Agricultural and Forest Meteorology 256–257 (2018) 482–491

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Comparing methane emissions estimated using a backward-Lagrangian stochastic model and the eddy covariance technique in a beef cattle feedlot

Prajaya Prajapati, Eduardo A. Santos*

Department of Agronomy, Kansas State University, United States

A R T I C L E I N F O

Keywords:
Eddy covariance
Inverse lagrangian model
Methane
Enteric fermentation
Footprint model

A B S T R A C T

Accurate methodologies to measure emissions of greenhouse gases (GHG) from livestock systems are necessary to improve the emission coefficients used in national GHG inventories and to evaluate mitigation strategies. The objective of this study was to compare methane (CH_4) emissions estimated using the eddy covariance (EC) technique and a backward-Lagrangian stochastic (bLS) model. A closed-path EC system was used to measure CH_4 fluxes in a commercial beef cattle feedlot. The EC fluxes were scaled from the feedlot to the animal scale using a footprint analysis. The EC measurements of CH_4 concentration and wind data were used with the bLS model to infer CH_4 emissions. The average CH_4 emissions (± standard deviation) during the experiment were 87 (± 30) g animal^{-1} d^{-1} and 85 (± 27) g animal^{-1} d^{-1} for EC and bLS techniques, respectively. These values are consistent with the results from previous studies with similar animal and feed characteristics. Both techniques were able to capture a pronounced daytime and nighttime variation in CH_4 emissions, with higher CH_4 emissions during the day and lower emissions at night. Our results indicate that the eddy covariance technique combined with footprint models can be successfully used to accurately measure enteric CH_4 from cattle.

1. Introduction

Enteric fermentation, i.e., the breakdown of complex carbohydrates into simple molecules by microbes in the stomach of ruminants with production of methane (CH_4) as a byproduct, accounts for up to one third of the global anthropogenic CH_4 emissions (IPCC, 2014). The magnitude of CH_4 emissions from ruminants is quite variable and depends on several factors, including cattle breed, animal weight, feed intake and ration composition (Broucek, 2014). Accurate measurements of CH_4 emissions from livestock systems are necessary to evaluate mitigation strategies to reduce livestock greenhouse gas emissions (GHG), to improve the accuracy of current GHG national inventories and whole farm models, and to understand the mechanisms controlling the CH_4 global cycle.

Chambers and the sulfur hexafluoride (SF_6) tracer technique are used to measure enteric greenhouse gas emissions from ruminants (Harper, 2005; Johnson et al., 1994; Lassey et al., 2011). These techniques are useful for comparing the effect of different diets, ration additives and genetic differences on CH_4 emissions from individual animals (Harper et al., 2011). Nevertheless, chamber and the SF_6 tracer techniques are labor intensive, often limited to a small number of animals and can interfere with animal behavior, introducing uncertainties in CH_4 emission measurements (Harper et al., 2011; Johnson et al., 1994). Micrometeorological techniques, such as backward Lagrangian stochastic dispersion analysis (bLS), mass balance and flux-gradient approaches, have been used to estimate ruminant CH_4 emissions at the farm level (Harper et al., 1999; Laubach et al., 2008; Leuning et al., 1999; McGinn et al., 2011). The major benefits of these techniques over non-micrometeorological methods are that they are non-intrusive, can be used to integrate fluxes from large herds reducing measurement uncertainties due to animal-to-animal variability, and provide high temporal resolution (< 1 h) flux measurements (McGinn, 2013).

The bLS technique is a micrometeorological method widely used to estimate CH_4 emissions from livestock systems. It requires gas concentration measurements taken downwind, within the source or upwind from the source area along with measurements of wind speed, wind direction and turbulence statistics (Flesch et al., 2005a, 2004; Flesch et al., 2005b, 1995; Wilson et al., 2013). The bLS technique calculates the advection of a gas by predicting the trajectory of particles from a source to a sensor. This technique relies on the basic assumption that the flow is horizontally homogenous and is described by Monin-Obukhov similarity relationships. One of the limitations of bLS is the need to accurately measure background and downwind concentration, requiring cross-calibrations of different gas analyzers used to measure those concentrations (Laubach et al., 2013; McGinn, 2013). In addition, the accuracy of bLS estimates is compromised under low wind speeds

* Corresponding author.
E-mail address: esantos@ksu.edu (E.A. Santos).

https://doi.org/10.1016/j.agrformet.2018.04.003
Received 15 December 2017; Received in revised form 14 March 2018; Accepted 8 April 2018
Available online 17 April 2018
0168-1923/

and strong stable and unstable atmospheric stratification reducing the amount of usable data (McGinn, 2013).

The eddy covariance (EC) technique is considered the most direct meteorological method and has been widely used to measure carbon dioxide (CO_2) and energy exchange in ecosystems around the world (Baldocchi, 2003). Recently, with the development of new optical sensors, the EC technique has also been applied to quantify CH_4 emissions from livestock (Coates et al., 2018; Dengel et al., 2011; Felber et al., 2015; Prajapati and Santos, 2017b; Taylor et al., 2017). Dengel et al. (2011) used the EC technique for the first time to measure CH_4 emissions from grazing sheep using an EC open-path CH_4 gas analyzer. They observed close agreement between annual CH_4 emissions per animal estimated using the EC technique and IPCC CH_4 emission estimates for sheep. However, they acknowledged that the EC CH_4 emission estimate may have been biased due to lack of information on the number of moving sheep within the flux footprint. Felber et al. (2015) used EC flux measurements, an analytical footprint model and GPS location of dairy cows to interpret CH_4 emissions estimates from a grazing system. Overall, they reported that CH_4 emissions estimated using the EC were similar to estimates reported by others. However, Felber et al. (2015) observed a systematic underestimation of CH_4 emission estimates from animals far from the flux tower, which they attributed to uncertainties in the analytical footprint model used to scale their fluxes. Coates et al. (2017) combined the EC technique with a Lagrangian stochastic model to estimate methane emissions from eight point sources within a limited area in a CH_4 controlled release study. They reported similar accuracy for the EC technique when compared with other micrometeorological techniques used to estimate livestock CH_4 emissions. Prajapati and Santos (2017a) compared two footprint models (Kljun et al., 2015; Kormann and Meixner, 2001) to estimate CH_4 emission from beef cattle in a feedlot. Their results showed large differences in the source areas estimated by the two footprint models. Nevertheless, their estimated CH_4 emissions per animal agreed with reported studies with similar animal characteristics and diets.

These studies show that quantifying CH_4 emissions from livestock using the EC technique is promising, but so far the assessment of EC performance to estimate CH_4 emissions from cattle has been restricted to comparisons with CH_4 emissions from previous studies and estimates based on animal diet and intake. Evaluations of the EC technique and other herd-scale micrometeorological techniques are necessary to identify the potential sources of error and to evaluate the performance of the EC method under a wide range of atmospheric conditions. Large commercial feedlots where thousands of heads of cattle are confined to a well-defined area provide a unique experimental site for comparing the EC technique with the bLS model. The objective of this study was to compare CH_4 emissions obtained using the EC technique combined with a footprint analysis (EC_{FFP}) with CH_4 emission estimates provided by a well-stablished backward-Lagrangian stochastic (bLS) model.

2. Material and techniques

2.1. Experimental site description

Field measurements were conducted at a commercial beef cattle feedlot in Kansas from August 2013 to May 2014. The site is 622 m above sea level over a near flat terrain (slope < 5%). The monthly average air temperature during the measurement period ranged from 2 to 26 °C and accumulated monthly precipitation varied from 7 to 83 mm (National Climatic Data Center, 2017). The feedlot has a total surface area of approximately 59 ha with a holding capacity of approximately 30,000 animals. Roads and alleys used for cattle and feed transportation account for approximately 21% of the total feedlot surface area. The pens near the flux tower, which were expected to contribute to the majority of the measured fluxes, were occupied by steers and heifers weighing 350 kg on average at the beginning of the experiment. The cattle were fed a corn-product based died. Further information on the ration composition is provided by Prajapati and Santos (2017a). The total feedlot occupancy was 24,116 animals during the summer and early fall months (August 2013 to November 2013) with an average stocking density of 19 m^2 $animal^{-1}$ (~526 animals ha^{-1}). In the late fall and spring months (December 2013 to April 2014), the number of animals was reduced by about 15% resulting in an average stocking density of 22 m^2 $animal^{-1}$ (~455 animals ha^{-1}).

2.2. Flux measurements and calculations

A detailed description of the flux measurements and calculations at the experimental site is provided by Prajapati and Santos (2017b). Here, we summarize the description of these measurements for completeness. Fluxes of CH_4 were measured using a closed-path EC system. The wind velocity components (*u, v, w*) and sonic temperature were measured with a sonic anemometer (CSAT3, Campbell Sci., Logan, UT). A wavelength-scanned closed-path analyzer (G2311-f, Picarro Inc., Santa Clara, CA) was used to measure CH_4, CO_2 and H_2O mixing ratios. In this study, only CH_4 mixing ratios were used for flux calculations.

The closed-path analyzer air intake consisted of a rain diverter connected to an in-line filter (Polypropylene/polyethylene 10 µm membrane, Pall Corporation, AnnArbor, MI). The downstream part of the filter was attached to a 7-m long high-density polyethylene tube with an inner diameter of 5.3 mm. The other end of this tube was connected to a second filter (Acrodisc Gelman 1 µm, PTFE membrane, Pall corporation) that was attached to the gas analyzer inlet. The sampling line was heated to prevent condensation of water on the tube walls. The flow rate within the sampling tube was maintained at 5 L min^{-1} using the closed-path analyzer internal mass flow controller and a vacuum pump (Vacuubrand GmbH, Wertheim, Germany). Field calibrations were performed at least every two weeks using certified calibration gas (CH_4 at 1.9 and 4.0 ppm, ± 1%). The anemometer and the gas analyzer air intake were mounted on the tower at 5 m above the ground at the northern edge of the feedlot. All the data were recorded at 10 Hz using a datalogger (CR1000, Campbell Sci.).

The high frequency data from the sonic anemometer and gas analyzer were initially tested for time stamp consistency to identify possible gaps in the data series. Next, calibrations were applied to the concentration files using a custom Matlab code (version 8.3.0.532, The Mathworks Inc., Natick, MA). Half-hourly CH_4 fluxes were then calculated using an EC software application (EddyPro, v. 6.0, Licor). The CH_4 flux calculations followed the common procedures for EC flux calculations: spike removal, double coordinate rotation, time lag compensation (Fan et al., 1990) and spectral corrections (Horst, 1997). Typical spectral corrections ranged from 20% to 30% during the experiment. Prajapati and Santos (2017b) observed the closed-path analyzer CH_4 and CO_2 frequency responses were similar and reported good agreement (slope = 1.05) and correlation (R^2 = 0.98) between CO_2 fluxes measured using the same closed-path analyzer and an established EC open-path analyzer (LI-7500, LI-COR Biogeosciences, Lincoln, NE). These previous results show that the closed-path EC system is capable of providing reliable EC measurements.

The quality control system developed by Foken et al. (2004) was used to eliminate half-hourly periods in which the atmospheric conditions were unsuitable for flux measurements.

2.3. Scaling of raw EC flux to flux per animal using flux footprint model

Fluxes measured using the EC technique were scaled from the feedlot scale to the animal scale based on the relative contributions of pens and non-pen surfaces within the feedlot to the measured flux, following Neftel et al. (2008) and Baum et al. (2008). Further details on the flux scaling approach is provided by Prajapati and Santos (2017a).