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Direct Measurements of Methane Emissions from Grazing and Feedlot Cattle[1]

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ABSTRACT: Methane (CH_4) emissions from animals represent a significant contribution to anthropogenically produced radiatively active trace gases. Global and national CH_4 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_4 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_4 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_4 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 $CH_4 \cdot animal^{-1} \cdot d^{-1}$, which corresponded to the conversion of 7.7 to 8.4% of gross energy into CH_4. When the same cattle were fed a highly digestible, high-grain diet, they produced .07 kg $CH_4 \cdot animal^{-1} \cdot d^{-1}$, corresponding to a conversion of only 1.9 to 2.2% of the feed energy to CH_4. These measurements clearly document higher CH_4 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_4 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_4) is the most abundant organic gas in the earth's atmosphere, and evidence has shown that CH_4 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_4 record from ice cores (Raynaud et al., 1988) indicates that atmospheric CH_4 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_4 and identify terrestrial sources.

Anthropogenic sources account for about 70% of the total annual production or release of CH_4 (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-

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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_4 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_4 emissions in which a sustained-release device containing sulfur hexafloride (SF_6) is placed in the rumen and the ratio of CH_4 to SF_6 concentration in the breath of the animal is used in conjunction with the known rate of SF_6 disappearance from the capsule to calculate CH_4 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_4 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_4 production by cattle under grazing and feedlot conditions and to test for feed quality on CH_4 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_4 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^2. 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 aquatic*) 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_4 production were made with a nonintrusive,

Table 2. Feedstuffs consumption and quality

Sample type	Dry matter consumed kg DM·d⁻¹·heifer⁻¹	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_4 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_4 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_4 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_4 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 ρ (cm^3/cm^3), 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_4 and dry air, respectively, ρ_z is the density of dry air, a function of temperature, and C is the mixing ratio of CH_4 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_4 into and out of the field is the rate of production by the cattle, F (cm^3/h).

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

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_4 production rate (Denmead et al., 1998) was then reduced by 15% for turbulent diffusion of CH_4 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_4 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-

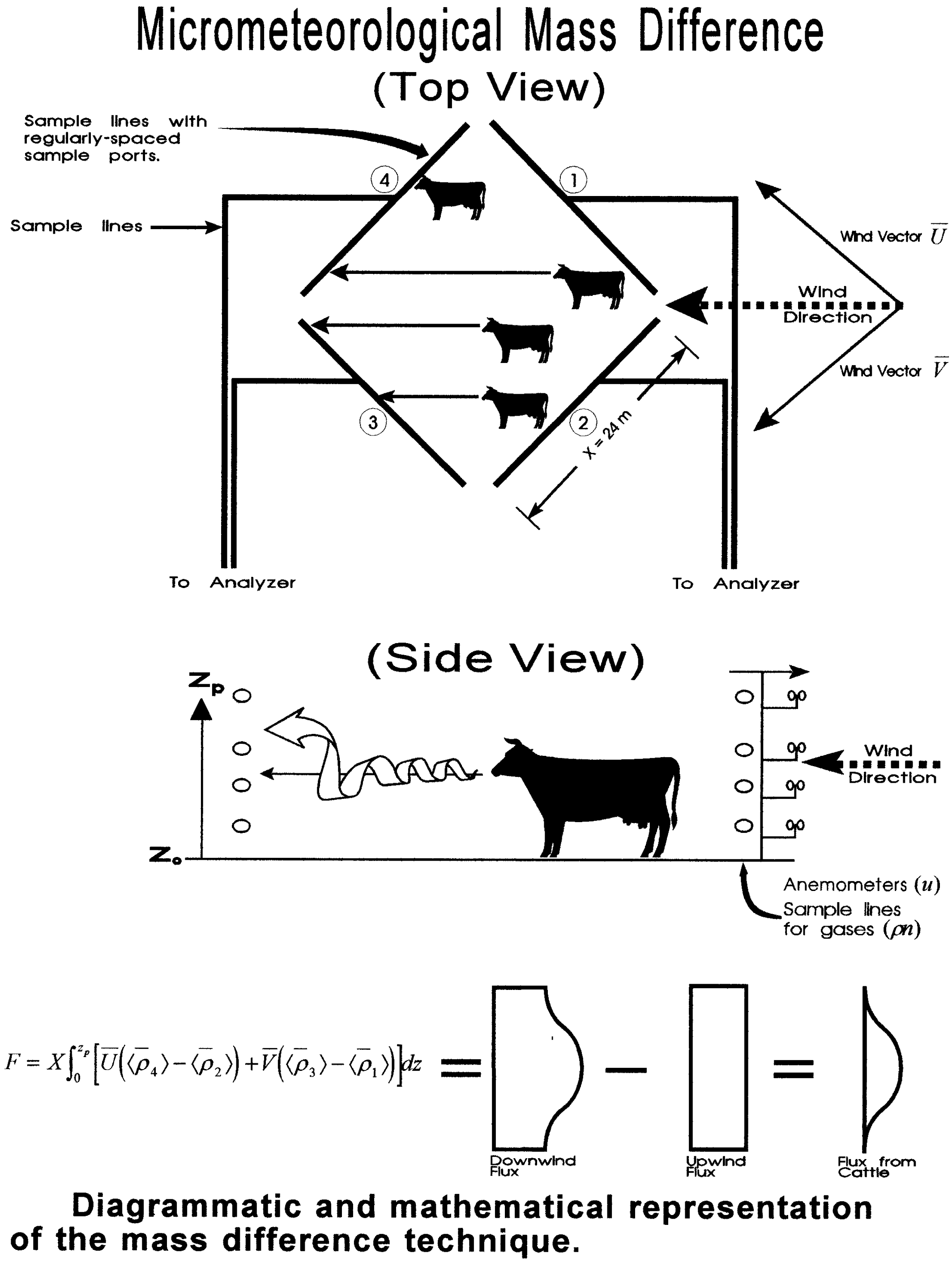

Figure 1. Measurement and calculation schemes for the mass balance technique. U = wind vector (cm/s), V = wind vector (cm/s) [perpendicular to U], F = flux density (cm^3/h), X = length of boundary (m), ρ = density of dry air (cm^3/cm^3), and z = vertical height (m). Overbars denote time averages and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

ing that the measurement heights were too low to capture all the CH_4 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_4 (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_4, 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.

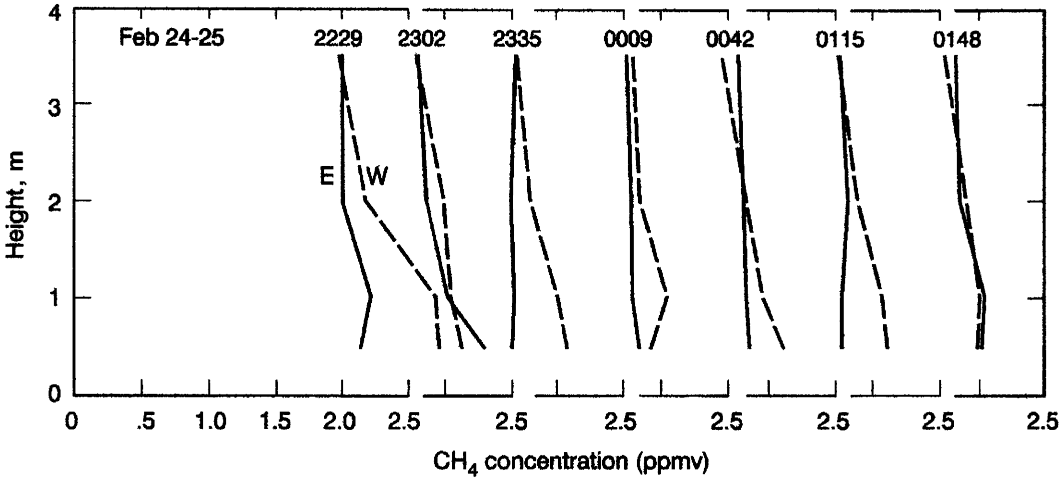

Figure 2. Vertical profiles of CH_4 concentration on the main upwind and downwind boudaries of the experimental field for successive runs in the feedlot experiment. E, W denote compass points; solid lines for upwind profiles; dashed lines for downwind profiles.

Tests. The developed method was tested and validated by constructing 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 CH_4 uptake within the test field, which is feasible given that dry soils act as atmospheric sinks for 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 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 CO_2 and CH_4 (Denmead et al., 1998) and a comparison with the sulfur hexaflouride (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 CO_2 and 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 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 CH_4

Table 3. Methane yield predicted from forage carbohydrate fractions digested

Diet forage fraction	Digestion (kg) of daily forage dry matter and carbohydrate fractions for diet forage components[a]						
	Time, h	DM	NDF	ADF	Soluble residue	Hemicellulose	Cellulose
Yorkshire fog	48	3.42	1.97	1.38	1.01	.59	1.38
	72	3.60	2.05	1.45	1.09	.60	1.45
Phalaris	48	.08	.04	.03	.04	.01	.03
	72	.09	.05	.03	.04	.02	.03
Dead grass	48	1.35	.97	.77	.28	.20	.77
	72	1.57	1.09	.84	.36	.25	.84

		Intercept	Soluble residue	Hemicellulose	Cellulose	Total	% of GE	kg/d	L/d
		Mcal/d[b]							
Methane	48 h digestion base	.439	.3636	.4109	3.033	4.28	11.66	.32	488
Methane	72 h digestion base	.439	.4068	.4443	3.228	4.52	12.31	.34	515

[a]Based on in situ Dacron satchel rate and extent of digestion studies.
[b]Based on forage carbohydrate fractions digested from a model of Moe and Tyrrell (1979).

production with the predictions of various models based on feed intake and feed quality. The models include those of Blaxter and Clapperton (1965), Moe and Tyrrell (1979), nonlinear models of data of Blaxter and Wainman (1964), and Byers (1974), Branine and Johnson (1990), and Giger-Reverdin et al. (1992). The first two models underpin most global and national inventories of CH_4 production by ruminants: for example, Crutzen et al. (1986), IPCC (1996), and the Australian National Greenhouse Gas Inventory (NGGIC, 1996). The main features of these models are summarized below.

Blaxter and Clapperton (1965). Based on statistical analysis of more than 2,500 determinations of CH_4 production by cattle and sheep in respiration calorimetry laboratory feeding experiments, the predicted CH_4 conversion rates Y(MJ CH_4/100 MJ energy intake, %) is given by

$$Y = 1.30 + .112 \times D + L(2.37 - .050 \times D) \quad [2]$$

where D is digestibility of feed (%) and L (dimensionless) is the ratio of gross energy intake to maintenance energy needs. Interestingly, predicted Y in Eq. [2] is in the range of 5 to 7% for most feeds, whereas the actual data ranged from 2 to 11%. Thus, extreme caution should be used because this model does not simulate the real range of feed differences. Based on Blaxter and Clapperton (1965), the Tier 2 methodology of IPCC (1996) uses a "rule of thumb" methane conversion rate of 6 ± 0.5% for developed countries. The NGGIC (1996) uses the actual conversion rate predicted with the Blaxter and Clapperton equation. Both methodologies estimate feed intake from formulae based on live weight and live weight gain.

Moe and Tyrrell (1979). This model uses relationships between dietary carbohydrate and CH_4 production derived from 404 energy balance trials with dairy cows, in which CH_4 production was measured in respiration chambers. Unlike the Blaxter and Clapperton (1965) model, methane yield is calculated directly from three particular carbohydrate fractions. In the units and notation in use here,

$$M_{CH4} = .1049 + .0652 \times S + .1223 \times H + .3328 \times C \quad [3]$$

where M is CH_4 yield (MJ CH_4/d) and S, H, and C are the daily consumption (kg) of digestible soluble residues, digestible hemicellulose, and digestible cellulose. Wilkerson and Casper (1995) found this was the best of many models tested. This model is used by NGGIC (1996) for feedlot cattle.

Blaxter and Wainman (1964) and Byers (1974). These models were developed from respiration calorimetry data for high-grain diets. Methane production from these databases was estimated from nonlinear equations relating Y (CH_4 energy as a percentage of metabolizable energy) to gross energy intake and dietary grain level. For high-grain diets, Y is predicted to lie between 1.5 and 3.0% for high vs lower intakes. This range is consistent with other recent research summarized by Branine and Johnson (1990), who indicated a range of 2 to 3% for cattle fed high-grain diets. The IPCC (1996), however, uses a "rule-of-thumb" CH_4 conversion rate for feedlot cattle receiving high grain diets of 4%.

Giger-Reverdin et al. (1992). These models are similar in principle to the earlier model of Moe and Tyrrell (1979). They are based on dietary fiber (cellulose) as well as NDF, ADF, fat, and protein. The model most appropriate for present purposes includes crude fiber as a percentage of organic matter and estimates CH_4 flux in terms of percentage of digested energy:

$$F_{CH4} = 9.77 + .87 \times CF \quad [4]$$

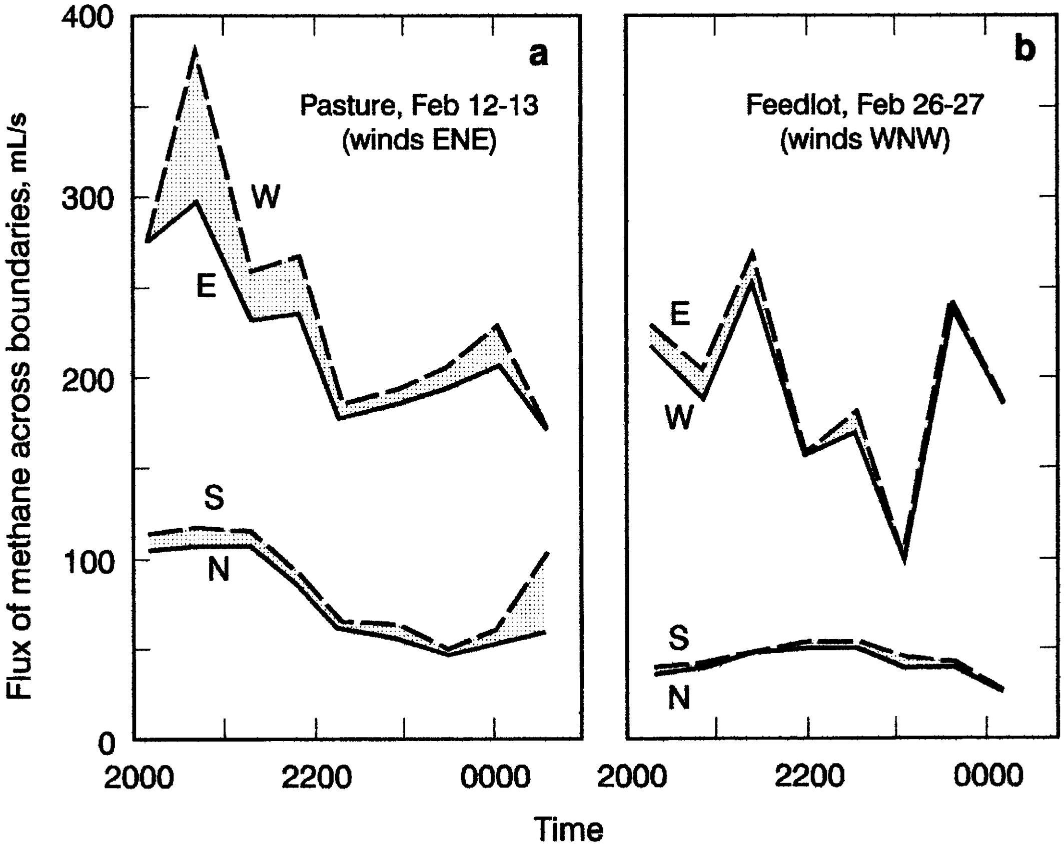

Figure 3. Horizontal fluxes (mL/s) of CH_4 across upwind and downwind boundaries of the test plot during (a) the pasture experiment and (b) the feedlot experiment. Stippled area represents CH_4 production by the cattle.

where F_{CH4} is methane emissions as a percentage of digestible energy and CF is crude fiber.

Results and Discussion

Flux Measurements. Mean profiles of atmospheric 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 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 ppm 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**) 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 CH_4 is 10 ppb by volume or better.

Figure 3 shows the 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 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 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 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 CH_4 production, but with a short lag. A similar lag between feeding and maximum CH_4 production was noted by Johnson et al. (1994). Lockyer and Jarvis (1995) have also detected periodicity in CH_4 production for sheep.

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

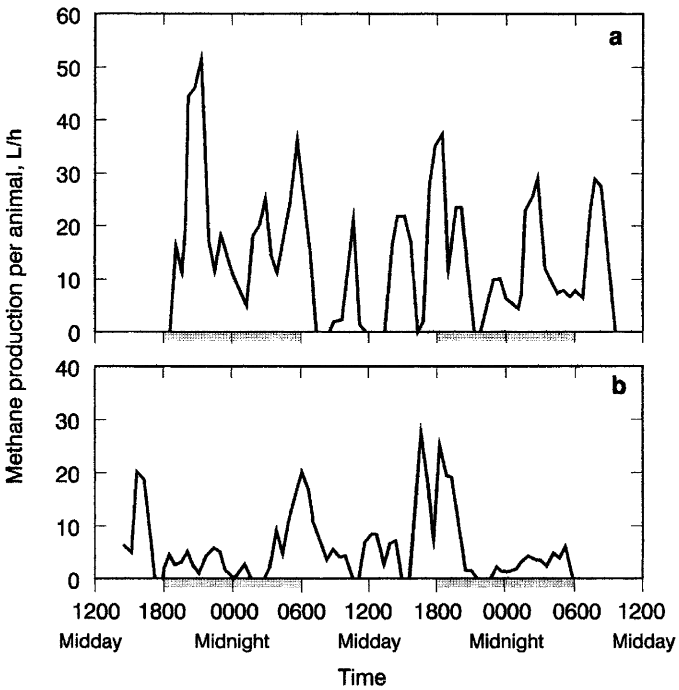

Figure 4. Running means of methane production (L/h) during (a) pasture experiment and (b) feedlot experiment.

dures. There was a large difference ($P < .1$) in 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 kg·animal^{-1}·d^{-1}, and for 53 33-min runs over 93 h for the feedlot study it was .066 kg·animal^{-1}·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), CH_4 emission was estimated to be .019 kg CH_4·animal^{-1}·d^{-1} when grazing the pasture and .009 kg CH_4·animal^{-1}·d^{-1} for the feedlot experiment. The NGGIC (1996) estimates of 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 CH_4 yields from the various methodologies. Predictions and observations are listed for the grazed pasture in Table 4. Predicted gross energy of 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 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 CH_4 production. Approximately 85% of the 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 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 CH_4 emissions as a percentage of gross energy intake along with measurement error (± 1 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 CH_4 in feedlot conditions (when fed high-grain diets). The

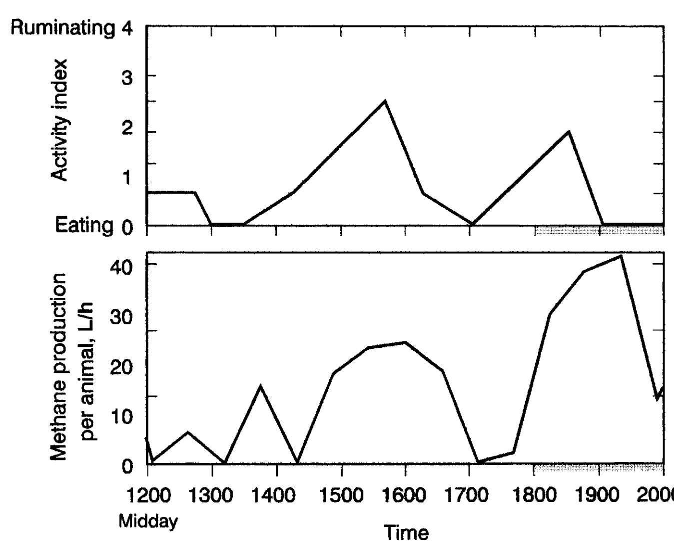

Figure 5. Animal activity index and corresponding methane production (L/h) in pasture experiment. See text for explanation of activity index.

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[a]	6.5	.180
NGGIC (1996)	131	6.7	.159
	153[a]	6.7	.186
Moe and Tyrell (1979)	—	11.9	.319
Giger-Reverdin et al. (1992)	—	7.9	.217
Field observation	153	7.7[b]	.213
	153	8.4[c]	.232

[a]Assuming same intake as observed.
[b]Corrected for fecal production following IPCC (1996).
[c]Corrected for fecal production following NGGIC (1996).

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[a]	4.0	.121
NGGIC (1996)	168[a]	5.8	.177
Branine and Johnson (1990)	168[a]	2.5	.075
Blaxter and Wainman (1964) and Byers (1974)	168[a]	1.5 to 3	.045–.090
Field Observation	168	1.9[b]	.057
	168	2.2[c]	.066

[a]Assuming same intake as observed.
[b]Corrected for fecal production following IPCC (1996).
[c]Corrected for fecal production following NGGIC (1996).

results, however, disagree with the IPCC (1996) and NGGIC (1996), which significantly overestimated CH_4 emissions.

Conclusions

The micrometeorological mass difference approach described herein has several advantages over other techniques used for measuring CH_4 production by 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_4 production by cattle in grazing and feedlot situations. The results document a larger influence of feed quality on CH_4 production than is

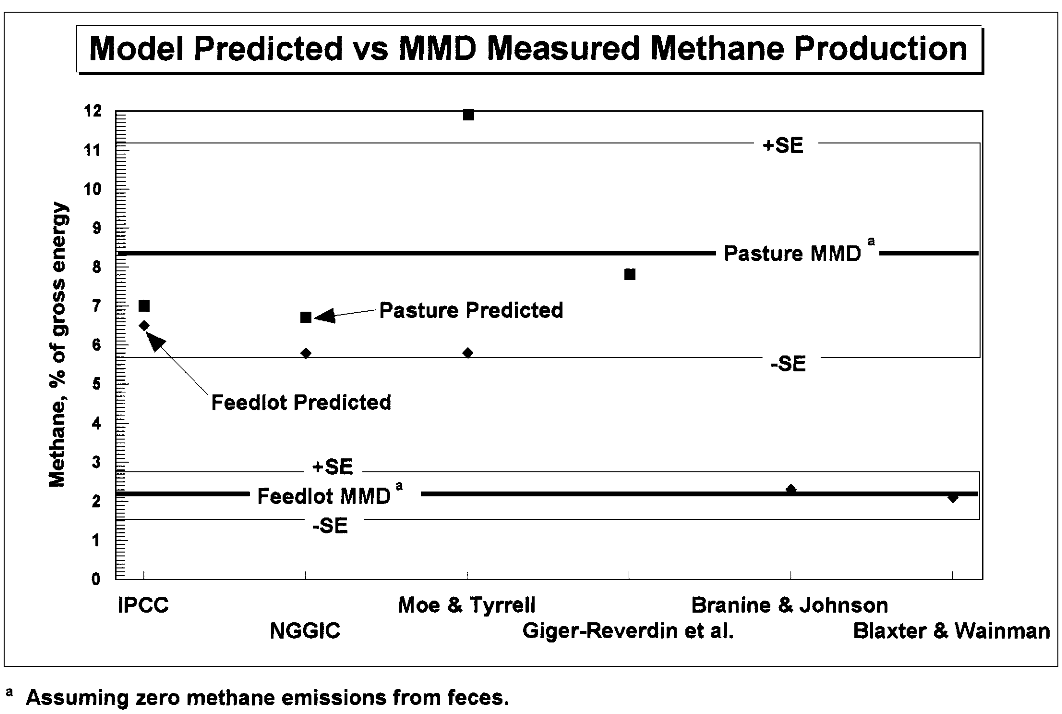

Figure 6. Model-predicted vs mass-difference measurement (MMD) of methane production. For the pasture measurements, n = 59 and the SE = .076 kg $CH_4 \cdot animal^{-1} \cdot d^{-1}$. For the feedlot measurements, n = 53 and the SE = .018 kg $CH_4 \cdot animal^{-1} \cdot d^{-1}$.

allowed for with current global and national inventory procedures; with significantly lower CH_4 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_4 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_4 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 stategies) 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.

Literature Cited

Blaxter, K. L., and J. L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. Br. J. Nutr. 19:511–522.

Blaxter, K. L., and F. W. Wainman. 1964. The utilization of the energy of different rations by sheep and cattle for maintenance and fattening. J. Agric. Sci. 63:113–128.

Branine, M. E., and D. E. Johnson. 1990. Level of intake effects on ruminant methane loss across a wide range of diets. J. Anim. Sci. 68(Suppl. 1):509–510 (Abstr.).

Byers, F. M. 1974. The importance of associative effects of feeds on corn silage and corn grain net energy values. Ph.D. dissertation. Colorado State Univ., Fort Collins.

Conrad, R. 1989. Control of methane production in terrestrial ecosystems. In: M. O. Andreae and D. S. Schimel (Ed.) Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere. pp 39–58. John Wiley & Sons, Chichester, U.K.

Crutzen, P. J., I. Asselman, and W. Seiler. 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. Tellus 38B:271–284.

Denmead, O. T., L. A. Harper, J. R. Freney, D. W. Griffeth, R. Leuning, and R. R. Sharpe. 1998. A mass balance method for non-disturbing measurements of surface-air trace-gas exchange. Atmos. Environ. 32:3679–3788.

Giger-Reverdin, S., M. Vermorel, and D. Sauvant. 1992. Factors of variation of methane energy-loss in ruminants given compound feeds. Ann. Zootech. 41:37–38.

IPCC. 1995. Climate Change 1994. Radiative Forcing of Climate and an Evaluation of the IPCC 1992 Emission Scenarios. J. T. Houghton, L. G. Meira Filho, J. Bruce, H. Lee, B. A. Callandar, E. Haites, N. Harris, and K. Maskell (Ed.). Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K.

IPCC. 1996. Intergovernmental Panel on Climate Change Greenhouse Gas Inventory Reference Manual, Revised 1996 IPCC Guidelines for National Greenhouse Inventories, Vol. 3. J. T. Houghton, L. G. Meira Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D. J. Griggs, and B. A. Callander (Ed.). OECD/OCDE, Paris.

Johnson, K., M. Huyler, H. Westberg, B. Lamb, and P. Zimmerman. 1994. Measurement of methane emissions from ruminant livestock using a SF_6 tracer technique. Environ. Sci. Technol. 28:359.

Johnson, K. A., and D. E. Johnson. 1995. Methane emissions from cattle. J. Anim. Sci. 73:2483–2492.

Jouzel, J., C. Lorius, J. R. Petit, C. Genthon, N. I. Barkov, V. M. Kotlyhakkov, and V. M. Petrov. 1987. Vostok ice core: A continuous isotope temperature record over the last climatic cycle (160,000 years). Nature (Lond.) 329:403–407.

Komarek, A. R. 1993a. A filter bag procedure for improved efficiency of fiber analysis. J. Dairy Sci. 76:250.

Komarek, A. R. 1993b. Improved efficiency of ADF analysis using a filter bag procedure. J. Anim. Sci. 71(Suppl. 1):284 (Abstr.).

Leuning, R., S. K. Baker, I. M. Jamie, C. H. Hsu, L. Klein, O. T. Denmead, and D.W.T. Griffith. 1998. Methane emission from free-ranging sheep: A comparison of two measurement methods. Atmos. Environ. (In press).

Lockyer, D. R., and S. C. Jarvis. 1995. The measurement of methane losses from grazing animals. Environ. Pollut. 90:383–390.

Moe, P. W., and J. F. Tyrrell. 1979. Methane production in dairy cows. J. Dairy Sci. 62:1583–1586.

NGGIC. 1996. Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks, Agriculture, Workbook for Livestock, Workbook 6.1, Revision 1, 1996. National Greenhouse Inventory Committee, Department of the Environment, Sport and Territories, Canberra.

Raupach, M. R., and B. J. Legg. 1984. The uses and limitations of flux-gradient relationships in micrometeorology. Agric. Water Manage. 8:119–131.

Raynaud, D., J. Chappelaz, J. M. Barnola, Y. S. Korotkevich, and C. Lorius. 1988. Climatic and CH_4 cycle implication of glacial-interglacial CH_4 change in the Vostok ice core. Nature (Lond.) 333:655–657.

Statsoft. 1997. Statistica™ For The Macintosh. Statsoft, Tulsa, OK.

Tilley, J.M.A., and R. A. Terry. 1963. A two-stage technique for the *in vitro* digestion of forage crops. J. Br. Grassl. Soc. 18:104–111.

Van Soest, P. J. 1982. Nutritional Ecology of the Ruminant. O & B Books, Corvallis, OR.

Wilkerson, V. A., and D. P. Casper. 1995. Nutrition, feeding, and calves. The prediction of methane production of Holstein cows by several equations. J. Dairy Sci. 78:2402–2414.

Wilson, J. D., and W.K.N. Shum. 1992. A re-examination of the integrated horizontal flux method for estimating volatilization from circular plots. Agric. For. Meteorol. 57:281–295.