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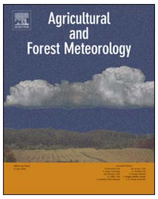

Estimating methane emissions from beef cattle in a feedlot using the eddy covariance technique and footprint analysis

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ABSTRACT

Measurements of methane (CH_4) emissions from cattle could provide invaluable data to reduce uncertainties in the global CH_4 budget and to evaluate mitigation strategies to lower greenhouse gas emissions. The eddy covariance (EC) technique has recently been applied as an alternative to measure CH_4 emissions from livestock systems, but heterogeneities in the source area and fetch limitations impose challenges to EC measurements. The main objective of this study was to estimate CH_4 emissions rates per pen surface (F_{pens}) and per animal (F_{animal}) from a beef cattle feedlot using the EC technique combined with two footprint models: an analytical footprint model (KM01) and a parametrization of a Lagrangian dispersion model (FFP). Fluxes of CH_4 were measured using a closed-path EC system in a commercial feedlot. The footprint models were used to investigate fetch requirements and to estimate F_{pens} and F_{animal}. The aggregated footprint area predicted by KM01 was 5–6 times larger than FFP estimates. On average, F_{pens} was 8 (FFP) to 14% (KM01) higher than the raw EC flux, but differences between F_{pens} and EC flux varied substantially depending on the location and size of the flux footprint. The monthly average F_{animal}, calculated using F_{pens} and the footprint weighed stocking density, ranged from 83 to 125 g animal^{-1} d^{-1} (KM01) and 75–114 g animal^{-1} d^{-1} (FFP). The emission values are consistent with the results from previous studies in feedlots. These results suggest that the EC technique can be combined with footprint analysis to estimate gas emissions from livestock systems.

1. Introduction

Enteric fermentation and manure management are major agricultural sources of CH_4 and account for about one third of the total CH_4 emissions from anthropogenic activities in the United States (EPA, 2017). Beef and dairy cattle production systems are estimated to account for about 71% and 25%, of enteric CH_4 emissions in the US, respectively (EPA, 2017). Accurate measurements of CH_4 emissions from livestock are necessary to reduce uncertainties in the CH_4 global budget and to identify appropriate mitigation strategies to reduce greenhouse gas (GHG) emissions from agriculture.

Micrometeorological techniques have been used to measure GHG from livestock production systems (Bai et al., 2015; Flesch et al., 2007; Laubach et al., 2013; McGinn, 2013). These techniques are non-intrusive and integrate fluxes over large areas, which minimizes flux uncertainties due to source heterogeneities commonly observed in livestock systems (Harper et al., 2011). In addition, micrometeorological approaches provide flux measurements at a high temporal resolution (< 1 h) over extended periods of time (months to years) which is required to improve the understanding of the mechanisms controlling GHG emissions from livestock and to improve whole-farm GHG models.

The eddy covariance (EC) technique has been the standard micrometeorological method to measure fluxes of CO_2 and energy in ecosystems around the world (Baldocchi, 2008). Recently, with the development of new optical sensors, the EC method has been also used to measure the fluxes of other trace gases such as CH_4, ammonia (NH_3) and nitrous oxide (N_2O) (Baldocchi et al., 2012; Famulari et al., 2010; Peltola et al., 2012; Sun et al., 2015). The major challenges for applying the EC technique to measure GHG emissions from livestock systems are: 1) fetch limitations and 2) heterogeneity of the underlying source area (Baum et al., 2008; Felber et al., 2015; Prajapati and Santos, 2017; Taylor et al., 2017). Baum et al. (2008) used the EC technique to measure CO_2 and energy fluxes from a beef cattle feedlot in Kansas. They showed systematic errors were introduced in their CO_2 flux measurements by fetch limitations as well as by the presence of weak CO_2 source areas (roads and alleys) within the feedlot. These challenges need to be addressed to improve the accuracy of GHG emission measurements from livestock systems using the EC technique. Furthermore, EC measurements of GHG emissions from livestock systems usually integrate contributions from different source areas, e.g. in a feedlot,

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fluxes can be a result of contributions from different surfaces: pens, lagoons, alleys and roads. Integrated flux measurements from different GHG sources at the farm level can provide useful datasets to validate whole-farm GHG models (Crosson et al., 2011; Taylor et al., 2017) but for other applications, such as dietary studies, GHG inventories and regulatory purposes, GHG emissions are usually expressed as fluxes per source unit, e.g.: CH_4 emissions per head of cattle and N_2O fluxes per paddock surface.

Footprint models have been used for about three decades to investigate the effect of the underlying surface on point flux measurements (Gash, 1986; Leclerc and Thurtell, 1990; Schmid and Oke, 1990; Schuepp et al., 1990). In livestock systems, footprint models have been applied to study the effect of source area heterogeneities on EC flux measurements and to scale EC measurements per unit of source area (Baum et al., 2008; Dengel et al., 2011; Felber et al., 2015). Baum et al. (2008) aggregated the results from a one-dimensional footprint model to determine the contributions from pen, road, and alley surface areas to EC flux measurements in a beef cattle feedlot. Felber et al. (2015) combined EC flux measurements, obtained from paddocks grazed by dairy cows, with an analytical footprint model and the location of the dairy cows to estimate the CH_4 emission rate per animal (F_{animal}). The analytical footprint models used in those studies are attractive for their simplicity and computation speed which makes them suitable to estimate the flux footprint for long-term datasets (Leclerc and Foken, 2014). However, analytical footprint models are often limited to homogeneous surface layer similarity conditions and to some specific atmospheric stability conditions (Schmid, 2002). More complex models, such as backward Lagrangian models, can overcome some of those problems but are usually computationally expensive. Parameterized versions of complex models could retain some of the skills of the complex models while requiring less computer resources and time for simulations (Hsieh et al., 2000; Kljun et al., 2015; Schmid, 2002).

Currently, only a few studies in livestock systems have applied the EC technique with footprint models to estimate methane emissions per animal (Dengel et al., 2011; Felber et al., 2015). Additional studies are necessary to investigate the performance of footprint models and the EC technique to estimate GHG emissions from different livestock production systems under a wide variety of atmospheric conditions. To our knowledge, this is the first study to apply this new methodology to estimate F_{animal} in an outdoor feedlot. Cattle feedlots are an important component of the beef cattle industry in North America. A total of 20.4 million heads of cattle were placed in feedlots for the slaughter market in 2015 (USDA, 2016).

The main objective of this study was to estimate CH_4 emissions from cattle in a feedlot using the EC technique combined with existing footprint models. The specific objectives of this study were to: 1) investigate the effect of fetch limitations and feedlot surface heterogeneities on EC CH_4 flux measurements and 2) estimate and compare the CH_4 emission rate per pen area and per animal from the feedlot using an analytical footprint model and the parameterized version of a Lagrangian stochastic particle dispersion model.

2. Material and methods

2.1. Site description

Field measurements were carried out at a commercial beef cattle feedlot in Kansas from August 2013 to May 2014. The total monthly precipitation ranged from 7 to 83 mm and average monthly air temperature ranged from 2 to 26 °C (Fig. 1) in the nearby weather station located 6 km west from the site (National Climatic Data Center, 2017). The site is located at an elevation of 622 m above the sea level over a near flat terrain (slope $< 5\%$). The feedlot has near rectangular shaped pens with a total surface area of approximately 59 ha surrounded by agricultural fields and a holding capacity of 30,000 head of cattle. Roads and alleys accounted for approximately 21% of the total feedlot surface area. The pens near the north edge of the feedlot (closer to the flux tower, Section 2.2) were occupied by steers and heifers weighing 300–350 kg at the beginning of the experiment. In this feedlot, the cattle spent about three to six months, gaining 250–300 kg in weight. The average stocking density in the pens was $19\ m^2\ animal^{-1}$ (~ 526 animals ha^{-1}), with a total of 24,116 head of cattle during the summer and early fall months (August 2013–November 2013). In the late fall and spring months (December to April), the number of animals was reduced by about 15% resulting in an average stocking density in the pens of $22\ m^2\ animal^{-1}$ (~ 455 animals ha^{-1}).

Ration samples from three pens immediately south of the flux tower were collected during the experiment on two different dates. The reason for the selection of those pens was that they were expected to contribute to the majority of the measured flux (Section 3.2). The composition of the cattle ration is shown in (Table 1). During the experiment, there was no substantial changes in the cattle ration (*feedlot manager personal communication*).

2.2. Flux measurements

Fluxes of CH_4 were measured using the eddy covariance method. The wind velocity orthogonal components were measured using a sonic anemometer (CSAT3, Campbell Sci., Logan, UT). A wavelength-scanned cavity ring-down spectroscopy closed-path gas analyzer (G2311-f, Picarro Inc., Santa Clara, CA) was used to measure CH_4, CO_2 and H_2O mixing ratios, but only CH_4 mixing ratio data were used for flux calculations in this study. The closed-path analyzer air intake consisted of a rain diverter connected to an inline filter (Polypropylene/polyethylene 10 µm membrane, Pall Corporation, AnnArbor, MI). The air was drawn from the intake through a 7-m long high density polyethylene tube with an inner diameter of 5.3 mm to a second filter (Acrodisc Gelman 1 µm, PTFE membrane, Pall corporation), which was connected to the closed-path analyzer inlet. A vacuum pump (MD 4 NT, Vacuubrand GmbH, Wertheim, Germany) drew air through the sampling tube. The flow rate was kept at $5\ L\ min^{-1}$ by the closed-path analyzer's internal mass flow controller. The sampling line was heated using a heating cable to minimize the adsorption of water by the tube walls. Field calibrations were performed at least every two weeks using certified calibration tanks (Tank 1: $CH_4 = 1.9$ ppm and Tank 2: $CH_4 = 4$ ppm, ± 1% accuracy, Matheson, Joliet, IL).

The sonic anemometer and closed-path analyzer air intake were set up on a tower at approximately 5 m above the ground. The closed-path analyzer air intake was positioned with a vertical separation of 8 cm, a northward separation of 18 cm and an eastward separation of 31 cm from the sonic anemometer. The flux tower was set up at the north edge of the feedlot with the sonic anemometer and the gas analyzer air intake oriented towards the south to maximize air flow over the source area within the feedlot and avoid potential air flow disturbances caused by buildings at the south edge of the feedlot. The signals of the sonic anemometer and closed-path gas analyzer were recorded at 10 Hz using a datalogger (CR1000, Campbell Sci.).

Prior to flux calculations, calibration corrections were applied to the raw concentration data and the consistency of time stamps was verified using a Matlab (version 8.3.0.532, The Mathworks Inc., Natick, MA) function. The half-hour high frequency files, generated by the same Matlab function, were analyzed following the procedures described by Aubinet et al. (2012) using the software package EddyPro (v. 6.0, Licor). The flux calculations included the following procedures: spike removal, double coordinate rotation, time lag compensation (Fan et al., 1990), and spectral corrections (Horst, 1997). Half-hourly fluxes were screened to ensure adequate turbulence development and steady state conditions suitable for flux measurements using the quality control flag system proposed by Foken et al. (2004). A detailed description of the flux measurements and calculations is provided by Prajapati and Santos (2017).