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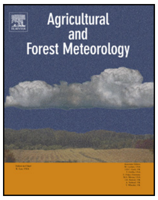

Measurements of methane emissions from a beef cattle feedlot using the eddy covariance technique

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A R T I C L E I N F O

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A B S T R A C T

The eddy covariance (EC) technique has been extensively used in several sites around the world to measure energy fluxes and CO_2 exchange at the ecosystem scale. Recent advances in optical sensors have allowed the use of the EC approach to measure other trace gases (e.g. CH_4, NH_3 and N_2O), which has expanded the use of eddy covariance for other applications, including measuring gas emissions from livestock production systems. The main objectives of this study were to assess the performance of a closed-path EC system for measuring CH_4, CO_2, and H_2O fluxes in a beef cattle feedlot and to investigate the spatial variability of eddy covariance fluxes measured above the surface of a feedlot using an analytical flux footprint analysis. A closed-path EC system was used to measure CH_4, CO_2, and H_2O fluxes. To evaluate the performance of this closed-path system, an open-path EC system was also deployed on the flux tower to measure CO_2 and H_2O exchange. The performance assessment of the closed-path EC system showed that this system was suitable for EC measurements. The frequency attenuations, observed for the closed-path system CO_2 and CH_4 cospectra in this study, are in agreement with results from previous instrument comparison studies. For the water vapor closed-path cospectra, larger attenuations were likely caused by water vapor molecule interaction with the sampling tube walls. Values of R^2 for the relationship between H_2O and CO_2 fluxes, measured by open-path and closed-path systems, were 0.94–0.98, respectively. The closed-path EC system overestimated the CO_2 by approximately 5% and underestimated the latent heat fluxes by about 10% when compared with the open-path system measurements. Measured CH_4 and CO_2 fluxes during the study period from the feedlot averaged 2.63 $\mu mol\,m^{-2}\,s^{-1}$ and 103.8 $\mu mol\,m^{-2}\,s^{-1}$, respectively. Flux values were quite variable during the field experiment and the footprint analysis was useful to interpret flux temporal and spatial variation. This study shows indication that consideration of atmospheric stability condition, wind direction and animal movement are important to improve estimates of CH_4 emissions per pen surface or per head of cattle.

1. Introduction

Methane (CH_4) is an important greenhouse gas (GHG) with a global warming potential 28 times greater than CO_2 over a 100-year period (IPCC, 2014). Methane, originating from microbial fermentation in the digestive system of ruminants (enteric fermentation) and manure management, accounts for approximately 30% of the total anthropogenic CH_4 emissions in the United States (USEPA, 2015). Accurate measurements of CH_4 from animal production systems are crucial for reducing uncertainties in national GHG inventories and evaluating mitigation strategies to reduce GHG emissions from agriculture.

Chamber and tracer techniques are often used to measure emissions from livestock. These techniques are useful in comparison studies aiming to evaluate the effect of different diets and mitigation strategies to minimize GHG emissions (Makkar and Vercoe, 2007). However, chambers and tracer techniques are intrusive. They can alter typical animal behavior, management conditions, and gas emission rates. In addition, their application is constrained to a limited number of animals increasing measurement uncertainties (Harper et al., 2011).

Micrometeorological approaches have also been used to estimate GHG emissions from livestock production systems and offer some advantages compared to chamber and tracer techniques (Bai et al., 2015; Baum et al., 2008; Flesch et al., 2007; Laubach, 2010; Laubach et al., 2013). For instance, micrometeorological methods are non-intrusive and integrate flux measurements from larger areas and from a larger number of animals in their natural environ-

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ment, reducing uncertainties in the fluxes caused by small sample sizes and changes in animal behavior (Harper et al., 2011; McGinn, 2013).

The eddy covariance (EC) technique is considered the most direct micrometeorological method to measure gas exchanges between the land and the atmosphere (Baldocchi, 2003; Dabberdt et al., 1993). EC requires fast response sensors (typically 10–20 Hz sampling rate) to capture fluxes measured by small turbulent eddies. Recent advances in optical sensors have allowed the development of fast response sensors capable of measuring other trace gases, such as CH_4, nitrous oxide (N_2O), and ammonia (NH_3), at a rate suitable for EC measurements (Detto et al., 2011; McDermitt et al., 2011; Peltola et al., 2013; Sun et al., 2015). The EC approach has been used to measure gas exchange from different surfaces, including: agricultural sites (Abraha et al., 2015; Baker and Griffis, 2005), urban plots (Feigenwinter et al., 2012; Velasco et al., 2005), landfills (McDermitt et al., 2013), and bodies of water (Nordbo et al., 2011; Norris et al., 2012). Recent studies have also applied the EC technique to estimate CH_4 emissions from grazing animals (Dengel et al., 2011; Felber et al., 2015).

The EC technique has been applied to measure gas exchange from beef cattle feedlots and the atmosphere (Baum et al., 2008; Sun et al., 2015). Whole farm emission measurements can be useful to improve current modeling approach uncertainties (Crosson et al., 2011). One of the basic assumptions of the EC technique is that measurements are taken above an extensive and homogeneous source area. In feedlots, fluxes measured using the EC approach integrate contributions from different surfaces, such as: pens, roads and alleys, which will influence the flux magnitudes (Baum et al., 2008). Flux footprint analyzes have been used to interpret flux variation in animal production systems and to investigate how changes in the underlying source surface affect flux measurements (Baum et al., 2008; Dengel et al., 2011; Sun et al., 2015). Baum et al. (2008) applied the eddy covariance technique to measure carbon dioxide (CO_2) and water vapor fluxes from a commercial beef cattle feedlot in Kansas. They utilized an analytical footprint model to determine the contributions of non-pen surfaces to the EC flux. They found alleys and roads contribute to 2 and 10% of the total flux, respectively. They also reported that the effect of these surfaces on the fluxes varied depending on the wind direction. More recently, Sun et al. (2015) used the EC approach to measure NH_3 fluxes in a beef cattle feedlot in Colorado. They were able to identify in their two-week measurement that the diel variation in the NH_3 flux was also influenced by the flux footprint.

Most of the CH_4 emission measurements from ruminants using micrometeorological techniques are restricted to short field campaigns ranging from a few days to weeks. Long-term studies are necessary to investigate how changes in environmental conditions affect GHG fluxes from livestock production systems and to reduce the uncertainties of current GHG inventories and emission factors. In addition, long-term studies could bring new insights into the factors affecting the performance of micrometeorological techniques. In this study, we evaluate the performance of a closed-path EC system to measure CH_4 and CO_2 emissions from a commercial beef cattle feedlot during an 8-month period. Few studies have applied the EC technique to quantify gas emissions from a beef cattle feedlot (Baum et al., 2008; Sun et al., 2015) and to our knowledge, this is the first study to utilize the EC technique to estimate long-term CH_4 emissions from a confined animal feeding operation. The main objectives of this study were (i) to assess the performance of a closed-path EC system for measuring CH_4, CO_2, and water vapor (H_2O) fluxes in a beef cattle feedlot against a well-established open-path gas analyzer, and (ii) to investigate the spatial variability of EC fluxes measured above the surface of a beef cattle feedlot using an analytical flux footprint analysis.

2. Material and methods

2.1. Site description

The field experiment was carried out in a commercial beef cattle feedlot in western Kansas from August 2013 to May 2014. This feedlot has a near rectangular shape with a total pen surface of approximately 59 ha surrounded by agricultural fields. The feedlot has the capacity to hold 60,000 head of cattle and was near full capacity (~58,000) during the experiment. The experimental site is on a near flat terrain (slope <5%) and located in one of the windiest regions of the United States (National Climatic Data Center, 2015), making this site ideal to evaluate micrometeorological methods.

2.2. Flux measurements

Fluxes of CH_4, CO_2, latent heat, and sensible heat were measured using the EC technique. Wind velocity, three orthogonal components, and temperature 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 concentrations. To evaluate the performance of the closed-path EC system, a well-established open-path gas analyzer (LI-7500, LI-COR, Lincoln, NE) was also deployed on the flux tower to measure CO_2 and H_2O concentrations.

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) and was positioned at 8 cm from the sonic anemometer. The air was drawn from the intake through a 7-m long high density polyethylene tube with an inner diameter of 5.3 mm and then to a second filter (Acrodisc Gelman 1 μm, PTFE membrane, Pall corporation), which was connected to the closed-path analyzer inlet. The feedlot is a very dusty environment, so the use of two filters in series was necessary to prevent clogging of the analyzer's internal filter by particulate material. A vacuum pump (MD 4 NT, Vacuubrand GmbH, Wertheim, Germany) and the analyzer internal mass flow controller kept the flow rate in the sampling line at 5 L min^{-1}. The sampling line was heated using a pipe heating cable and covered with pipe insulation material to lower the relative humidity within the sampling tube and minimize the adsorption of water by the tube walls. Field calibrations were performed in two-week intervals using certified calibration tanks (Tank 1: CH_4 = 1.9 ppm and CO_2 = 350.1 ppm, and Tank 2: CH_4 = 4 ppm and CO_2 = 450.3 ppm, ±1% accuracy, Matheson, Joliet, IL).

The sonic anemometer, closed-path analyzer air inlet, and open-path analyzer were setup on a tower at approximately 5 m above the ground. The tower was mounted on the top of a flatbed trailer at the northern edge of the feedlot. The instrumentation setup location was chosen to maximize air flow over the source area within the feedlot and to maximize the distance between the tower and buildings at the south side of the feedlot that could disturb the air flow. The open-path analyzer was set up with a slight angle from the vertical (~15°) to minimize the accumulation of rain droplets on the analyzer windows after rain events. To minimize synchronization errors among the instruments, the signals of the sonic anemometer, open-path and closed-path gas analyzers were recorded at 10 Hz by a single datalogger (CR1000, Campbell Sci.). The sensors and the datalogger were connected using synchronous devices for measurement (SDM, Campbell Sci) cables for sonic anemometer and open-path analyzer and a serial (RS232) cable for the closed-path analyzer.