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Accuracy of micrometeorological techniques for detecting a change in methane emissions from a herd of cattle

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ABSTRACT

Micrometeorological techniques are effective in measuring methane (CH_4) emission rates at the herd scale, but their suitability as verification tools for emissions mitigation depends on the uncertainty with which they can detect a treatment difference. An experiment was designed to test for a range of techniques whether they could detect a change in weekly mean emission rate from a herd of cattle, in response to a controlled change in feed supply. The cattle were kept in an enclosure and fed pasture baleage, of amounts increasing from one week to the next. Methane emission rates were measured at the herd scale by the following techniques: (1) an external tracer-ratio technique, releasing nitrous oxide (N_2O) from canisters on the animals' necks and measuring line-averaged CH_4 and N_2O mole fractions with Fourier-transform infra-red (FTIR) spectrometers deployed upwind and downwind of the cattle, (2) a mass-budget technique using vertical profiles of wind speed and CH_4 mole fraction, (3) a dispersion model, applied separately to CH_4 mole fraction data from the FTIR spectrometers, the vertical profile, and a laser system measuring along four paths surrounding the enclosure. For reference, enteric CH_4 emissions were also measured at the animal scale on a daily basis, using an enteric tracer-ratio technique (with SF_6 as the tracer). The animal-scale technique showed that mean CH_4 emissions increased less than linearly with increasing feed intake. The herd-scale techniques showed that the emission rates followed a diurnal pattern, with the maximum about 2 h after the feed was offered. The herd-scale techniques could detect the weekly changes in emission levels, except that the two vertical-profile techniques (mass-budget technique and dispersion model applied to profile) failed to resolve the first step change. The weekly emission rates from the external tracer-ratio technique and the dispersion model, applied to data from either the two FTIR paths or the four laser paths, agreed within ±10% with the enteric tracer-ratio technique. By contrast, the two vertical-profile techniques gave 33–68% higher weekly emission rates. It is shown with a sensitivity study that systematically uneven animal distribution within the enclosure could explain some of this discrepancy. Another cause for bias was the data yield of the vertical-profile techniques being higher at day-time than at night-time, thus giving more weight to times of larger emission rates. The techniques using line-averaged mole fractions were less sensitive to the exact locations of emission sources and less prone to data loss from unsuitable wind directions; these advantages outweighed the lack of a method to calibrate CH_4 mole fractions in situ.

1. Introduction

Methane (CH_4) emissions from ruminant livestock constitute about 30% of New Zealand's and 12% of Australia's greenhouse gas emissions. For any future practice or technology to mitigate these emissions, it must be verified at the "herd scale" (or "paddock scale"), under representative farming conditions, that the expected emissions reduction is achieved. In New Zealand (NZ) and Australia, cattle and sheep are farmed outdoors year-round. To measure CH_4 emissions outdoors, micrometeorological techniques are effective at the herd scale (Laubach et al., 2008). These can potentially verify small changes in emission rates, provided that the uncertainty with which such changes are detected is accurately known. Here, we report an experiment measuring the emissions from a herd of

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beef cattle that was designed to specify this uncertainty for a suite of micrometeorological techniques. These include: a mass-budget technique using vertical profiles of wind speed and CH_4 mole fraction ([CH_4]), a backward-Lagrangian stochastic (BLS) dispersion model using the same [CH_4] profiles, the same BLS model using line-averaged [CH_4] data gathered with two types of instruments, and an external tracer-ratio technique, releasing nitrous oxide (N_2O) co-located with the CH_4 emission sources and measuring line-averaged N_2O and CH_4 mole fractions upwind and downwind of the sources. The last technique was classified by Harper et al. (2011) as "non-micrometeorogical", since it does not require any meteorological information to compute emission rates; however, as its feasibility relies on atmospheric transport, we consider it more appropriate to include it among the "micrometeorological" techniques. With these, it also shares the spatial and temporal scales at which it operates. To obtain non-micrometeorological reference values of CH_4 emissions on a daily basis, an enteric tracer-ratio technique was employed, commonly known as the SF_6 tracer-ratio technique. This technique operates at the "animal scale", i.e. individual animals. Details and references for all techniques are given in later sections.

Laubach et al. (2008) already reported an experiment at the same site, with similar animals, and using the same techniques except for the external tracer-ratio technique. In that experiment, the animals were freely grazing in rectangular strips that were changed daily. This represented usual farming practice in NZ but had two disadvantages: the instrumentation had to be moved frequently to be in suitable locations for capturing the emissions, and the feed intake of the animals could not be measured. Knowing the feed intake is desirable because it is a major factor determining CH_4 emissions. The "methane yield" Y_m, defined as the ratio of CH_4 emissions per dry-matter intake (DMI) where both variables are expressed in units of combustion energy, is recommended for inventory purposes (IPCC, 2006; Lassey, 2007). To overcome the two disadvantages in the present experiment, the cattle were held in a grass-free area and were fed known quantities of pasture baleage. The experiment was run for three weeks. Within each week, daily feed rations were held constant, then increased for the following week in order to produce a measurable step change in the herd's CH_4 emissions. The objective was to test for each technique whether it was possible to detect this step change on the basis of weekly averages, which in turn required quantification of the uncertainty of these averages. Factors determining this uncertainty are not only measurement accuracy, but also for each technique its data yield, i.e. the number of runs meeting specific quality criteria, and its sensitivity to the spatial distribution of sources (which is always assumed homogeneous across a prescribed area, except for the external tracer-ratio technique, where no such assumption is needed).

A side issue, inadvertently discovered from consistency checks between the different CH_4 instruments, is a strong temperature dependence of the "GasFinder" CH_4 laser, previously unreported in the micrometeorological literature. This result is presented and empirically corrected for in the main text; the causes are discussed in the Appendix.

2. Experimental design

The experiment was conducted in November 2008. The site (40.336° S, 175.465° E) was located on the Aorangi Research Farm, ca. 20 km inland from the west coast of the North Island of NZ, near the city of Palmerston North. It is ideally suited for micrometeorological techniques and tracer dispersion studies because the surrounding terrain is flat for several km in all directions and there is a predominant wind direction, from W (which includes frequent afternoon sea breezes when synoptic winds are weak). The cattle were managed in two groups, of 30 and 31 animals, respectively, with identical treatments as described in Section 2.2.

2.1. Site preparation and setup geometry

A paddock area of about 200 m × 200 m had been sprayed with herbicide prior to the experiment, so that the ground was initially bare; by the end, a thin cover of herbage had grown back. In the NW quarter of this area, a rectangle of 80 m × 55 m was fenced to contain the cattle herd. A 7 m tall mast to collect vertical profiles of wind speed and CH_4 mole fraction was erected at the midpoint of the E boundary of the fenced area, and with additional fencing of a semicircle with 20 m radius, the cattle were kept at a minimum distance of 20 m from the mast. The nominal source area (rectangle minus semicircle) thus covered 3772 m^2. This area was subdivided into two equal-size enclosures (Fig. 1) to allow handling of the cattle in two separate groups and to limit clustering of the animals at feeding time.

The surrounding terrain consisted mainly of flat paddocks, with no significant flow obstacles to the W, S and E for at least 500 m. To the N, there was a water ditch dropping 2 m below ground level at 50 m distance from the profile mast, and a shelterbelt at ca. 150 m distance. The bare ground extended ca. 100 m from the mast to the W, S and E, and 45 m to the N.

Two types of line-averaging optical sensors (described below) were employed (Fig. 1). One was a CH_4-specific laser system with four paths that were mounted outside the cattle area, with one path along each side of the rectangle, at 5–10 m distance from the fence. Path lengths were between 53 and 57 m, measured with 0.1 m accuracy, and path heights above ground were 1.85, 1.37, 1.38 and 1.07 m (±0.02 m) for the W, S, E and N path, respectively. The other instrument type was a Fourier-transform infra-red (FTIR) spectrometer, measuring mole fractions of multiple gas species simultaneously along an open path. Two identical FTIRs were set up parallel to the W and E sides of the rectangle, at about 5 and 12 m distance to W and E, respectively. The path lengths were 88.9 and 89.5 m and the heights above ground were 1.39 (±0.05) m.

Wind direction, atmospheric stability and velocity statistics (required as inputs for the dispersion model) were measured with a sonic anemometer (81,000 V, RM Young, Traverse City, MI, USA), mounted on top of a telescope mast, 3.85 m above ground and 13 m NNW of the profile mast.

2.2. Animals and feed

The experiment involved 61 one-year-old Friesian-Hereford crossbred steers. They were fed perennial ryegrass/white clover baleage that had been prepared on-farm, with an approximate content of white clover of 20% (DM basis). The chemical composition of the feed was determined by near-infrared spectroscopy.

Prior to the start of measurements, the animals were acclimatised to the management conditions over a period of 10 d by gradually increasing the baleage fraction in the diet while decreasing herbage allowance. At the same time, the animals were accustomed to wear the gas collection gear required for the SF_6 tracer-ratio technique. Starting on the 6th day of acclimatisation, baleage constituted 100% of the diet. The cattle were fed at three increasing feeding levels (low, medium and high) over three consecutive periods of one week duration each. The first 3 d of each week were considered as adjustment periods to the new feeding level, and the last 4 d were used to conduct CH_4 emissions measurements with the animal-scale technique. Feeding levels were set with the intention of making 1.0, 1.5, and 2.0 times maintenance energy requirements available to the steers during Weeks 1, 2 and 3, respectively. The maintenance energy requirement was