 1,000 metric tons; CO_2eq calculated by assuming the global warming potential of CH_4 to be 25 that of CO_2 over a 100-year time horizon (Forster et al., 2007).

* from Lower Nyando, Western Kenya (chapter 6)

** from 2009 national livestock census

*** from 2010 FAOSTAT (Food and Agriculture Organization database) data

Young cattle had the highest emissions possibly due to the large numbers of replacement and fattening stock kept as security against high mortality probably as a result of poor calf management. Competition for milk for sale, household consumption, and feeding calves is indeed common (Lukuyu et al., 2009). Improved calf management would lower mortality rate and reduce the demand for large stocks minimizing emissions from this category. High emissions from high adult male numbers kept for draught power can be reduced by using superior breeds of oxen for draft to reduce the number of oxen per team and sharing of oxen between neighbours so that households only need to own fractions of teams. Non-productive populations are mainly replacement heifers and other cows which due to genetics and/or poor nutrition experience long periods before and in-between calving resulting in high emissions and emission intensities. Farmers can explore the use of cows for dual purposes i.e., milk production and draft power as is the case in Bangladesh and Pakistan (Saadullah, 2001; Raja, 2001). However, such cows must be fed properly to ensure their nutritional requirements for such dual production are met (Saadullah, 2001). Studies on enteric CH_4 EFs of cattle in SH systems in SSA are scarce but the EFs in the present study were similar to those of Kouazounde et al. (2014) in Benin which were however much lower than the EFs in large-scale temperate systems (Gibbs and Leng, 1993 cited in Olivier et al., 1999; Dong et al., 2006). However, higher farm system optimization in temperate systems ensures high productivity which lowers their emission intensities (Gerber et al., 2011). The small-scale dairy production system results in lower emissions than the small-scale dairy-meat production system. This is probably because farmers in the dairy system regularly cull unproductive stock such as male calves sold after weaning (Lukuyu et al., 2009). They also keep few draught animals because farms are small and the population density is high which ensures that human labour is readily available. Also, they tend to keep high producing cross-breeds so they can realize similar or higher production with

fewer animals than in the dairy-meat system. Additionally, more use artificial insemination service in the dairy-only system (Lukuyu et al., 2009) eliminating the need to keep breeding males.

According to Food and Agriculture Organization database (FAOSTAT) data for the year 2010, CH_4 emissions made up 58% of the total agricultural emissions in Kenya.

Sources of agricultural CH_4 emissions are enteric fermentation in cattle, small ruminants, non-ruminants, livestock manure, and agricultural soils especially flooded soils for growing rice. The data from FAOSTAT is an aggregate of all these sources based on official, semi-official, estimated or calculated data and as such have uncertainties. From our estimations, SH enteric CH_4 from cattle alone contribute 26% of the total agricultural emissions in Kenya (Table 1). Differences in EFs of the young, adult male, and lactating cattle categories (i.e., between Tier 1 and Tier 2, and between the zones) occurred between and not within the two small-scale cattle systems (chapter 6, Tables 5 and 6).

It should be noted that these estimations only represent parts of three (i.e., Inner Lowland, Upper Midlands, and Lower Highland) of the seven typical agro-ecological zones of Kenya (Jaetzold and Schmidt (1983) as cited in Chesterman and Neely, 2015) and only cover one year despite the fact that at least five years of continuous measurement of emissions data are required for the production of reliable and stable emissions data in rain-fed agriculture (Herd et al., 2015). They are, however, a good indicator of the contribution of SH cattle system to enteric CH_4 emissions. This is because although differences may exist between agro-ecological zones, the large differences likely to skew these results one way or the other are likely to fall in different ruminant systems, such as large-scale pastoralism in the arid and semi-arid zones. Other sources of uncertainty are possibly the differences in herd compositions and changes in cattle numbers within the different ruminant systems and in the whole country. Nevertheless, despite

these uncertainties, these results show that the SH cattle system is still the largest contributor to agricultural CH_4 and thus total GHG emissions in Kenya. This contribution is higher than in Swaziland (Dlamini and Dube, 2014) where all enteric emission comprises 27% of total agricultural emissions and in Benin (Benin's Ministry of Environment, Urban Settlement and Town Planning (2011) cited in (Kouazounde et al., 2014)) where cattle in all systems contribute 29% to the total agricultural emissions. For more accurate estimates of SH contribution, there is need for longer periods of measurement covering other agro-ecological zones of Kenya.

These enteric CH_4 emissions represent wastage of feed energy in systems where feeding is already constrained by low availability and nutritional quality of locally available feed resources and high prices of commercial concentrates. Moreover, CH_4 emissions lead to climate change. Hence, there is an urgent need for development of mitigation options for SH cattle systems in Kenya and other countries in SSA. Measures to increase productivity of these systems while simultaneously reducing cattle numbers have shown to be very effective in reducing emission intensities. Possible measures may include, as mentioned above, improved feeding and feed management, enhanced veterinary care, and breeding practices.

7.5 Future research needs

There is need for solutions to liveweight measurements under challenging conditions while delivering a high degree of accuracy. Studies into LW-HG equations that are sensitive to large and seasonal LW fluxes would help in eliminating/minimizing current inaccuracies. A feed value database for tropical feedstuffs in SSA that takes into account the high temporal and spatial variability of data in this area would help greatly in making decisions regarding feeding. These would also help in updating existing databases especially in the case of tropical feedstuffs such as feedipedia. *In vivo* based methods are needed for accurate determination or improved

estimation of digestibility of tropical feedstuffs which is currently lacking, while studies into bioavailability of minerals in tropical feedstuffs will help in ascertaining whether the mineral concentrations in the feedstuffs are sufficient for animal requirements. There is a need for studies carried out for longer periods, covering a wider area, and involving actual measurements to estimate emissions in SH systems of SSA and thus improve accuracy while reducing uncertainties in inventories. Calculations of emission intensities need to factor in marketable, non-market and by-product benefits. Moreover, nitrogen emissions (i.e., urinary and manure), CH_4 emissions from manure as well as emissions from small ruminants need to be studied to provide a complete picture of the contribution of SH systems to greenhouse gas emissions.

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8. General conclusion

Algorithms developed relating heart girth measurements to liveweight of shorthorn East African zebu cattle can be used to estimate the liveweight of other local breeds of smallholder cattle in sub-Saharan Africa (SSA). Liveweight determination is a first step towards characterizing cattle for estimation of enteric emissions. The algorithms developed were sufficient for general husbandry, veterinary care, and marketing purposes, but are insufficient in cases where more accurate liveweight estimates are required. Along the same line, digestibility of feedstuffs offered to cattle is important in enteric emission estimations. Across different geographical zones, nutritional quality of native pasture herbage in Western Kenya is superior to most local crop residues and agricultural by-products, but its availability and digestibility limit nutrition and performance of ruminant livestock during the long dry season. Local supplement feedstuffs cannot compensate for nutritional imbalances and deficiencies in two of the three zones showing the potential for use of local feedstuffs as solutions to nutritional deficiencies. Additionally, the high temporal and spatial variability in the nutritive value of native pasture herbage and the inaccuracy in estimating their nutrient digestibility require considerable safety margins in developing supplementation strategies. Hence, more comprehensive information on the nutritional quality of ruminant feeds and accurate *in vivo* based methods for estimating digestibility are needed to predict the nutrient, energy, and mineral supply to grazing cattle and small ruminants.

Grazing cattle in smallholder systems of Western Kenya are an important source of enteric methane (CH_4) emissions in Kenya. A new Tier 2 approach for estimating emission factors (EF) of smallholder cattle which does not rely on assumed diet digestibility and *ad libitum* feed intake results in EF estimates that may be up to 40% lower than Intergovernmental Panel on Climate Change (IPCC) Tier 1 EF estimates. Similarly, using the IPCC Tier 2 methodology yields EFs estimates that are lower or higher than Tier

1 IPCC EF depending on the animal category. Hence, there is need for further actual measurements of cattle and feed characteristics, and use of Tier 2 approach taking into consideration feed intake in systems where intake may be restricted. There is a considerable uncertainty in the estimated Tier 2 EFs for grazing cattle in smallholder systems of Western Kenya, although it is lower than the uncertainty associated with the IPCC Tier 1 approach. Therefore, more accurate measurements or use of methods developed in the present study to estimate input variables that contribute most to overall uncertainty in EF of grazing cattle in smallholder systems (i.e., milk yields, liveweight, and diet digestibility) is necessary. Finally, estimation of emission intensities must consider the multi-functionality of cattle for valid conclusions and possible mitigation measures.