

# Direct Measurements of Methane Emissions from Grazing and Feedlot Cattle<sup>1</sup>

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**ABSTRACT:** Methane (CH<sub>4</sub>) emissions from animals represent a significant contribution to anthropogenically produced radiatively active trace gases. Global and national CH<sub>4</sub> budgets currently use predictive models based on emission data from laboratory experiments to estimate the magnitude of the animal source. This paper presents a method for measuring CH<sub>4</sub> from animals under undisturbed field conditions and examines the performance of common models used to simulate field conditions. A micrometeorological mass difference technique was developed to measure CH<sub>4</sub> production by cattle in pasture and feedlot conditions. Measurements were made continuously under field conditions, semiautomatically for several days, and the technique was virtually nonintrusive. The method permits a relatively large number of cattle to be sampled. Limitations include light winds (less than approximately 2 m/s), rapid wind direction changes, and high-precision

CH<sub>4</sub> gas concentration measurement. Methane production showed a marked periodicity, with greater emissions during periods of rumination as opposed to grazing. When the cattle were grazed on pasture, they produced .23 kg CH<sub>4</sub>·animal<sup>-1</sup>·d<sup>-1</sup>, which corresponded to the conversion of 7.7 to 8.4% of gross energy into CH<sub>4</sub>. When the same cattle were fed a highly digestible, high-grain diet, they produced .07 kg CH<sub>4</sub>·animal<sup>-1</sup>·d<sup>-1</sup>, corresponding to a conversion of only 1.9 to 2.2% of the feed energy to CH<sub>4</sub>. These measurements clearly document higher CH<sub>4</sub> production (about four times) for cattle receiving low-quality, high-fiber diets than for cattle fed high-grain diets. The mass difference method provides a useful tool for “undisturbed” measurements on the influence of feedstuffs and nutritional management practices on CH<sub>4</sub> production from animals and for developing improved management practice for enhanced environmental quality.

Key Words: Micrometeorology, Feed Conversion Efficiency, Models, Global Greenhouse Gases, Pastures, Feedlots

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## Introduction

Methane (CH<sub>4</sub>) is the most abundant organic gas in the earth's atmosphere, and evidence has shown that CH<sub>4</sub> concentrations have increased globally at a

rate of about .7%, or 12 ppb/yr, during the decade preceding 1994 (IPCC, 1995). Methane affects tropospheric ozone, hydroxyl radicals and carbon monoxide concentrations, and stratospheric chlorine and ozone chemistry, and because of its radiative forcing properties (infrared absorption or greenhouse effect), the earth's energy balance. The CH<sub>4</sub> record from ice cores (Raynaud et al., 1988) indicates that atmospheric CH<sub>4</sub> has been correlated with variation in the earth's temperature record (Jouzel et al., 1987); this makes it imperative that we understand the natural processes that control atmospheric CH<sub>4</sub> and identify terrestrial sources.

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Anthropogenic sources account for about 70% of the total annual production or release of CH<sub>4</sub> (IPCC, 1995). The largest biogenic sources are rice production, accounting for about 11% of all methane sources; enteric fermentation in all animals, 16%; and produc-

Table 1. Grass quantity and consumption

Type	Initial quantity available, kg DM/ha	Percentage of total available	Final quantity available, kg DM/ha	Percentage of total available	Grass disappearance, kg DM/ha	Percentage of total	Percentage of available grass remaining
Yorkshire fog	1,381.5	27.1	279.0	8.7	1102.5	58.5	20.2
Phalaris	594.5	11.7	551.5	17.2	43.0	2.3	92.8
Dead grass	3,120.5	61.2	2,381.5	74.1	739.0	39.2	76.3
SE mean	313.0	6.1	175.6	5.5	116.9	6.2	15.1

tion from wastes, 17% (animals, estimate 5%). Most of the estimates of CH<sub>4</sub> production by ruminants are based on models arising from data of careful measurements with confined animals made in respiration-chamber experiments conducted to assess the energy value of feeds (Johnson and Johnson, 1995). The data of Blaxter and Clapperton (1965), for example, were obtained in this way, and they are the basis of a number of current methodologies for estimating national and global production from ruminants. Given the wide variation in feedstuffs and animals around the world, there is need to assess the applicability of isolated, laboratory-defined relationships.

Respiration chambers are expensive to construct and operate and, of course, are not able to mimic animal grazing under natural conditions. Johnson et al. (1994) and others suggest that because a chamber is an artificial, constrained environment, the extent to which chamber results can be extrapolated to cattle in production environments (range, pasture, feedlots, etc.) with a full range of normal animal activities is open to question. They developed an alternate method for measuring CH<sub>4</sub> emissions in which a sustained-release device containing sulfur hexafluoride (SF<sub>6</sub>) is placed in the rumen and the ratio of CH<sub>4</sub> to SF<sub>6</sub> concentration in the breath of the animal is used in conjunction with the known rate of SF<sub>6</sub> disappearance from the capsule to calculate CH<sub>4</sub> production rate. Another approach has been to graze animals in a portable wind-tunnel. Methane production is calculated from changes in the concentration of CH<sub>4</sub> in the air entering and leaving the tunnel (Lockyer and Jarvis, 1995).

In this study we report the use of a nonintrusive, micrometeorological technique to make direct measurements of CH<sub>4</sub> production by cattle under grazing and feedlot conditions and to test for feed quality on CH<sub>4</sub> production.

## Materials and Methods

*Location and Site.* Field studies were conducted at the CSIRO Experiment Station at Ginninderra, near Canberra, Australia, 35° S, 149° E during January and February 1993. Two separate experiments were conducted to compare CH<sub>4</sub> emissions by the same

group of cattle grazing pasture or fed a grain diet in simulated feedlot conditions. Mostly dry, sunny weather prevailed during both experiments with minimum daytime relative humidities between 20 and 50% and maximum solar radiation intensities near 900 W/m<sup>2</sup>. Maximum air temperatures were between 18 and 31°C and minimum temperatures were between 5 and 13°C.

*Pasture.* The botanical composition of the pasture included Yorkshire fog (*Holcus lantus*) and phalaris (*Phalaris aquatica*) along with dead grass residue of phalaris, soft brome (*Bromus mollis* L.), and a small amount of subterranean clover (*Trifolium subterranean* L.). Herbage was sampled at the beginning and end of each study period by sampling plots in eight (.5 × .5 m) random locations, two in each quarter of the paddock. The herbage was then separated into the major species and plant condition (live/dead), dried, and weighed to determine pasture consumption by the cattle (Table 1). Table 2 gives the amounts of the different species consumed along with their N content and measurements of grass quality and in vitro digestibility (Tilley and Terry, 1963).

*Animals and Feeding Procedure.* Four 19-mo-old, pregnant (approximately 3 mo) Murray Grey × (Charolais × Angus) heifers, with a mean weight of 435.5 kg (SD of 21.1 kg) were used. For both the grazing and feedlot experiments, the cattle were enclosed in a small square field, 22 m on each side. An internal fence kept animals greater than 1 m from the boundary gas collection tubes. The grazing experiment was conducted first. After grazing for 14 d in the pasture site, the animals were introduced into the experimental field plot and allowed to graze at will for 3 d. They were then removed to a holding area where they were fed a finishing diet containing oats and lucerne (Table 2) for 10 d to allow digestive adaptation to the grain diet prior to beginning the feedlot field measurements. In the interval between experiments, sheep were introduced into the test paddock to remove all remaining forage. The cattle were then reintroduced into the measurement paddock, and the finishing diet was fed from feedbunks in the center of the paddock for 4 d. The two studies, thus, simulated grazing and feedlot conditions. In both cases, water was continuously available. Measurements of CH<sub>4</sub> production were made with a nonintrusive,

Table 2. Feedstuffs consumption and quality

Sample type	Dry matter consumed kg DM·d <sup>-1</sup> ·heifer <sup>-1</sup>	Dry matter consumed SD	Percentage of total	Crude protein, %	NDF, %	ADF, %	Total N %	Protein N (insoluble) %	Soluble N %	Ash, %	Dry matter digestibility, %
Pasture											
Yorkshire fog	4.86	4.02	58.27	11.77	53.48	35.07	2.16	1.99	.17	11.44	58.90
Phalaris	.19	3.10	2.28	3.57	60.59	42.57	1.06	1.00	.06	8.64	41.70
Dead grass	3.29	4.60	39.45	6.60	58.80	44.64	1.31	1.08	.23	8.31	34.30
Total grass	8.34										
Feedlot											
Oats	7.28	.21	20.00	11.50	27.85	17.60	2.00	1.66	.34	2.85	75.90
Lucerne	1.82	.05	80.00	14.73	46.34	42.62	2.62	2.41	.21	8.73	55.47
Total feed	9.10										

micrometeorological method during both grazing and feeding periods.

*Flux Measurement Procedure.* The micrometeorological mass difference technique was used in this study. Tests to establish its validity are described in detail in Denmead et al. (1998). Methane budgets were calculated for the field in which the animals were feeding from measurements of windspeeds and atmospheric CH<sub>4</sub> concentrations on the upwind and downwind boundaries.

Figure 1 provides a schematic of the experimental layout and a simplified calculation procedure. Measurements of atmospheric CH<sub>4</sub> concentration were made at four heights on each boundary of the field with 25-mm-diameter sampling tubes at each height extending along the length (24 m) of the boundary. In the pasture experiment, the tubes were mounted at .5, 1, 1.5, and 2.5 m above the ground and in the feedlot experiment at .5, 1, 2, and 3.5 m above the ground. Air was drawn into the sampling tubes equally along their entire length through capillary tubes (.3 mm diameter) inserted at 1-m intervals and pumped through separate heated air lines at 4 L/min to a mobile laboratory where measurements of CH<sub>4</sub> concentration were made with infrared gas analysis (Series 225 Gas Analyser, fitted with a methane detector; the Analytical Development Co. Ltd., Hoddesdon, U.K.) and gas chromatography (gas chromatography results used as verification; Model 5710A Hewlett Packard GC, with a Poropak N column and a flame ionization detector; Hewlett Packard, Sydney, Australia). Before analysis, the samples were passed through a buffering volume of 45 L to damp out fluctuations and then dried and brought to constant temperature and pressure. With measurements of windspeed and wind direction at the same heights, the concentration measurements permitted calculation of the fluxes of CH<sub>4</sub> across each boundary. A complete measuring cycle (run) involving sequential measurements on each of the 16 air lines plus a calibrating gas and a reference gas (N) required 33 min.

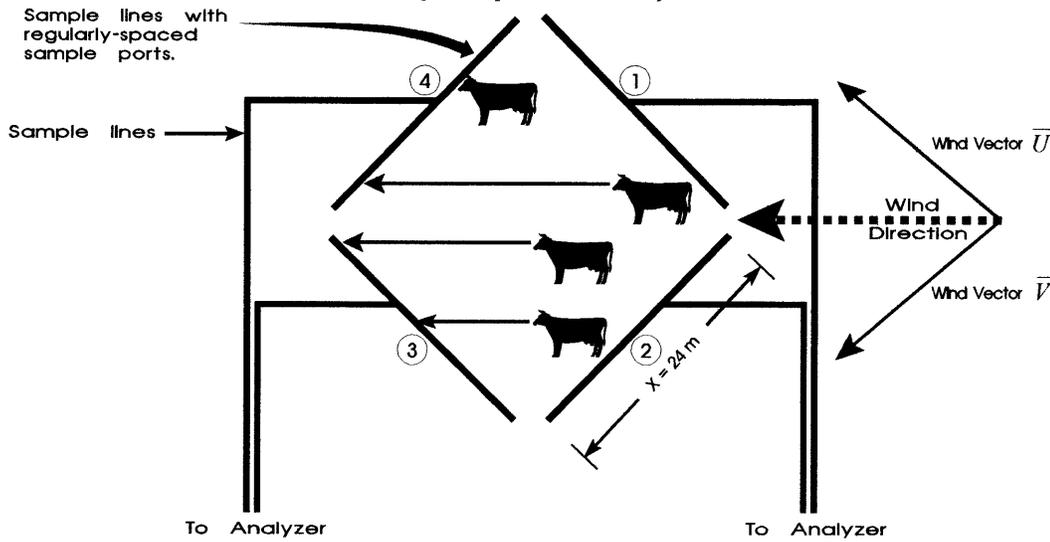
Following Figure 1, we denote height by  $z$  (m), horizontal distance by  $x$  (m), boundary sides by  $n$  ( $n = 1$  to 4), gas density by  $\rho$  (cm<sup>3</sup>/cm<sup>3</sup>), and horizontal wind speed by  $u$ . Note that  $\rho = (m_c/m_z)\rho_z C$ , where  $m_c$  and  $m_z$  are the molecular masses of CH<sub>4</sub> and dry air, respectively,  $\rho_z$  is the density of dry air, a function of temperature, and  $C$  is the mixing ratio of CH<sub>4</sub> with respect to dry air. From measurements of wind direction,  $u$  was resolved into components  $\bar{U}$  normal to Boundaries 2 and 4, and  $\bar{V}$  normal to Boundaries 1 and 3 (Figure 1). The horizontal flux density across boundary  $n$  at height  $z$  is the product of  $\bar{U}_z$  (or  $\bar{V}_z$ ) and  $\rho_{n,z}$ , and the total flux across the boundary is obtained by integrating the horizontal fluxes over the length of the boundary  $X$  and its height  $Z$ . The difference between the fluxes of CH<sub>4</sub> into and out of the field is the rate of production by the cattle,  $F$  (cm<sup>3</sup>/h).

$$F = X \int_0^{z_p} [\bar{U}(\langle \bar{\rho}_4 \rangle - \langle \bar{\rho}_2 \rangle) + \bar{V}(\langle \bar{\rho}_3 \rangle - \langle \bar{\rho}_1 \rangle)] dz \quad [1]$$

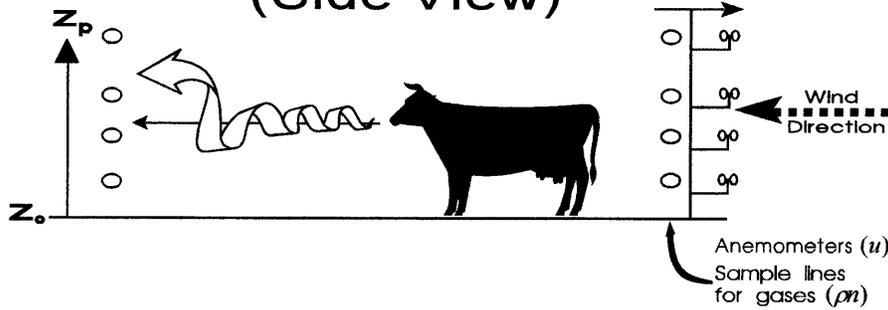
Overbars denote time averages and the angular brackets represent spatial averages. The integral in Eq. [1] was evaluated numerically using the trapezoidal rule. The apparent CH<sub>4</sub> production rate (Denmead et al., 1998) was then reduced by 15% for turbulent diffusion of CH<sub>4</sub> back along the horizontal concentration gradient (Raupach and Legg, 1984; Wilson and Shum, 1992). Methane budgets were thus generated at 33-min intervals.

*Measurement Heights.* Emissions of gas at the ground generally affects gas concentrations up to a height equivalent to approximately 1/10 of the upwind fetch. Accordingly, the maximum measuring height was set at 2.5 m in the pasture experiment. However, because the animals release CH<sub>4</sub> normally at heights vertically above the soil surface, on occasions the 2.5-m concentration on the downwind boundary was notably higher than on the upwind boundary, indicat-

# Micrometeorological Mass Difference (Top View)



# (Side View)



$$F = X \int_0^{z_p} [\bar{U}(\langle \bar{\rho}_4 \rangle - \langle \bar{\rho}_2 \rangle) + \bar{V}(\langle \bar{\rho}_3 \rangle - \langle \bar{\rho}_1 \rangle)] dz = \text{Downwind Flux} - \text{Upwind Flux} = \text{Flux from Cattle}$$

## Diagrammatic and mathematical representation of the mass difference technique.

Figure 1. Measurement and calculation schemes for the mass balance technique.  $U$  = wind vector (cm/s),  $V$  = wind vector (cm/s) [perpendicular to  $U$ ],  $F$  = flux density (cm<sup>3</sup>/h),  $X$  = length of boundary (m),  $\rho$  = density of dry air (cm<sup>3</sup>/cm<sup>3</sup>), and  $z$  = vertical height (m). Overbars denote time averages and angular brackets represent spatial averages.

ing that the measurement heights were too low to capture all the CH<sub>4</sub> released in the plot. The top measuring height was therefore raised to 3.5 m in the subsequent feedlot experiment. This was sufficient to capture all the released CH<sub>4</sub> (Figure 2).

The feedlot experiment provided a means of establishing a coefficient for ascertaining and correcting for

the flux beyond 2.5 m in the pasture experiment. Based on data from four 24-h periods with varying conditions of windspeed and atmospheric stability, the export of CH<sub>4</sub> from the same plot between heights of 2.5 and 3.5 m averaged 28% of the total flux. The pasture flux measurements were therefore increased by this amount.

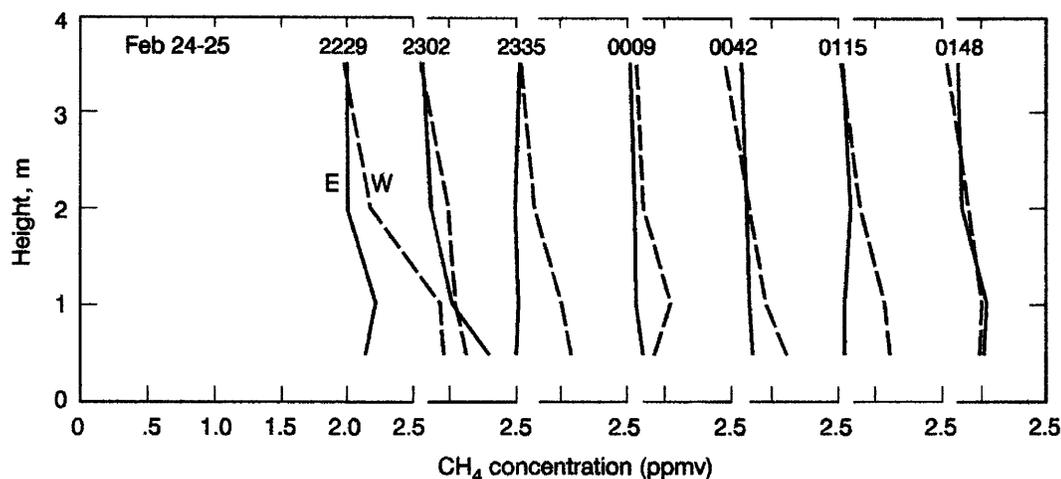


Figure 2. Vertical profiles of  $\text{CH}_4$  concentration on the main upwind and downwind boundaries of the experimental field for successive runs in the feedlot experiment. E, W denote compass points; solid lines for upwind profiles; dashed lines for downwind profiles.

*Tests.* The developed method was tested and validated by constructing  $\text{CH}_4$  budgets for the test field when no cattle were present. Over a period of 40 h, there was a very small apparent net  $\text{CH}_4$  uptake within the test field, which is feasible given that dry soils act as atmospheric sinks for  $\text{CH}_4$  (Conrad, 1989). Our uptake rate, however, was not significantly different from zero. In another trial (Denmead et al., 1998), the rate of uptake of  $\text{CO}_2$  by pasture in the test field was measured by the mass balance technique and compared with that in the surrounding field (also pasture) calculated by a conventional micrometeorological approach. Over 2 d, the mass difference rates agreed with the micrometeorological mean rates within 14%, as explained in Denmead et al. (1998). The relatively small difference was due to the fact that the pasture in the test plot was regenerating after being grazed heavily, whereas the surrounding pasture was ungrazed. Recent tests have involved measurements of recovery from known releases of  $\text{CO}_2$  and  $\text{CH}_4$  (Denmead et al., 1998) and a comparison with the sulfur hexafluoride ( $\text{SF}_6$ ) tracer method developed by Johnson et al. (1994); the results were in excellent agreement (Leuning et al., 1998).

Other recent tests (Denmead et al., 1998) involved point releases of  $\text{CO}_2$  and  $\text{CH}_4$  in the test field, with excellent recovery (> .90%) when releases were made in the center of the test plot, provided windspeeds exceeded 2 m/s. When gas was released only 1 m from the downwind boundary, recovery dropped to 75%. Underestimates of  $\text{CH}_4$  production might, thus, be expected if animals were allowed to reside closer to the fence line than the 1 m in this study.

As noted in the previous paragraph, recoveries of released gases indicated that the method became unreliable when windspeeds were less than 2 m/s or when wind directions changed rapidly. In light winds,

anemometers can stall and the wind direction is often variable. As well, the large buffering volume of the gas sampling necessitated 1 h for new equilibrium concentrations to be established in the buffer volumes after a large change in wind direction. Accordingly, only data from runs with mean wind speeds above 2 m/s and where the standard deviation of wind direction in a run was less than 20° are reported here.

*Feed Analysis.* Collected forage species and grain diet components were subsampled, ground, and composited for laboratory analysis. Forage analyses included NDF and ADF with Komarek (1993a,b) modifications to the Van Soest (1982) techniques using #F57 bags (Ankom) rinsed five times for 5 min in 100°C distilled water, for refluxing and filtration; crude protein via Kjeldahl N; ADF nitrogen; soluble and insoluble nitrogen; and ash. Further, rate and extent of digestion of dry matter and nutrient fractions for each of the dietary feed components was assessed with time series in sacco Dacron satchel digestion experiments (Table 3). For these studies, the recipient ruminally-cannulated steers were fed forage diets for 2 wk prior to initiating the digestion experiments. Replicated 2-g bags of each feedstuffs were placed in the rumen and removed at 0, 6, 12, 18, 24, 48, and 72 h of digestion. All bags were washed under a stream of water upon removal from the rumen and dried (55°C). Sequential NDF and ADF analyses were conducted in which each bag was refluxed in NDF solution, rinsed, dried, weighed, and then refluxed in ADF solution, rinsed, dried, and weighed. The digestible cell soluble (1 - NDF), hemicellulose (NDF - ADF), and cellulose (initial and time series ADF - 72-h ADF) fractions were derived for each feedstuff for 0 to 72 h of digestion (Table 3).

*Models of Methane Production by Cattle.* One of our objectives was to validate the mass difference technique by comparing the field observations of  $\text{CH}_4$



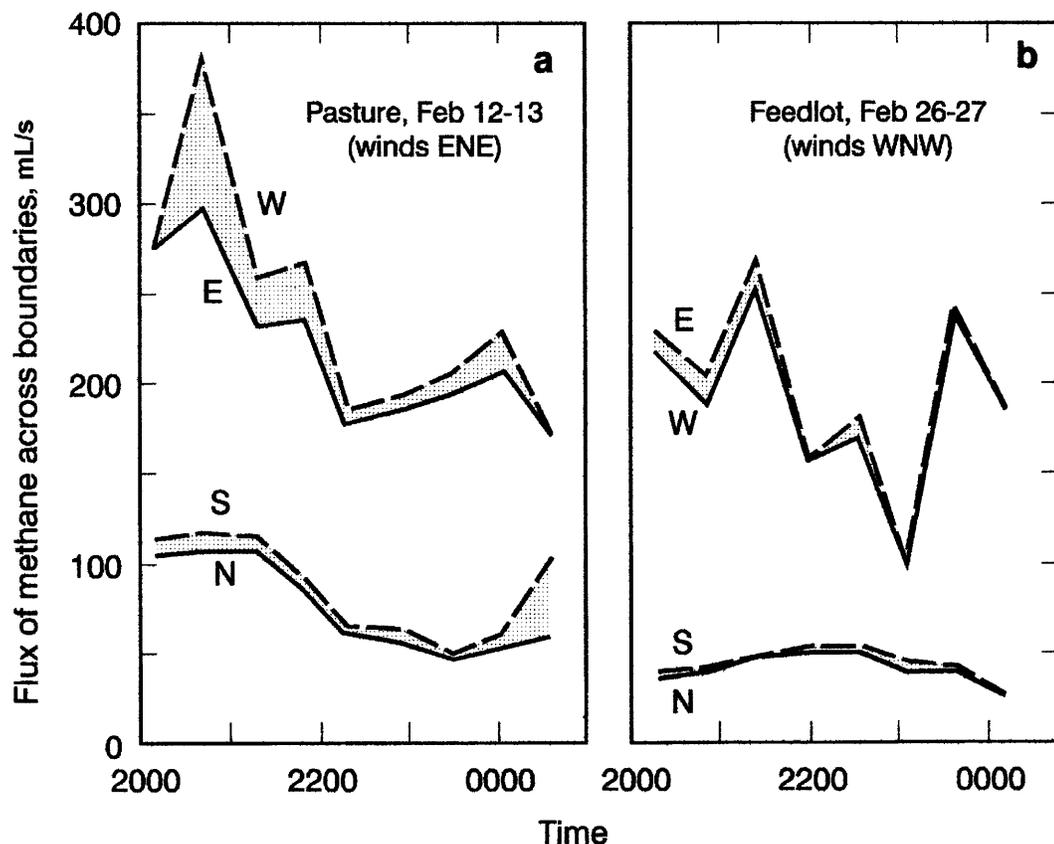


Figure 3. Horizontal fluxes (mL/s) of  $\text{CH}_4$  across upwind and downwind boundaries of the test plot during (a) the pasture experiment and (b) the feedlot experiment. Stippled area represents  $\text{CH}_4$  production by the cattle.

where  $F_{\text{CH}_4}$  is methane emissions as a percentage of digestible energy and CF is crude fiber.

## Results and Discussion

**Flux Measurements.** Mean profiles of atmospheric  $\text{CH}_4$  concentration on the main upwind and downwind boundaries of the test field during the feedlot experiment are illustrated in Figure 2. The background  $\text{CH}_4$  concentrations on the upwind boundaries usually varied little with height and were close to the clean air, baseline value for Australia of 1.7 ppmv by volume (ppmv). Methane production by the cattle enriched atmospheric concentrations on the downwind boundaries up to a height between 2.5 and 3.5 m. Maximum concentration increases were approximately 1 ppmv in the pasture experiment and .5 ppmv in the feedlot experiment, necessitating a resolution better than .1 ppmv. This resolution is close to the limits of the nondispersive infrared (NDIR)  $\text{CH}_4$  analyzer used in these experiments, but it is well within the capabilities of newer NDIR, tuneable diode laser (TDL), and Fourier transform infrared (FTIR) analyzers, whose resolution for  $\text{CH}_4$  is 10 ppb by volume or better.

Figure 3 shows the  $\text{CH}_4$  fluxes across each boundary over periods of approximately 4 h during the pasture and feedlot experiments, respectively. The

fluxes were obtained by integrating the profiles of horizontal flux density over the area of each boundary, following Eq. [1]. The net rate of production in the field was obtained by adding the two incoming fluxes and subtracting the two outgoing fluxes, Eq. [1]. The fluctuating nature of  $\text{CH}_4$  production, the hatched areas between upwind and downwind fluxes, and the much larger production rates during the pasture experiment are clearly evident.

Figure 4 shows the net rates of  $\text{CH}_4$  fluxes across each boundary over periods of approximately 42 h in each. The data in the figures have been smoothed by applying three-run running means (average of three runs). The periodicity in  $\text{CH}_4$  production displayed in both experiments reflected ruminating and feeding activity. An activity index (0 = no cattle feeding, 4 = all cattle eating) was formed from visual observations of cattle activity. An example of the data is shown in Figure 5 for a period of 4 h when the cattle were grazing pasture. The index was correlated with  $\text{CH}_4$  production, but with a short lag. A similar lag between feeding and maximum  $\text{CH}_4$  production was noted by Johnson et al. (1994). Lockyer and Jarvis (1995) have also detected periodicity in  $\text{CH}_4$  production for sheep.

Data for all variables were analyzed via Statistica Mac (Statsoft, 1997), with repeated measures proce-

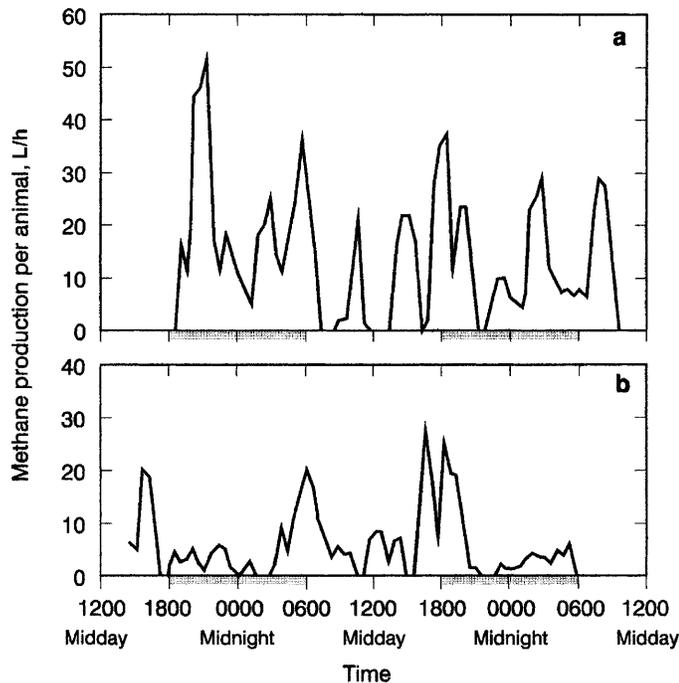


Figure 4. Running means of methane production (L/h) during (a) pasture experiment and (b) feedlot experiment.

dures. There was a large difference ( $P < .1$ ) in  $\text{CH}_4$  production between the grazing and feedlot measurements (Figure 4). During grazing, the mean production rate for 59 33-min runs collected over a period of 60 h was  $.26 \text{ kg}\cdot\text{animal}^{-1}\cdot\text{d}^{-1}$ , and for 53 33-min runs over 93 h for the feedlot study it was  $.066 \text{ kg}\cdot\text{animal}^{-1}\cdot\text{d}^{-1}$ . Methane production for both situations included some contribution from feces, but this production was probably small. Based on the methodology of IPCC (1996),  $\text{CH}_4$  emission was estimated to be  $.019 \text{ kg}\cdot\text{animal}^{-1}\cdot\text{d}^{-1}$  when grazing the pasture and  $.009 \text{ kg}\cdot\text{animal}^{-1}\cdot\text{d}^{-1}$  for the feedlot experiment. The NGGIC (1996) estimates of  $\text{CH}_4$  from feces was zero for both situations.

*Comparison with Models.* The data on feed quality and nutrient availability (Tables 2 and 3) have been used to calculate  $\text{CH}_4$  yields from the various methodologies. Predictions and observations are listed for the grazed pasture in Table 4. Predicted gross energy of  $\text{CH}_4$  as a fraction of feed intake range from these models from 6.5 to 11.9%. The field conversion, after allowing for feces production, was between 7.7 and 8.4%, which is 15 to 25% greater than predicted by the Blaxter and Clapperton (1965) model, which uses intake as the basis for calculation. Field conversion was 30 to 35% less than that predicted by the model of Moe and Tyrrell (1979), which is based on digested carbohydrate fractions; Wilkerson and Casper (1995) found that this model included the most effective variables for  $\text{CH}_4$  production. The best agreement between field observations and a model was for that of

Giger-Reverdin (1992), which is based on crude fiber intake.

Based on the carbohydrate fractions digested and the Moe and Tyrrell models, the extensive digestion of cellulose, especially in the highly digestible Yorkshire Fog grass, contributed much (~40%) of the total predicted  $\text{CH}_4$  production. Approximately 85% of the  $\text{CH}_4$  (15.2 of 17.8 MJ/d) was attributed to the total cellulose fermented, and 60% of this total was from the Yorkshire Fog grass alone (Table 3).

In the feedlot experiment (Table 5), the measured  $\text{CH}_4$  production represented only 1.9 to 2.2% of the gross energy intake and about one-fourth that of the grazing study. This is well within the range of 1.5 to 3% for cattle on high-grain diets predicted from data of Byers (1974) and Blaxter and Wainman (1964) and reported by Branine and Johnson (1990).

Figure 6 shows the comparison of pasture and feedlot  $\text{CH}_4$  emissions as a percentage of gross energy intake along with measurement error ( $\pm 1 \text{ SE}$ ). It also shows the ability of the various models to predict emissions based on our feedstuffs input data. For the pasture conditions, the Moe and Tyrrell (1979) methodology seems inappropriate. The model of Giger-Reverdin et al. (1992) most closely predicted the observed (see squares in Figure 6) emissions, whereas the IPCC (1996) and NGGIC (1996) methodologies underestimated, but not significantly, due to the large but real variability of the measurements evident in Figure 4. This level of agreement for the last three cases is satisfactory.

The feedlot models (see diamonds in Figure 6) of Branine and Johnson (1990) and Blaxter and Wainman (1964) closely predicted our measured emissions (not significantly different). This experiment confirms the suggestion that cattle produce much less  $\text{CH}_4$  in feedlot conditions (when fed high-grain diets). The

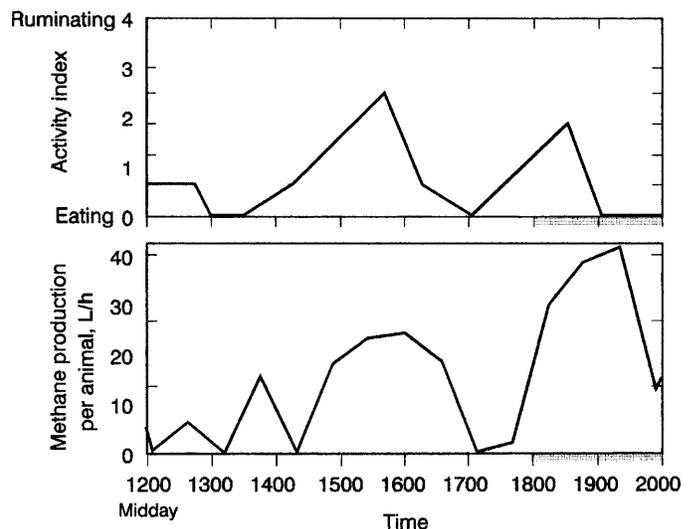


Figure 5. Animal activity index and corresponding methane production (L/h) in pasture experiment. See text for explanation of activity index.

Table 4. Comparison of predicted and observed feed intake and methane production by cattle grazed on pasture (approximately 60% digestibility)

Methodology	Feed intake, MJ/d	Methane conversion rate, %	Methane from animals, kg/d
IPCC (1996)	170	6.5	.198
	153 <sup>a</sup>	6.5	.180
NGGIC (1996)	131	6.7	.159
	153 <sup>a</sup>	6.7	.186
Moe and Tyrell (1979)	—	11.9	.319
Giger-Reverdin et al. (1992)	—	7.9	.217
Field observation	153	7.7 <sup>b</sup>	.213
	153	8.4 <sup>c</sup>	.232

<sup>a</sup>Assuming same intake as observed.

<sup>b</sup>Corrected for fecal production following IPCC (1996).

<sup>c</sup>Corrected for fecal production following NGGIC (1996).

results, however, disagree with the IPCC (1996) and NGGIC (1996), which significantly overestimated CH<sub>4</sub> emissions.

### Conclusions

The micrometeorological mass difference approach described herein has several advantages over other techniques used for measuring CH<sub>4</sub> production by

Table 5. Comparison of predicted and observed feed intake and methane production by cattle on high-grain (+80%) feedlot rations (approximately 80% digestibility)

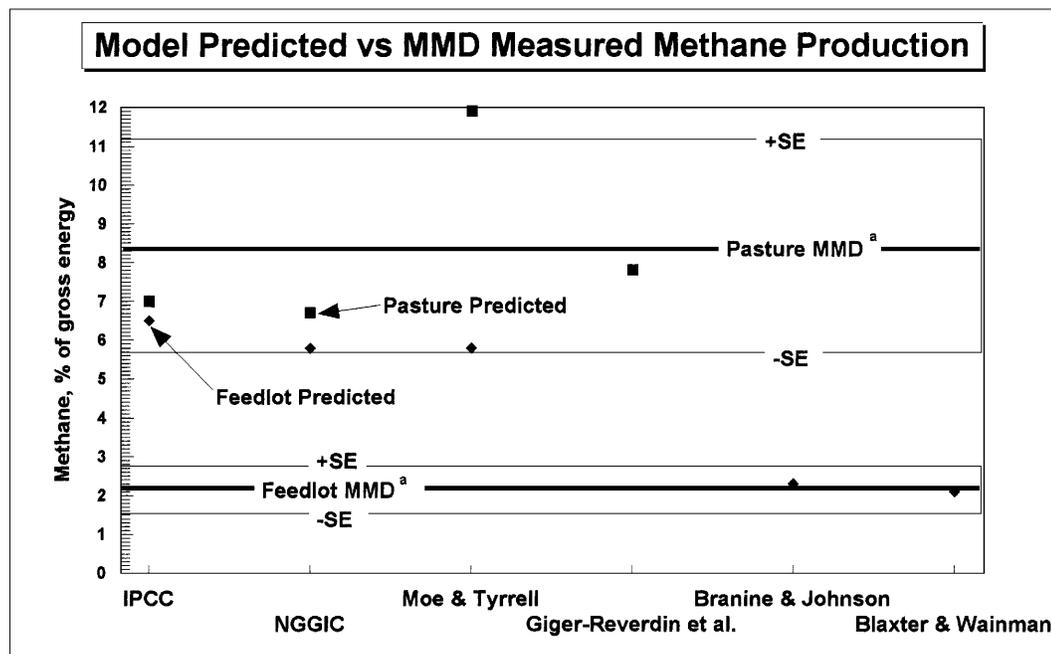
Methodology	Feed intake, MJ/d	Methane conversion rate, %	Methane from animals, kg/d
IPCC (1996)	89	4.0	.064
	168 <sup>a</sup>	4.0	.121
NGGIC (1996)	168 <sup>a</sup>	5.8	.177
Branine and Johnson (1990)	168 <sup>a</sup>	2.5	.075
Blaxter and Wainman (1964)	168 <sup>a</sup>	1.5 to 3	.045–.090
and Byers (1974)			
Field Observation	168	1.9 <sup>b</sup>	.057
	168	2.2 <sup>c</sup>	.066

<sup>a</sup>Assuming same intake as observed.

<sup>b</sup>Corrected for fecal production following IPCC (1996).

<sup>c</sup>Corrected for fecal production following NGGIC (1996).

animals: it is a field technique; it is virtually nonintrusive; it can be operated continuously and semiautomatically over periods of several days; and it permits a relatively large sample size in terms of animal numbers and number of observation intervals. This paper describes application of the technique to measure CH<sub>4</sub> production by cattle in grazing and feedlot situations. The results document a larger influence of feed quality on CH<sub>4</sub> production than is



<sup>a</sup> Assuming zero methane emissions from feces.

Figure 6. Model-predicted vs mass-difference measurement (MMD) of methane production. For the pasture measurements,  $n = 59$  and the  $SE = .076 \text{ kg CH}_4 \cdot \text{animal}^{-1} \cdot \text{d}^{-1}$ . For the feedlot measurements,  $n = 53$  and the  $SE = .018 \text{ kg CH}_4 \cdot \text{animal}^{-1} \cdot \text{d}^{-1}$ .

allowed for with current global and national inventory procedures; with significantly lower CH<sub>4</sub> production for high-grain diets. The short-term variability in the measurements seems to be a real consequence of animal behavior (Figures 4 and 5), but it makes for a high SE, which in turn makes statistical comparisons with the various estimating methodologies difficult. Nonetheless, the mass difference method should provide a useful tool for real-time exploration of the influences of various feedstuffs and nutritional management practices on CH<sub>4</sub> production from ruminants, particularly in grazing situations. It does, however, require at least 2 m/s winds and is limited with rapidly changing wind direction.

Other potential applications include measurement of emissions of CH<sub>4</sub> from animal wastes and landfills, emissions of ammonia and nitrous oxide from dung and urine patches during grazing, nondestructive or noninvasive measurement of emissions from moderately sized measurement plots (plants or animals), gas emissions from small lagoons or waste storage tanks, the measurement of photosynthesis in free-air carbon dioxide enrichment (FACE) systems, and others for which minimal measurement disturbance is required or desired.

### Implications

The use of a mass difference technique provides onsite, unintrusive measurements of methane emissions from cattle without the requirement of unnatural conditions of confinement and hand-feeding. This technology provides evaluation capability for the application of animal biotechnologies delivered through supplements (ionophores and other specific strategies) to reduce methane production and increase animal efficiency in field-scale studies. Current field studies using this measurement technique have shown that grain diets are environmentally friendly.

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