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Evaluating an eddy covariance technique to estimate point-source emissions and its potential application to grazing cattle

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ABSTRACT

Measurement of gas emissions from grazing cattle presents a challenging application of the eddy-covariance (EC) technique. A cattle herd represents point sources on the landscape, violating the assumptions of spatial homogeneity made in typical EC applications. A proper evaluation of EC fluxes in this case requires an analysis based on the overlap between the EC flux footprint and animal positions. A controlled gas release study was conducted to evaluate the potential of a Lagrangian stochastic (LS) dispersion model to interpret EC fluxes and estimate emissions from point sources. Methane (CH_4) gas was released from eight fixed points within a confined area (representing animals in a paddock) while two EC systems monitored CH_4 fluxes at two distances downwind of the source area (a near and far tower). Overall accuracy was greater at the far tower location with estimates within 3% of the actual emission rate. The near tower overestimated total emissions by 16%. Deviations from the true emission rate were greatest for night-time and morning periods and least for mid-afternoon to early evening periods when neutral stability and favorable wind directions prevailed. We also investigated the effect of treating the simulated paddock as a homogeneous area emission source. The near tower emission estimate improved with the area source approach (9% overestimation). The far tower suffered a loss of accuracy (17% underestimation), but this was substantially improved (7% underestimation) by reducing the source area to the minimum required to contain the eight release points. Our study suggests that EC can be used to measure animal emissions from grazing cattle on pasture with a level of accuracy similar to other micrometeorological approaches.

1. Introduction

Global livestock production accounts for 14.5% of anthropogenic greenhouse gas (GHG) emissions, with methane (CH_4) from enteric fermentation in ruminant animals contributing 39% to this sector's total (Gerber et al., 2013). Globally, enteric CH_4 is the largest single contributor to GHG emissions from agriculture (Francesco et al., 2013) and has consequently been an active area of focus for GHG mitigation efforts. Grazing systems associated with beef production are of particular interest as they generate the highest emission intensities of all agricultural sectors (Beauchemin et al., 2010), due mainly to the longer time to slaughter of grazing animals and variable feed quality of pastures (Gerber et al., 2013).

Monitoring of emissions from the grazing environment is a challenge. Mitigation studies typically rely on individual animal techniques for validation (i.e., chambers or SF_6 tracer). Open-circuit respiration chambers are routinely used, however, it is generally recognized that emission values derived under controlled chamber conditions are difficult to extrapolate to the pasture scale (Harper et al., 2011). The SF_6 tracer technique (Johnson et al., 1994) was developed to overcome the limitations of chamber measurements, and the technique provided the first estimates of CH_4 emissions from grazing cattle (Lassey et al., 1997; McCaughey et al., 1997). Its subsequent widespread use has led to a number of refinements (Deighton et al., 2014), however, labour requirements typically limit the number of animals included and the length of time for monitoring. While easier to employ with dairy animals accustomed to daily handling, beef cattle require extensive training (DeRamus

Abbreviations: EC, eddy covariance; IDM, inverse dispersion method; LS, Lagrangian Stochastic; GHG, greenhouse gases; SD, standard deviation; CI, confidence interval; CL, confidence limit; KM, Korman-Meixner footprint model.

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et al., 2003) and daily mustering of cattle for sampler changes is impractical in extensive grazing operations. A better understanding of the character of emissions from grazing systems, and assessment of GHG mitigation strategies in the grazing environment, requires measurement techniques capable of inexpensive herd-scale monitoring (Pacheco et al., 2014).

Micrometeorological methods offer the advantage of a non-interference measurement of herd-scale emissions on a near continuous basis (McGinn, 2013). Mass balance approaches, which estimate the horizontal flux of gas downwind of the target animals using profile measurements of the gas concentration and wind velocity, can be used for small groups of animals (Denmead et al., 2000), but set-up and instrumentation demands can be high. Inverse-dispersion methods (IDM) combined with open-path concentration sensors (Fourier transform infrared spectrometers, lasers) have proven versatile tools for calculating emissions from small pens (McGinn et al., 2009) to large paddocks (Laubach and Kelliher, 2005) to whole farms (Flesch et al., 2005). The capability of IDM relies upon concentration sensors with sufficient sensitivity to detect the rise in concentration (above background) downwind of animals. This becomes challenging in a grazing environment where cattle density is low and roaming cattle make it difficult to spatially define the source and to determine an appropriate background concentration. Tomkins and Charmley (2015) overcame this difficulty of IDM with grazing animals by taking advantage of the natural behaviour of cattle to congregate after a morning grazing period. During this period, animals were confined in a pen while open-path measurements were used to calculate emissions for several hours during the day.

Eddy covariance (EC) is another micrometeorological technique for calculating surface emissions that is increasingly being utilized for CH_4 emission measurements from a wide range of environments including cattle-grazed landscapes. The basis of the technique is a direct measure of the vertical flux of gas at a single measurement point in the atmosphere. This flux represents a spatially weighted average of the gas exchanges between the underlying surface (mostly upwind of the measurement) and the atmosphere. Areas of the surface that contribute to the calculated flux (and their relative contributions) constitute the flux footprint (Schuepp et al., 1990). The extent and shape of this footprint varies with sensor height, the aerodynamic roughness of the surface, and atmospheric conditions.

In many EC applications it is assumed the underlying surface is spatially extensive and homogeneous, so that a footprint analysis is not required. In a large feedlot for example, the cattle may nominally meet this assumption (Gao et al., 2011) and EC becomes a straightforward application. However, this is not generally the case in a grazing environment. Obtaining an animal emission estimate in this case requires careful interpretation of the flux in relation to the number and position of cattle within the measurement footprint of the EC instrumentation. If animal positions are not known, e.g., where GPS collars (McGinn, 2013; McGinn et al., 2014; Felber et al., 2015) or time-lapse images (Benvenutti et al., 2015) are not used, location information can be inferred through confinement of animals within pens (Dumortier et al., 2017; Tallec et al., 2012) or by assuming that over a long averaging period, the pasture can be treated as a spatially uniform source equivalent to the average stocking density (Dengel et al., 2011; Dumortier et al., 2017).

The application of EC to estimate emissions in the grazing environment will generally require a computational overlap of animal positions with a footprint model. Tallec et al. (2012) and Felber et al. (2015) used the footprint weighting tool of Neftel et al. (2008), based on the 2-dimensional analytical footprint model of Kormann and Meixner (2001), to interpret EC fluxes in terms of animal emission rates. While the author's concluded that EC was sufficiently accurate for animal studies, a systematic underestimation of emissions when animals are far from the tower was noted. Felber et al. (2015) proposed that the use of a more sophisticated Lagrangian footprint model could yield better predictability.

Our study reports on the capability of a Lagrangian stochastic (LS) dispersion model to interpret EC fluxes and derive point-source emissions. This methodology was tested in a controlled gas release experiment designed to mimic a grazing environment with some confinement of animals.

2. Methods

2.1. Study site

The experiment took place at the CSIRO Lansdown Research Station in north Queensland (19.658°S 146.835°E, elevation 75 m) from February 5–13, 2014. A 60 × 60 m plot, representing a hypothetical cattle paddock, was established in the middle of an 85 ha open pasture with no animals and no substantial barriers to wind flow within 400 m. Rainfall in January led to a greening up of the pasture consisting mainly of Rhodes grass (*Chloris gayana* Kunth) and Sabi grass (*Urochloa mosambiensis* (Hack.) Dandy) with a canopy height of 0.4 m. The predominant wind direction was easterly, with temperatures ranging from 19 to 35 °C during the study. Dry conditions generally prevailed with two light rain events (<5 mm) recorded in the early morning hours of February 9 and 10.

2.2. Gas release

Methane gas was released from a G2 sized cylinder (12.3 m^3 containing 99.995% pure CH_4) within the artificial paddock at a nominal rate of 5 standard L min^{-1} (3.3 g CH_4 min^{-1}) through a mass flow controller (Alicat Scientific Incorporated, Tucson, AZ, USA). A datalogger (CR1000 Campbell Scientific, Logan UT, USA) recorded the flow rate and powered off the flow controller when a cylinder was empty. A large diameter gas manifold, downstream of the controller, distributed the gas flow to eight release lines terminating at random positions within the paddock to represent confined cattle (Fig. 1). The position of two release points was changed on February 11 to better accommodate a prevailing south easterly wind. Release outlets were secured at 0.8 m height. The distance from the release points to the EC towers ranged from 30 to 60 m for the near tower and 80–108 m for the far tower. Gas release at each outlet was visually verified at the start and end of each release period and it was assumed that the large diameter manifold coupled with equal length (33 m) small diameter release lines would deliver equal flow at the outlets. The mass flow controller delivered gas to each of the eight outlets at a rate of 594 g CH_4 d^{-1} (roughly equivalent to two to four cows per outlet). Approximately 34 m^3 of CH_4 was released over the study period comprising 113 h of gas release. Each of the three G2 size cylinders used in this study was weighed before and after the experiment to confirm performance of the mass flow controller. The average release rate as determined through cylinder weighing was found to be 1.8% higher than that inferred from the flow controller set point. This cylinder derived release rate of 600.8 g source $^{-1}$ d^{-1} was used as the true release rate for subsequent analysis.

2.3. Eddy covariance

Two EC systems were placed downwind of the predominant wind direction; a near tower placed 5 m due west of the artificial paddock, and on a far tower placed 50 m further west (Fig. 1). Each system consisted of an open-path CH_4 analyser (LI-7700, LI-COR Biosciences, Lincoln, NE, USA), an open-path CO_2/H_2O analyser (LI-7500A, LI-COR Biosciences, Lincoln, NE, USA) and a three-axis sonic