Enteric methane emission estimates for Kenyan cattle in a nighttime enclosure using a backward Lagrangian Stochastic dispersion technique

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Abstract

This study provides methane (CH_4) emission estimates for mature female African beef cattle in a semi-arid region in Southern Kenya using open-path laser spectroscopy together with a backward Lagrangian Stochastic (bLS) dispersion modeling technique. We deployed two open-path lasers to determine 10-minute averages of line-integrated CH_4 measurements upwind and downwind of fenced enclosures (so-called bomas: a location where the cattle are gathered at nighttime) during 14 nights in September/October 2019. The measurements were filtered for wind direction deviations and friction velocity before the model was applied. We compared the obtained emission factors (EFs) with the Intergovernmental Panel on Climate Change (IPCC) Tier 1 estimates for the Sub-Saharan African (SSA) countries, which were mostly derived from studies carried out in developed countries and adapted to the conditions in Africa. The resulting mean EF of 75.4 ± 5.69 kg yr^{-1} and the EFs calculated from other studies carried out in Africa differ considerably from each other, which indicates the need for the further development of region-specific EFs to improve the IPCC Tier 1 estimates.

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Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
bLS	backward Lagrangian Stochastic
EC	Eddy Covariance
EF	Emission Factor
FAO	Food and Agriculture Organization of the United Nations
IDM	Inverse Dispersion Model
ILRI	International Livestock Research Institute
LW	Live Weight
MOST	Monin-Obukhov Similarity Theory

SSA Sub-Saharan Africa

1 Introduction

At present anthropogenic greenhouse gas (GHG) emissions are the highest in history and are still on the rise (IPCC 2019b). Although global methane (CH_4) emissions constitute only 4 % of the global anthropogenic carbon dioxide (CO_2) emissions in units of carbon mass flux, they contribute 20 % to the additional radiative forcing in the lower atmosphere (Ciais et al. 2013). Methane has a global warming potential of 28 on a per mass basis over a time horizon of 100 years without the inclusion of feedback cycles (IPCC 2014), making it the second most important greenhouse gas contributing to human-induced climate change. The main contributors to anthropogenic CH_4 emissions are energy production and agriculture via rice cultivation and enteric fermentation of ruminants (Thorpe 2009). More specifcally, the Agriculture, Forestry and Other Land Use (AFOLU) sector accounted for 44 % of the anthropogenic CH_4 (and 82 % of the nitrous oxide) emissions during the period between 2007 and 2016, representing 23 % of the total net anthropogenic GHG emissions (IPCC 2019b). In absolute numbers global these methane emissions from the AFOLU sector were 162 ± 49 Mt CH_4 yr^{-1} (4.5 ± 1.4 Gt CO_2-equivalents (eq) yr^{-1}) between 2007 and 2016 (IPCC 2019b) with livestock accounting for almost two thirds of those emissions (Saunois et al. 2020). Cattle dominate the CH_4 emissions from the livestock sector, accounting for 64 – 78 % (Herrero et al. 2013; Milich 1999). Patra (2014) projects an increase of enteric fermentation CH_4 emissions from cattle of 26 % until 2050 compared to 2010 due to the expected population increase and the corresponding increase in animal-derived food demand (Dangal et al. 2017; van den Pol et al. 2016).

National GHG inventories are used to monitor countries' annual GHG emissions and help them to achieve the goals set by the Paris Climate Agreement (Horowitz 2016). According to the good practice guidance outlined by the IPCC (Penman 2000), emission factors (EF) are used to derive those national inventories. EFs are the average emission rate of a given source, relative to units of activity or processes (Mareddy 2017). The IPCC suggests three different approaches (Tier 1 – Tier 3) to derive national GHG inventories for individual components within the agricultural sector. The Tier 1 approach is the most basic method and based on default values of methane emissions per head which are then multiplied by the number of animals (Gavrilova et al. 2019). In the specific case of Sub-Saharan Africa (SSA), the default value is 41 kg CH_4 $head^{-1}$ for free-grazing mature female African beef cattle (Dong et al. 2006). Up to date, even though it is the most straight forward approach, this value causes large uncertainties in national GHG inventories. Reasons for the uncertainties are for instance inaccuracies in the livestock census data and the fact that the default EFs for SSA were derived from former studies almost exclusively carried out in developed Western countries and adapted to developing countries based on expert knowledge. To date, only little localized empirical data are available to verify the default Tier. While some new information (Tier 2) has become available, this information has only recently been taken up by the IPCC (2019a) (Goopy et al. 2018; Goopy et al. 2020; Ndung'u et al. 2019). Tier 2 approaches provide advanced GHG inventories necessary to achieve countries' goals set by the Paris Climate Agreement (Horowitz 2016) by helping to understand the impact of different productivity measures on GHG emissions to find ways to mitigate those without necessarily decreasing the animal numbers. The Tier 2 approach is based on country-specific livestock data (i.e. live weight (LW) as well as detailed feed basket information) to derive region-specific emission factors (Gavrilova et al. 2019). Available studies that have developed and/or used Tier 2 EFs in SSA countries show substantial differences to the Tier 1 estimates (Du Toit et al. 2013; Goopy et al. 2018; Kouazounde et al. 2015; Ndung'u et al. 2019; Tongwane and Moeletsi 2020). Tier 2 values are expected to be superior to the Tier 1 values by taking more data into account and have so far been developed for smallholder farming systems and/or dairy systems in SSA but not yet for pastoral livestock systmes. Such rangeland/grazing systems are completely different from the smallholder farming systems as livestock (e.g. cattle) graze during the day and are kept in enclosures (so-called bomas or kraals) throughout the night to avoid theft or predation (Butterbach-Bahl et al. 2020). As a consequence, feed is often unavailable throughout the night (Nicholson 1987). Additionally, the movement and feeding patterns of such grazing animals in SSA are further affected by feed shortages during the dry seasons or distinct droughts (Norman 1965) and thus also affect CH_4 emissions from enteric fermentation.

Methane EFs from enteric fermentation from cattle can be derived via indirect approaches, e.g. through activity data (Goopy et al. 2018), or direct approaches, e.g. via a combination of eddy covariance (EC) flux and GPS data (Felber et al. 2015), via cattle respiration chambers (Charmley et al. 2016; Goopy et al. 2020), with the sulfur hexafluoride (SF_6) tracer technique (Goopy et al. 2016; Storm et al. 2012), or the proposed backward Lagrangian Stochastic (bLS) methodology. Here, we aim at deriving region-specific EFs in rangeland/dryland systems in SSA through methane concentration measurements using two open-path laser spectrometers (GasFinder2.0, Boreal Laser Inc., Edmonton, AB, Canada). This method is based on the bLS technique described by Flesch et al. (1995) that has not been used in Africa before for estimating EFs for enteric methane production but has been demonstrated to be feasible in multiple other locations in developed countries (e.g.: Flesch et al. (2014), Gao et al. (2009), Laubach et al. (2013)). Hence, the goals of this study were to test the applicability of the bLS technique for Kenyan cattle in nighttime bomas (1), to adapt data filtering methods to our specific location (2), to determine EFs for free-grazing mature female African beef cattle in SSA-countries using the bLS inverse dispersion model (IDM) method (3), and to compare the calculated EFs with the IPCC Tier 1 values and existing literature for improving the greenhouse gas inventories of SSA countries (4).

2 Methods

2.1 Backward Lagrangian Stochastic (bLS) model

The bLS technique as described by Flesch et al. (2014) is an IDM that generates trajectories backwards from the sensor to locations within the defined source area allowing the calculation of emission per unit time.

For this study, we used the IDM software WindTrax, (Thunder Beach Scientific, Halifax, Canada) that was successfully compared to other methods (Bonifacio et al. 2016; Yang et al. 2017) as well as gas release experiments (Flesch et al. 2004; Gao et al. 2009), and that has been applied for the quantification of agricultural emissions (Bai et al. 2015; Bai et al. 2020; Flesch et al. 2007; Laubach et al. 2014; McGinn et al. 2019; Prajapati and Santos 2018; Rhoades et al. 2010; Todd et al. 2014; van Haarlem et al. 2008). The underlying bLS model is based on the Monin-Obukhov Similarity Theory (MOST) and assumes that friction velocity $u*$, the Obukhov length L, the surface roughness length $z_{0,}$ and the wind direction β sufficiently describe the wind properties in a horizontally homogenous surface layer (Monin and Obukhov 1954). Besides horizontally homogeneous turbulence, the model assumes stationary atmospheric conditions at every location in the measured area.

The emission rate Q [M T-1L-2] is calculated by the bLS model from the simulated ratio between the concentration, C [M L-3], increase at the sensor's location due to the source (C_L-C_B) and the source emission rate $((C_L - C_B)/Q)_{sim}$, and the measured concentration increase due to the source with C_L and C_B representing the downwind and background concentration, respectively:

$$Q = \frac{C_L - C_B}{\left(\frac{C_L - C_B}{Q}\right)_{sim}}. \qquad (1)$$

In this study, downwind concentration increase was determined using a line-averaging open-path laser absorption spectrometer. To obtain the simulated ratio of concentration increase and source strength, 50000 (N) particles each were released from 30 points (P) along the laser light path and the average inverse vertical wind speed w_0 at each touchdown location within the source area for each particle set and release location was calculated as shown in equation (2):

$$\left(\frac{C_L - C_B}{Q}\right)_{sim} = \frac{1}{P}\sum_{j=1}^{P}\left(\frac{1}{N}\sum\left|\frac{2}{w_0}\right|\right). \qquad (2)$$

2.2 Calibration of the laser spectrometers

We used two GasFinder2.0 open-path tunable diode laser absorption spectrometers for the methane concentration measurements. The lasers record an absorption spectrum between 1.3 and 1.7 µm (Boreal Laser Inc. 2017). Multiple studies verified the usability of one or two open-path lasers together with the WindTrax software for estimating methane concentrations (Denmead 2008; Flesch et al. 2004; Flesch et al. 2005a; Flesch et al. 2005b; Flesch et al. 2014; Gao et al. 2009; Hofschreuder et al. 2004).

We calibrated the two laser instruments in the laboratory before and after the field deployment, with 2.5 months lying between the two calibrations, using four different standard gases (Air Liquide) with the mixing ratios of 200 ± 4 ppm, 400 ± 8 ppm, 600 ± 12 ppm, and 800 ± 16 ppm together with a one-meter long calibration tube. Data were stored every second with a runtime of two times 15 minutes after reaching a stable concentration. We found a good linear relationship between measured and actual standard gas concentration using linear regression with R^2 for quality analysis (**Fig. 1**).

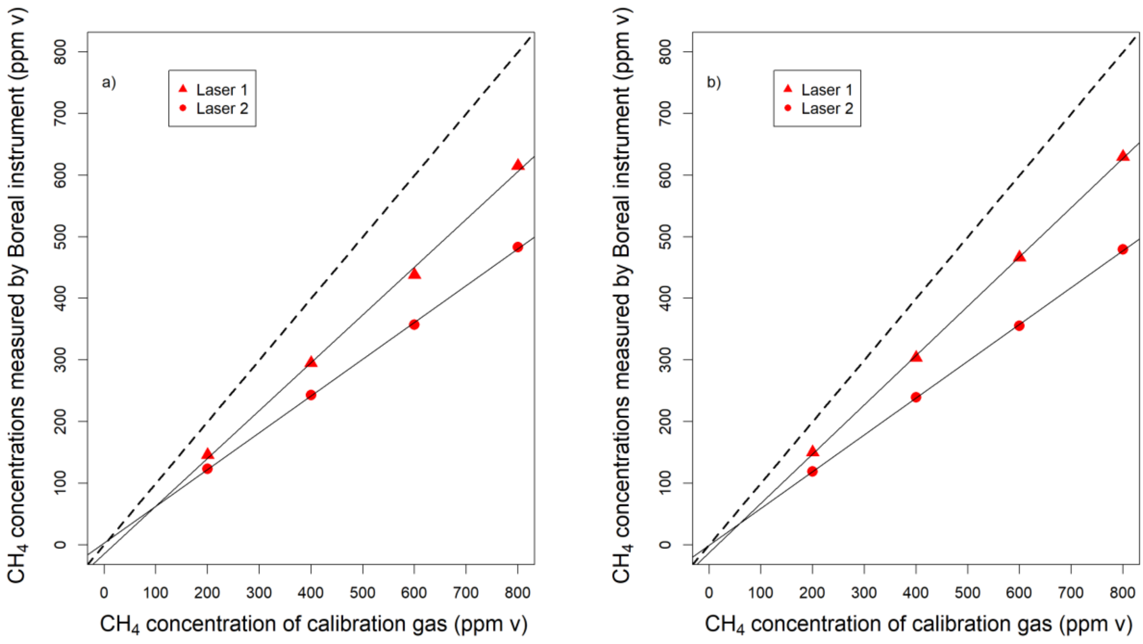

Fig. 1 *Calibration results for the open-path methane lasers 1 and 2 before (a) and after (b) the field deployment where the dotted line represents the identity line*

Both laser instruments underestimated the CH_4 concentrations resulting in the usage of the mean correction factors of 1.325 and 1.665 and mean detection limits of 0.045 ppm v and 0.015 ppm v for Laser 1 and Laser 2, respectively (for further information see **Table 1**).

Table 1 *Calibration results for the both laser spectrometers 1 and 2 before and after the field deployment with R^2, the resulting correction factors (Cor. fac.), the slopes of the linear regression lines, the standard errors (SE) of the y-estimates of the regression analysis and the resulting detection limits (Det. l.)*

Laser	**R^2**		**Cor. fac.**		**Slope**		**SE (ppm v)**		**Det. l. (ppm v)**	
No.	before	after	before	after	before	after	before	after	before	after
1	0.998	0.999	1.35	1.30	0.776	0.801	4.11	1.33	0.07	0.02
2	0.999	0.999	1.65	1.68	0.597	0.599	1.22	0.85	0.02	0.01

2.3 Site characteristics

Our field campaign took place in South Central Kenya at Kapiti Research Station managed by the International Livestock Research Institue (ILRI) (Rivero et al. 2021). The Research Station can be identified as a ranching system located in the semi-arid region of Southern Kenya (1° 37' 49.908"S, 37° 8' 43.195" E). The climate is typical for semi-arid savannas, with the annual precipitation being lower than the potential evapotranspiration. The mean annual precipitation is 550 mm, with rainfall being distributed in a bimodal precipitation regime (Berliner and Kioko 1999; McCown and Jones 1992). Approximately 80 % of the annual precipitation occurs during the two rainy seasons (Mar-Jun and Oct-Dec). The mean annual temperature is 20.2 °C, with 4 °C of annual variation.

Livestock management on the farm is typical for pastoral systems, where herders graze animals during the day and keep them in enclosures (bomas in East Africa) during the night. There are bomas distributed in different areas of the farm, and each area is used for a few months (2-3) every year until cattle are moved when the pasture in the area surrounding the bomas is exhausted. Some of the bomas are subject to occasional extraction of manure by local farmers.

2.4 Field experiment

The measurements took place during a one-month period in 2019 (27th of September till 23rd of October). During this time, we recorded measurements over 14 nights with the rainy season starting on the 8th of October 2019. Methane emission measurements from cattle were only possible during the night since the cattle are only then located in the bomas. We used two open-path laser spectrometers together with two retroreflectors to carry out the field measurements (**Fig. 2**, **Fig. 3**).

Fig. 2 *Typical field setup, with one of the laser spectrometers on the right-hand side and bomas in the background*

The lasers were erected up- and downwind of the bomas with the laser path being perpendicular to the main wind direction of 112.5 degrees from North to also measure background methane concentrations.

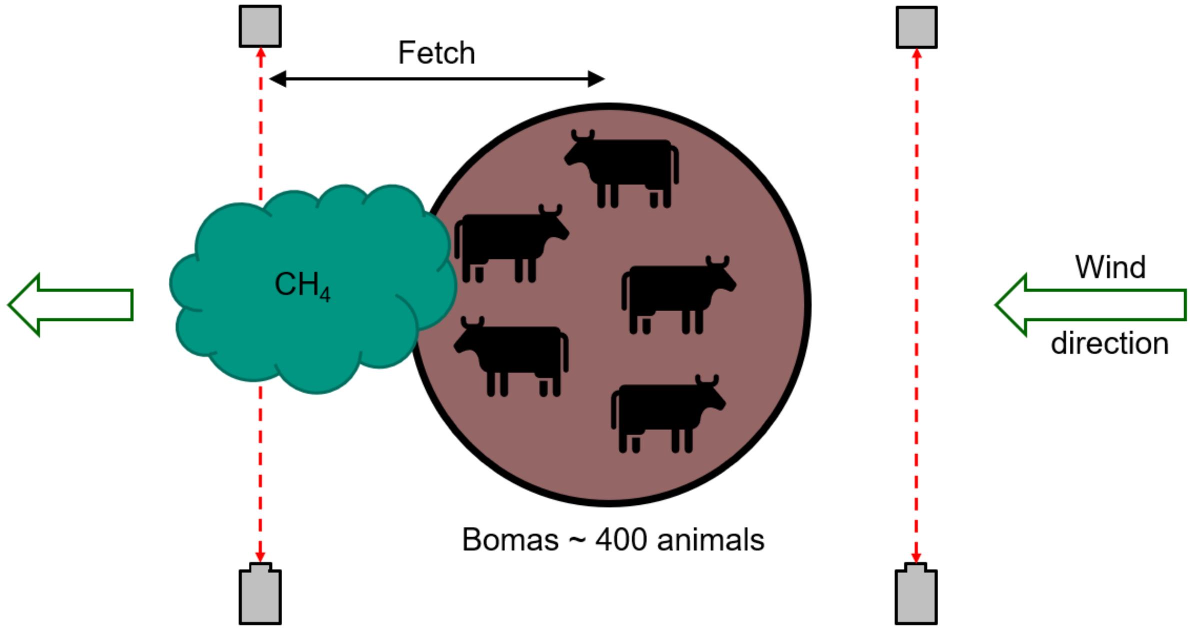

Fig. 3 *Scheme of the typical field set up, where the gray boxes represent the GasFinders (bottom side) and the retroreflectors (top side)*

We took the measurements at two different enclosure locations. Location 1, called Kilahani, consists of three connected bomas (Ø ~ 20 m) with around 140 animals in each boma. Location 2, called Potha, consists of four connected bomas (Ø ~ 18 m) with around 100 animals in each boma. We then excluded pre-ruminant calves (0 – 3.5 months old) from the EF calculations since they produce negligible emissions which were around 15 % of the animals at Location 1 and 10 % at Location 2 (Reed et al. 1990). Since the herds mainly consisted of female adult animals (> 50 %) and we could only measure the emissions of the entire herd we decided to assume that the herd only consisted of female adult animals after excluding pre-ruminant calves by using equation 3:

$$n_{total} = n_{cows} + n_{heifers}\frac{m_{heifers}}{m_{cows}} + n_{bulls}\frac{m_{bulls}}{m_{cows}} + n_{calves}\frac{m_{calves}}{m_{cows}}, \qquad (3)$$

where *n* represents the number of animals and *m* (kg) the mean LW.

To reduce potential disturbances induced by obstacles in the bLS dispersion model we set up our measurements in approx. 17 m distance of the enclosure fence. This is ten times the height of the fence (1.7 m), following the suggestion of Flesch et al. (2005b) to minimize measurement errors. Besides that, we chose a measurement height of around 1.7 m, staying lower than the maximum of 0.1 times of the available fetch, after Flesch et al. (2004) for a homogenous surface layer, where fetch is the distance between the center of the source and the laser path (**Fig. 3**), to avoid making measurements at the edge of the tracer plume. The different wind and turbulence parameters necessary for the EF calculation have been provided by the Mazingira Centre, International Livestock Research Institute (ILRI), observed by their eddy covariance (EC) tower located approximately 200 m away.

To receive reliable results, unrealistic and erroneous measurements have to be filtered from the collected laser absorption spectrometer data. Following the suggestion of Boreal Laser Inc. (2017) we kept those data with a light value output by the instruments between 3,000 and 11,000 units to avoid gas concentration misreadings caused by either not enough returning light or by a saturation of the receiver, whereas the full range is between 1 and 16,368 units. Since the wind direction was with 112.5 degrees from north generally very consistent during our measurement period we filtered out data with deviations from the main wind direction of ± 22.5 °. Additional data filtering criteria followed the findings from Gao et al. (2009) and Flesch et al. (2014) who reported strong over-/underestimations of the emission rates for extremely stable/unstable conditions, respectively, which is why we chose the friction velocity $u* > 0.15$ m s^{-1} as a threshold. The presented data show the remaining values after applying the different filters resulting in 67.7 % remaining data (**Table 2**). Other proposed filtering methods like Obhukov length $|L| > 10$ m (Flesch et al. 2014) or discarding the data when the standard deviation exceeding 2/3 of the mean EF (Gao et al. 2009) showed no effect in our specific location and were, therefore, neglected.

Table 2 *Total number of measured 10-minute periods for every observed night before and after data filtering, nights when precipitation occurred are marked*

Night	No. of periods	No. after filtering	Percentage (remaining)	Precipitation (X = yes)
28.09.-29.09.	41	33	80.5	
30.09.-01.10.	50	45	90.0	
02.10.-03.10.	60	39	65.0	
03.10.-04.10.	53	45	84.9	
05.10.-06.10.	36	27	75.0	
06.10.-07.10.	55	47	85.5	
08.10.-09.10.	56	19	33.9	X
09.10.-10.10.	35	31	88.6	X
11.10.-12.10.	46	41	89.1	X
14.10.-15.10.	39	22	56.4	
15.10.-16.10.	56	37	66.1	
18.10.-19.10.	43	26	60.5	X
19.10.-20.10.	58	39	67.2	
22.10.-23.10.	47	6	12.8	X
Total	675	457	67.7	

3 Results

The CH_4 EFs per head estimates ranged from 41.0 kg yr^{-1} to 119.0 kg yr^{-1} which resulted from averaging ten-minute measurement periods (**Fig. 4**).

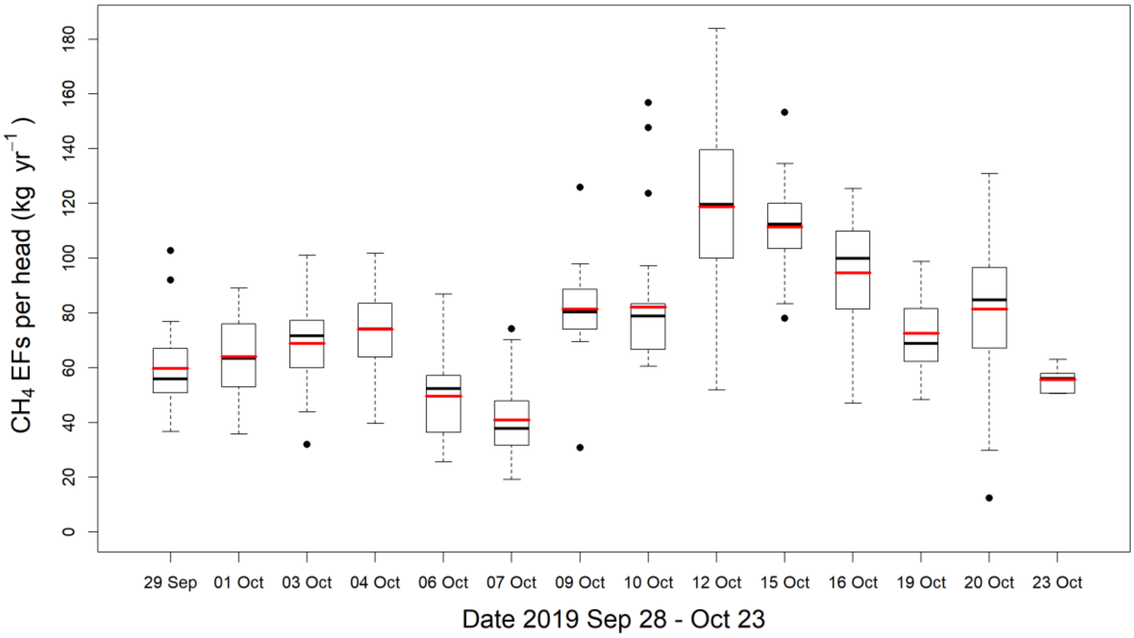

Fig. 4 *Boxplots of single livestock CH_4 emission rates determined each night during the period September 28th to October 23rd. Boxes indicate the range from the first quartile (Q1) to the third quartile (Q3) after applying the data filtering methods and the error bars represent the minimum/maximum values. Data are defined as outliers (black dots) when lower/higher than Q1 – 1.5/Q3 + 1.5 times the interquartile range (Q3 – Q1), respectively. Red and black lines represent the nighttime median and mean values, respectively*

During the measurmement period, the mean wind direction was stable during the course of the night, whereas the friction velocity showed a decreasing trend. The same trend was observed for the nighttime methane emissions data (**Fig. 5**).

Table 3 shows the nightly mean methane emissions together with the nightly extrapolated annual EFs. Methane emissions are shown in the different units mg s^{-1}, g d^{-1} and the EFs in kg yr^{-1} to facilitate comparability with other publications.

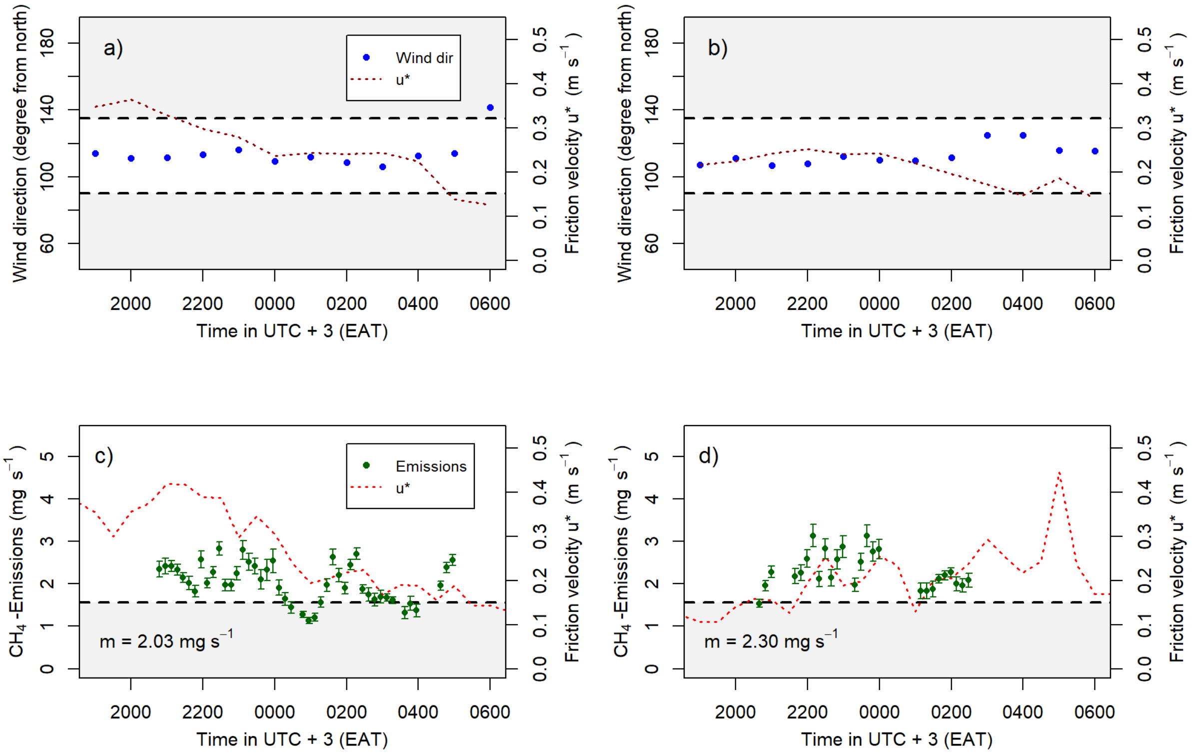

Fig. 5 *Mean wind direction and friction velocity in the observed nights before (a) and after (b) the first rain fell together with an example of the course of the methane emissions per head with included error bars and the friction velocity u* for a typical dry (c) and rainy (d) night together with the mean (m) emissions calculated with the WindTrax software. The critical values (black dotted lines) used for data filtering of 90 ° clockwise from north and 135 ° clockwise from north for the wind direction and of 0.15 m* s^{-1} *for the friction velocity are shown and the parts where data are filtered are grayed out*

Table 3 *Methane emissions ± S.E.M. calculated with WindTrax in different units, where every value represents a single female adult animal together with its methane EF ± S.E.M*

Night	**CH_4 emissions ($mg\ s^{-1}$)**	**CH_4 emissions ($g\ d^{-1}$)**	**CH_4 EF ($kg\ yr^{-1}$)**
28.09.-29.09.	1.89	163.3	59.6
30.09.-01.10.	2.03	175.4	64.1
02.10.-03.10.	2.19	189.2	69.1
03.10.-04.10.	2.35	203.0	74.2
05.10.-06.10.	1.57	135.6	49.5
06.10.-07.10.	1.30	112.3	41.0
08.10.-09.10.	2.58	222.9	81.4
09.10.-10.10.	2.61	225.5	82.4
11.10.-12.10.	3.77	325.7	119.0
14.10.-15.10.	3.53	305.0	111.4
15.10.-16.10.	3.00	259.2	94.7
18.10.-19.10.	2.30	198.7	72.6
19.10.-20.10.	2.58	222.9	81.4
22.10.-23.10.	1.77	152.9	55.9
Mean	2.39 ± 0.18	206.6 ± 15.58	75.4 ± 5.69

4 Discussion

4.1 Methodology

The main advantage of the bLS technique is that methane fluxes can be determined with only one concentration measurement as long as the background methane concentration is known. Moreover, it is very useful for measuring gas concentrations from well-defined area sources, if the size of the area does not exceed the maximum path length of the open-path laser, which is the case for the bomas under study. For our setup, the path length was limited to 60 to 80 m depending on the kind of retroreflector used. Denmead (2008) reports maximum path lengths of 1000 m but suggests to only use lengths of 100 to 300 m for more reliable results. The technique requires sufficiently strong wind speeds and steady wind directions to maximize the yield of high quality single measurements. It can be improved by mounting the laser instruments on pan-tilt scanning units with multiple retroreflectors to be able to react to changing wind directions and by adding small silicone heaters and electrical fans to prevent condensation on the reflector's surface overnight as done by Gao et al. (2009) and Flesch et al. (2014). Such a complex setup was not required for our measurements due to the optimal site conditions.

Our calculated values might have systematically overestimated the EFs by around 10 % since other studies also recognized similar overestimations. Flesch et al. (2014) reported that the bLS technique overestimated the release rate at night by about 8 - 12 % depending on the chosen filtering method in their gas release experiment while it underestimated the emission rate during the day. Gao et al. (2009) reported GHG overestimations during typical stable nighttime conditions and underestimations during unstable conditions. They suggested that this bias might be caused by a deficiency in the bLS model of Flesch et al. (2004). Furthermore, the authors suggested that it might be caused by an error in the parameterization of the turbulent kinetic energy dissipation rate, which is the rate at which turbulence energy is absorbed by breaking turbulent air fluxes down into smaller and smaller fluxes until it is converted into heat by viscous forces. Flesch et al. (2014) suspected that the bias might be caused by problems with the laser temperature sensitivity of the instruments. They based their suspicion on the work from Laubach et al. (2013) who found out that at least for their instruments the temperature sensitivity was greater than the value given by Boreal Laser Inc. and also reported sensitivity differences between their lasers.

4.2 Data filtering

The bLS technique worked generally well for our site during nighttime in most of the dry nights until around 0300 - 0500 EAT and until 0100 - 0300 EAT in the rainy nights until the friction velocity decreased or condensation occurred on the retroreflector (**Fig. 5**). The latter can also be seen in the smaller number of measurements remaining after data filtering (Table 2). We chose the relatively restrictive filter that only allowed for data with deviations of 22.5 ° from the mean wind direction since the wind was coming from the same direction all the time. Interestingly, using the Obhukov length as filter criterion showed no results since it was always inside the proposed range of Gao et al. (2009). The same applies for a filter using integral turbulence characterists (Foken and Wichura 1996) and for one using a threshold of the standard deviation reported by WindTrax (Gao et al. 2009). Only the friction velocity filter criterion resulted in some rejected data points mainly at the end of the night when the turbulence intensity declined (**Fig. 5**). This shows that it is important to adapt the filtering methods to the measurement location in order to retain as much high quality data as possible. Due to the very homogenous wind conditions, 67.7 % of the data passed the filtering criteria. In comparison, Gao et al. (2009) retained 40 % and Flesch et al. (2014) 63 % of the nighttime data after applying their filters, indicating that the conditions at the site were beneficial for the bLS approach in general and specifically for a setup that cannot be adjusted to changes in the main wind direction.

4.3 Diurnal variations

Measurements we took during daytime in order to determine methane emissions from manure showed no significant concentration increases indicating that the manure emissions were below the detection limit of the two open-path laser absorption spectrometers. Latest research has shown that methane emissions from manure in semi-arid landscape are considerably lower than suggested by the IPCC EFs (Pelster et al. 2016; Zhu et al. 2018).

As expected, the CH_4 production in animals decreases over the course of the night due to the absence of feed inside the bomas and the resulting decrease in the rumination process. This decrease leads to the conclusion that our results might underestimate the total annual emissions since the animals are free-grazing during the day, indicating that the actual methane emissions are in the range of the values of the first hours of the night. Our measurements took place at the end of the dry season and went on into the beginning of the rainy season. Feed availability increases in the rainy season due to plant growth which is leading to increases in beef (milk) production and, therefore, also methane production. As a consequence, highest productivity of animals is usually observed towards the end of the rainy season (Demarchi et al. 2016). The animals experience a clear seasonal effect of feed restriction through LW losses in productive females and reduced gains in other cattle classes mainly during the dry season and/or droughts. This results in a lower daily methane production since they have to meet their energy requirements by mobilization of their endogenous tissue rather than through consumption and fermentation of feed (Goopy et al. 2020). Considering these factors we are still confident that our observations show the correct order of magnitude for methane emissions per head and year.

Yet, we suggest undertaking additional investigations during the whole day to verify or correct our calculated mean methane emission values in the future. Places such as Kapiti Research Station could provide a well-suited platform to carry out such measurements. In addition, more repetitions of similar measurements as ours could potentially reduce the uncertainty of the mean

EF estimates since we only observed a total of 14 nights. Our measurements took place during a period of one month, which restricts the usability of the calculated emission estimates on an annual scale because we observed the animals during a period of relatively low emissions leading to a potential underestimation of the actual EFs.

4.4 Comparison with other studies

The predicted methane emission factors of the IPCC are based on measurements from the Organization for Economic Cooperation and Development (OECD) countries and thus may not be representative of the African livestock systems, breeds, soil and climate conditions (i.e. Goopy et al. 2020; Pelster et al. 2016). The Tier 1 EFs for cattle in Africa were largely adjusted by expert knowledge depending on countries' national inventories. Due to a scarcity of data on GHG sources and sinks, most developing countries currently quantify agricultural GHG emissions and reductions using IPCC Tier 1 emission factors with few exceptions such as Kenya for its dairy sector. However, conducting in-situ measurements leads to more accurate measurements and can be used to validate the IPCC values at the same time (Dong et al. 2006) while simultaneously providing an opportunity to track GHG mitigation actions. At the moment, the lack of reliable information on agricultural GHG emissions for developing economies limits the possibility for low-carbon agricultural development and also the opportunities for livestock keepers to benefit from carbon markets and the negotiating position of developing countries in the global climate policy discussions (Rosenstock et al. 2013).

Our calculated mean value of 75.4 ± 5.69 kg yr^{-1} $head^{-1}$ is considerably higher than the IPCC Tier 1 value. As shown in Table 4, six other studies also calculated their own methane EFs for enteric fermentation of cattle in SSA countries. However, the observed breeds and the corresponding different LWs differ widely and limit the comparability. The observed LWs range from 162.3 kg in the IPCC values (Dong et al. 2006) to up to 440 kg in the study from Tongwane and Moeletsi (2020). Du Toit et al. (2013) observed Holstein and Jersey cattle in

South Africa, Kouazounde et al. (2015) observed Borgou, Somba and Lagune breeds in Benin, Goopy et al. (2018), and Ndung'u et al. (2019) collected their data from East African shorthorn Zebus and Zebu - Bos Taurus crossbreeds from smallholder livestock systems. Goopy et al. (2020) observed Boran yearling steers, whereas, Tongwane and Moeletsi (2020) looked at the total number of South African cattle including multiple breeds with Bonsmara being the dominant beef cattle breed. In addition, this study observed mature female Zebu - Bos Taurus crossbreeds.

Table 4Comparison of the calculated methane emission factors for mature female cattle with other publications located in Africa

Author	**Cattle Type**	**Mean LW (kg)**	**CH_4 EF (kg yr^{-1} $head^{-1}$)**	**Location**
Dong et al. (2006)	Beef	200.0	41.0	IPCC Tier 1 (SSA)
Goopy et al. (2018)	Dairy	216.3	28.3	Kenya
Goopy et al. (2020)	Beef steers	162.3	37.2	Kenya
Ndung'u et al. (2019)	Dairy	306.9	47.8	Kenya
Du Toit et al. (2013)	Beef	360.0	73.1	South Africa
Tongwane and Moeletsi (2020)	Beef	440.0	96.6	South Africa
Kouazounde et al. (2015)	Multi-purpose	187.8	63.3	Benin
Present study	Beef	420.0	75.4	Kenya

Additionally, each of the studies mentioned here, based their EF estimates on different methodologies causing further difficulties when comparing results. Kouazounde et al. (2015) collated the data they used for their EF calculations from different sources of country-specific data as proposed by the IPCC (Dong et al. 2006) without collecting data themselves. The authors made several assumptions as some (often crucial) data such as the average LW per day for the Borgou and Lagune cattle were sparse or simply not available. They derived that information from expert opinions and reported data from Togo, an adjacent West African country. Tongwane and Moeletsi (2020) obtained and used data from the South African Department of Environmental Affairs and the Department of Agriculture, Forestry and Fisheries to calculate their EFs.

Du Toit et al. (2013) based their calculations on methods from the Australian National Inventory Report which includes Australian country-specific and IPCC default methodologies. They adapted them to South African conditions and management systems where possible. The authors report much higher EFs than the IPCC Tier 1 default values, which is not surprising since the breeds they used for their calculations are around twice as heavy as the ones used by the IPCC.

While the studies of Kouazounde et al. (2015), Tongwane and Moeletsi (2020) and Du Toit et al. (2013) are relying on other literature without knowing the precision of those studies, Goopy et al. (2018) and Ndung'u et al. (2019) improved the IPCC Tier 2 methodology for SSA countries by adapting it to smallholder livestock systems (1 - 19 animals per household) with no access to feed overnight and reduced feed availability during the dry season. Even though the two studies expected to gain similar results since they used the same method in a similar region in the western Kenyan highlands, their results show substantial differences. This may have been caused by slightly different climatic conditions leading to greater LWs in the study by Ndung'u et al. (2019) than the study by Goopy et al. (2018).

The other study cited here, Goopy et al. (2020), tested the relationship between feed intake and enteric CH_4 production to simulate the influence of the dry seasons by feeding different maintenance energy requirement levels. Their mean EF is higher than the one from Goopy et al. (2018) despite lower LW. However, it has to be noted that Goopy et al. (2020) did not observe female nor mature animals and the experiment aimed at simulating extreme conditions in terms of feed scarcity.

The values reported in this study are even higher than those from the two studies in Kenyan smallholder farms – dominated by dairy cattle - who also sampled data in the dry and the rainy season. This shows the need for developing not only country - but even region-specific and/or livestock system-specific emission factors. It needs to be noted that both Goopy et al. (2018) and Ndung'u et al. (2019) collected data over a full year covering rainy and dry seasons. In comparison, we measured during a very short period of 14 nights only, and with an entirely different method. The existing studies used additional data including daily weight increase, locomotion, and milk yield to indirectly calculate methane emissions from energy expenditure, whereas we directly measured the methane concentrations. Our mean EF value is close to the EFs in the South African studies (Kouazounde et al. 2015; Tongwane and Moeletsi 2020) which seems plausible since the mean LW in our study was similar to the ones in their studies. Furthermore, the observed livestock system – cattle ranching – was also similar to the South African studies.

Methane EFs from African cattle are generally lower than those from cattle in developed countries. Ominski et al. (2007) reported EFs of 90 kg CH_4 yr^{-1} $head^{-1}$ and 94 kg CH_4 yr^{-1} $head^{-1}$ for beef cows and bulls in Canada, Castelán-Ortega et al. (2014) reported 82.5 kg CH_4 yr^{-1} $head^{-1}$ for the tropical regions and 70.5 kg CH_4 yr^{-1} $head^{-1}$ for the temperate regions in Mexico as mean values for calves, heifers, steers and bulls, and Basarab et al. (2005) reported 102.5 kg CH_4 yr^{-1} $head^{-1}$ for beef cows in Alberta, Canada. All of the available studies no matter from which continent urge for country and/or even region-specific EFs for the different cattle breeds since one or few EFs cannot reliably predict the methane emissions for cattle breeds in all of the 51 SSA countries.

5 Conclusions

In this study, we determined the CH_4 emissions from free-grazing mature female African beef cattle using an IPCC Tier 2 approach for Kenya. The measurements were conducted for a herd of 300 to 400 animals during 14 nights in 10-min intervals resulting in a mean EF of 75.4 ± 5.69 kg yr^{-1} $head^{-1}$. These estimates might differ from the actual methane emissions due to a systematic bias of the bLS technique reported by Flesch et al. (2014) leading to overestimations of around 10 % for nighttime conditions or to underestimations due to the fact that the animals could not be observed during daytime or during a period of high CH_4 production such as at the end of the rainy season. Our results, together with the six other publications carried out in Africa, express the need for the continued development of country-specific or ideally region-specific EFs since the estimates differ depending on the region, animal breed, and livestock systems.

In the course of most nights, methane emissions showed a decreasing trend due to the lack of feed in the bomas and, therefore, reduced rumination. Improved EF estimates could be obtained, if measurements based on the bLS technique were carried out together with a modeling approach that quantifies EFs from field measurements of LW, milk production, locomotion, etc., similar to the study by Ndung'u et al. (2019). Differences in the methodologies could be investigated, which would help to improve the accuracy of a range of methods. Additionally, observing a herd for an entire diurnal cycle would help to detect and characterize regular CH_4-emission patterns. Furthermore, measurements distributed over the whole year, especially at the end of the rainy season, could help to verify or improve the calculated EFs.

Declarations

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Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

Not applicable.

Code availability

Not applicable.

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kevin Wolz, Sonja Leitner, Lutz Merbold, Benjamin Wolf and Matthias Mauder. The first draft of the manuscript was written by Kevin Wolz and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval

Not applicable.

Consent to participate

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