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Taihoro Nukurangi

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NIWA specialises in meeting information needs for the sustainable development of water and atmospheric resources. It was established on 1 July 1992.

Introduction

A programme of measuring methane emissions directly from grazing ruminant animals was commenced in FY 1994/95 as a collaboration between two New Zealand Crown Research Institutes, NIWA and AgResearch. Each institute had its own longer-term objectives: NIWA, to provide a scientific basis for assessing New Zealand's anthropogenic emissions of methane (CH_4), a potent greenhouse; and AgResearch, to provide a basis for investigating both the improved nutritional performance of New Zealand ruminants and a reduction in microbial methane production. The goal of the present trials was to gain experience prior to embarking on a more extensive programme aimed towards those objectives.

New Zealand (NZ) has an unusually high level of methane emissions per capita from human activities, of which ruminant methane production is the dominant component (Lassey et al., 1992). Such production represents a loss of nutritional energy to the animal which is potentially avoidable if rumen microbial activity can be effectively modified (Leng, 1992). The twin goals of better quantifying the ruminant methane source, and better understanding nutritional performance, are advanced by new developments in directly measuring methane emitted at the mouth from individual grazing ruminants.

As part of the NIWA programme, three of the authors (PRZ, HHW and KAJ) came to NZ to transfer the technology their team had developed; two of these were funded by NIWA. Field trials conducted by the combined NIWA-AgResearch-USA team are the subject of this report.

Method

The basic technique is described by Johnson et al. [1994]. A lightweight collection system is mounted on each animal, and collects an integrated sample of the 'air' from the vicinity of the nostrils and mouth while the animal is grazing. The 'air' comprises an unknown mixture of respired breath (from the lungs), eructed gases (from the rumen), and ambient air. Throughout this report, the term 'exhaled air' is used to describe the sampled mixture. A knowledge of the actual mixture and of the details of the collection plumbing, is avoided by novel use of an inert tracer (sulphur hexafluoride, SF_6): an SF_6 source of known strength is placed within the animal's rumen. The production rate of CH_4 in the rumen, Q_{CH4}, is then related to the SF_6 source strength, Q_{SF6}, by:

$$Q_{CH4} = Q_{SF6} \times [CH_4] / [SF_6]$$

where square braces denote gas concentrations in the exhaled air in excess of ambient levels.

This method is dubbed the **ERUCT** technique (Emissions from **R**uminants **U**sing a **C**alibrated **T**racer).

The collection system:

The collection system comprises:

- a halter mounted on the animal with suitable plumbing attached; and
- easily removable and interchangeable lightweight cannisters.

The cow halter is similar to those commonly used to lead cattle into rings for shows or auctions, and a smaller version was designed for sheep. To the halter is attached a flowlimiting capilliary tube whose length is selected so that a pre-evacuated cannister fills to about 0.5 atmosphere of pressure over the chosen sampling duration. (This choice of pressure ensures a fairly uniform rate of collection). The inlet end terminates in a 15 micron filter and protector attached to a leather nose-patch on the halter; this is designed to sample exhaled air efficiently while at the same time denying entry to the capilliary of water, dust or other solid material into which the animal may thrust its nose. At the outlet end of the capillary, a flexible tube is terminated by a Swagelok Quick-Connect stem. This enables quick and easy connection to the Quick-Connect body on the cannister.

The cannister itself is a light-weight pvc yoke. This design supersedes the stainless steel cannister described by Johnson et al., and was developed by two of us (HHW and KAJ) and colleages at Washington State University. The yokes used in this study were fabricated by NIWA staff from commercial high-pressure-rated pvc tubing. Each was pre-formed from 32mm or 50mm i.d. tubing in the form of two legs joined symmetrically by a 90° elbow and with end caps at the "feet". This right-angled configuration was shaped towards a "U" after heating to a pliable state at about 130°C. A Swagelok needle valve was tapped into the yoke and a Swagelok Quick-Connect body connected to it.

Each yoke was thoroughly leak tested, and its volume determined manometrically — even though the yoke volume is not required for calculating methane production. Properties of the yokes are shown in Table 1. All 22 cow yokes (C1 to C22) are based on 50mm i.d. tube and have volume around 2.5 litre. Of the 21 sheep yokes (S0 to S20), all but 6 were based on 32mm i.d. tube and these had volumes 800 to 900 ml; the other 6 differed only in i.d. (50mm) and had about twice that volume. As noted in Table 1, a selection of yokes were exposed to 11 days of weather, with no detriment to their performance. Note that actual i.d.s exceed the nominal 32 and 50mm by more than 10%, and these were further increased due to stretching when heated.

With the animal conditioned to wearing the halter, the yokes can be mounted and interchanged quickly by means of velcro straps attached to the halter. The yokes are oriented with the valve pointing along the animal's back. With the Quick-Connect firmly connected, turning on the valve commences sampling.

The photographs in Fig. 1 illustrate the yokes in place on the animals.

The inert tracer:

The inert SF_6 is released from a permeation tube placed in the animal's rumen, in advance of the trials. Each tube, fabricated from brass rod of about 12 mm diameter and 3 cm in length, releases SF_6 at a steady rate from an initial charge of about 0.5 g. The SF_6 is released through a permeable teflon (PTFE) membrane retained by a porous frit and Swagelok nut. The permeation rate is determined by regular weighings over several weeks. As permeation is strongly temperature dependent, the tubes are maintained at rumen temperature, 39°C, during this time.

The permeation tubes used in these trials were kindly fabricated and charged with SF_6 by staff of Washington State University (WSU). Table 2 records the properties of the 9 tubes supplied, along with the results of weekly weighings — also by WSU staff — to determine the rate of SF_6 release. Regression fits confirm the uniform loss rate beyond the initial weighing when the tubes may not have equilibrated with their environment.

Typical permeation rates are 1.5 mg/day (1000 ng/min), though two had rates nearly 3 times larger. These two were used for cows, and three others were selected for sheep.

The laboratory analyses:

The field trials were conducted at Palmerston North using animals and pasture managed by AgResearch staff. The gas analyses were conducted by RJM and GWB in NIWA laboratories at Gracefield, Lower Hutt. The logistics of this arrangement required a 48-hour turnaround of yokes, at best.

Analyses were conducted by gas chromatography (GC), using flame ionisation detection (FID) for CH_4, and using electron capture detection (ECD) for SF_6. As air samples are collected at ~0.5 atmosphere pressure, each yoke is first over-pressured with 'zero air' (air free of trace gases such as CH_4, SF_6) to about 1.8 atmosphere, to provide sufficient sample for GC analyses. This 'dilution factor' is measured manometrically. Each analysis is repeated 3 times, or until stable values are obtained against working standards.

The 48-hour yoke turnaround has 2 disadvantages over on-site laboratory analysis:

1. it requires a relatively large number of yokes be fabricated per animal, especially if the chosen sampling frequency is high; and
2. without a pressure gauge in the field, it takes too long to detect any problems in the field, such as leaks in the yokes (samples at excessive pressure) or blocked capilliaries (no sample at all).

The 150 km separation of field trial venue and analytical laboratory is viewed as interim for these trials only. Future field work would deploy on-site GC.

Sampling Strategy

Given our physical resources, primarily constrained by yoke numbers and separation between field venue and laboratory, a sampling regime of thrice per day (two 6-hour, one 12-hour) on each of 2 sheep and 2 cows was chosen. A third sheep with inserted permeation tube was not used. Sampling was from Monday 20 March through to the following Friday. The sheep were Romney-cross wethers, about 3 years old and weighing 58 and 69 kg. The cows were 6-year old dry (ie, not lactating) Fresians weighing about 600 kg.

The capilliary lengths on the halters were selected appropriately as follows:

Sheep: The smaller yokes (based on 32mm i.d. tubing) would be used for 6-hour sampling, and the larger yokes for overnight 12-hour samples. Since the volume ratios were 1:2 a common delivery rate was required, and a capilliary length of 45cm delivers the required 1.2 ml/min (0.43 litre per 6 hr).

Cows: With only one yoke design available, we planned to compare two strategies, one for each cow:

◊ *parallel yokes:* deploy two yokes in parallel overnight with no halter change; appropriate "T" plumbing was designed to facilitate this. The two yokes were strapped together in advance and mounted with an unavoidably forward-facing valve.

◊ *alternate capilliaries:* deploy a different halter for the overnight sample incorporating a capilliary tube with half the flow rate.

A capilliary length of 15cm delivers the required 3.6 ml/min (1.3 litre per 6 hr), and a 30cm length delivers half this rate for the alternate capilliary.

All prepared capilliary lengths were equipped with an identifying tag (a farm "ear tag"). Since the capilliaries were retained with the host halter, the tag served to identify the halter also.

A 5th yoke was also deployed to collect an ambient integrated sample near, and upwind of, the grazing animals. In practice, adjustments due to background CH_4 and SF_6 levels were modest during the week of sustained but light westerly winds. Some compromises were therefore made to minimise yoke deployment: either the sampling duration was extended, or 'grab samples' were taken using a portable pump (NIWA's Thomas pump) to over-pressure stainless steel cannisters (2 atmosphere pressure).

Results

Tables 3–5 summarise the results for the two cows (identified as #223 and #54), the two sheep (#36 and #38), and for ambient air, respectively.

Cows:

Results for cow #54 proved to be somewhat unsatisfactory, with few useful samples being collected. This turned out to be due a blockage in capilliary tube #273 which developed after Day 1 but which went undetected during the trials. This underlines the need to be able to check yoke pressure quickly after collection, rather than await analysis at a remote lab. This animal was also relatively belligerent, which may have contributed to damaged halter tubing, and/or to leaks which developed in 2 previously leak-free yokes (C7 and C9) — though other yokes also developed leaks.

Cow #223 provided a good time series of measurements, marred only by a slightly leaky yoke (C4) which nevertheless appeared to give a satisfactory CH_4 release estimate, and by the inadvertent deployment of a wrong halter for one overnight sample. Methane production rates varied throughout the week, perhaps related to pasture availability. The duration-weighted average methane production rate during the almost 4 days of sampling was 162 g/day (adjusted for ambient levels), extrapolating to annual production of 59 kg CH_4. This is quite consistent with estimates for NZ cattle byLassey et al. (1992) based on physiological energy demand: 80.6 kg/yr (mature dairy cows), 46.1 kg/yr (herd-weighted 'other' dairy cattle), 69.1 kg/yr (breeding beef cows), 51.8 kg/yr (herd-weighted 'other' beef cattle.

Cow #223 had her halter changed for overnight sampling (the 'alternate capilliaries' sampling strategy), while the more belligerent cow #54 carried 'parallel yokes' overnight (denoted 'twin yokes' in Table 3). The experience gained here favoured the former sampling strategy: the forward-facing valve made inevitable with parallel yokes was prone to damage by a 'careless' cow. It is possible that yokes C7 and C9 were damaged by cow #54 in this way. The 'alternate capilliaries' strategy need not require alternate halters; 2 capilliaries on the one halter would suffice, provided the idle capilliary could be suitably protected.

Sheep:

Both sheep provided useful time series of measurements, yet the inferred methane production rates were quite dissimilar. The heavier sheep #38 averaged 16.6 g/day (6.06 kg/yr), while sheep #36 averaged 23.4 g/day (8.54 kg/yr). Both animals displayed considerable production variability during the week, perhaps due to variations in both feed availability and anxiety levels (due to a small flock and the proximity of cows). The average productions compare favourably with estimates for NZ sheep by Lassey et al. (1992) based on physiological energy demand: 11.5 kg/yr (breeding ewes), 6.9 kg/yr (flock-weighted 'other' sheep older than 1 year).

The apparently significant variation in methane production between the 2 sheep is intriguing. A subsequent trial conducted by one of us (GCW) — with lab. analyses by RJM and GWB — involved also the third sheep (#33) with inserted permeation tubes. The 3 sheep in this trial were confined indoors in crates and supplied a succession of 3 dietary feeds over 3 weeks. Again there were significant variations in methane production among the sheep, though #38 was not consistently the lowest. To the extent that there was a consistent pattern between both trials, sheep #38 appeared to react most strongly to a change in environment by reducing feed consumption (and therefore methane production) at those times.

Ambient air samples:

Table 5 shows the results for two overlapping collections of ambient air — also termed background agricultural air (BAA).

Integrated collections earlier in the week deployed a sheep or cow halter mounted on a fence-post near, but not directly downwind of, the grazing animals. Methane concentrations were variable, but not high enough to impact markedly on the calculation of ruminant production rate. Daily 'grab samples' of air, taken from at least 20m further away, showed much better consistency, and suggested lower levels of both CH_4 and SF_6, than the integrated samples. While this suggests that the integrated samples might be unduly influenced by proximate animals, it is not clear which sample set is the more representative of the air available for inhalation by the grazing animals. We used the daily grab samples as representative of the actual BAA used to adjust the inhaled air samples.

Conclusions

The trials encountered few problems, and so the goal was achieved. From the points of view of both NIWA and AgResearch, immeasurable benefit was obtained from the experience and participation those involved in developing the ERUCT technique (PRZ, HHW, KAJ).

The main strategic recommendations for future campaigns in NZ are:

1. Avoid the use of parallel yokes; rather, for multiple sampling durations, adopt alternate capilliaries, either on separate halters or on a common halter.
2. Animals should be acclimatised to the sampling conditions, especially to wearing the halters, in advance of the trials.
3. Ensure pasture availability does not vary throughout the trial, and that grazing is not influenced by avoidable external factors such as small flock/herd size or other anxiety factors.
4. Plan to analyse samples soon after collection. This will *(a)* enable sampling problems (such as blocked capilliary) to be detected quickly, *(b)* minimise the effect of an introduced leak in a yoke, and *(c)* greatly reduce the number of yokes needed. It will require that the GC laboratory be located near the trial venue.

5. Preferably fabricate yokes from 50mm i.d. pvc, avoiding 32mm pvc. This is because the former has no deployment disadvantage, while the sample collected by the smaller yoke could prove too small if GC problems necessitated more aliquots be analysed.

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Figure 1. Gas collection systems mounted on animals

Table 1. Properties of yokes used for gas collections.

Ident	Volume (ml)	PVC i.d. (mm)	Comments
C1	2600	50	survived 11 days on roof, Feb/95
C2	2505	50	
C3	2286	50	
C4	2317	50	leak repaired post return, May 95
C5	2823	50	
C6	2668	50	
C7	2750	50	
C8	2512	50	
C9	2565	50	
C10	2395	50	cracks repaired in P.N.
C11	2654	50	
C12	2604	50	
C13	2619	50	
C14	2685	50	
C15	2619	50	
C16	2517	50	
C17	2663	50	
C18	2658	50	
C19	2571	50	
C20	2573	50	
C21	2717	50	cracks repaired in P.N.
C22	2591	50	
S0	963	32	WSU yoke
S1	1746	50	
S2	1753	50	
S3	1741	50	
S4	1687	50	
S5	840	32	
S6	885	32	
S7	878	32	
S8	851	32	
S9	894	32	preliminary sample by GW, Mar/95
S10	1076	32	
S11	859	32	
S12	822	32	survived 11 days on roof, Feb/95
S13	883	32	survived 11 days on roof, Feb/95
S14	837	32	leak repaired post return, May 95
S15	872	32	
S16	844	32	
S17	1645	50	
S18	1723	50	
S19	926	32	leak repaired post return, May 95
S20	878	32	

Table 2. Measured SF_6 release rates from permeation tubes.

Ident	Release Rate (ng/min)	Release Rate (mg/day)	S.D. (ng/min)
P97	984.6	1.418	3.5
P202	989.0	1.424	2.2
P203	912.7	1.314	7.4
P205	2780.4	4.004	2.0
P210	1003.3	1.445	5.5
P213	1018.0	1.466	5.3
P216	2338.8	3.368	5.1
P225	965.3	1.390	4.3
P227	1197.6	1.725	3.9

Release rates are determined from regression analyses (right)

Individual release measurements / Regression fit, time beyond 0 minutes

P97 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			31.12773	(empty)		Constant	2.504952	mg	
17-Jan	15:28	0	31.68964	0.00	561.91	Std Err of Y Est	0.142225	mg	2.505
20-Jan	15:24	4316	31.68308	6.56	555.35	R Squared	0.999949		6.754
27-Jan	15:51	14423	31.67277	16.87	545.04	No. of Observations	6		16.705
02-Feb	11:36	22808	31.66458	25.06	536.85	Degrees of Freedom	4		24.961
09-Feb	12:18	32930	31.65471	34.93	526.98				34.927
16-Feb	12:50	43042	31.64475	44.89	517.02	X Coefficient(s)	0.000985	mg/min	44.883
23-Feb	11:20	53032	31.63500	54.64	507.27	Std Err of Coef.	3.5E-06	mg/min	54.719

P202 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.84040	(empty)		Constant	0.467846	mg	
17-Jan	15:29	0	31.42300	0.00	582.60	Std Err of Y Est	0.088694	mg	0.468
20-Jan	15:24	4315	31.41828	4.72	577.88	R Squared	0.999980		4.735
27-Jan	15:52	14423	31.40817	14.83	567.77	No. of Observations	6		14.732
02-Feb	11:37	22808	31.39999	23.01	559.59	Degrees of Freedom	4		23.025
09-Feb	12:19	32930	31.39010	32.90	549.70				33.035
16-Feb	12:51	43042	31.37995	43.05	539.55	X Coefficient(s)	0.000989	mg/min	43.036
23-Feb	11:21	53032	31.37003	52.97	529.63	Std Err of Coef.	2.2E-06	mg/min	52.916

P203 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.90467	(empty)		Constant	3.738293	mg	
17-Jan	15:30	0	31.48832	0.00	583.65	Std Err of Y Est	0.302281	mg	3.738
20-Jan	15:25	4315	31.48080	7.52	576.13	R Squared	0.999734		7.677
27-Jan	15:53	14423	31.47112	17.20	566.45	No. of Observations	6		16.902
02-Feb	11:38	22808	31.46362	24.70	558.95	Degrees of Freedom	4		24.555
09-Feb	12:20	32930	31.45499	33.33	550.32				33.794
16-Feb	12:52	43042	31.44519	43.13	540.52	X Coefficient(s)	0.000913	mg/min	43.023
23-Feb	11:21	53031	31.43611	52.21	531.44	Std Err of Coef.	7.4E-06	mg/min	52.140

P205 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.84872	(empty)		Constant	5.079196	mg	
17-Jan	15:31	0	31.34088	0.00	492.16	Std Err of Y Est	0.083183	mg	5.079
20-Jan	15:26	4315	31.32381	17.07	475.09	R Squared	0.999996		17.077
27-Jan	15:54	14423	31.29579	45.09	447.07	No. of Observations	6		45.181
02-Feb	11:39	22808	31.27232	68.56	423.60	Degrees of Freedom	4		68.494
09-Feb	12:21	32930	31.24418	96.70	395.46				96.637
16-Feb	12:53	43042	31.21607	124.81	367.35	X Coefficient(s)	0.002780	mg/min	124.753
23-Feb	11:23	53032	31.18844	152.44	339.72	Std Err of Coef.	2.0E-06	mg/min	152.529

P210 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.80015	(empty)		Constant	4.863624	mg	
17-Jan	15:32	0	31.39590	0.00	595.75	Std Err of Y Est	0.227191	mg	4.864
20-Jan	15:27	4315	31.38699	8.91	586.84	R Squared	0.999876		9.193
27-Jan	15:56	14424	31.37647	19.43	576.32	No. of Observations	6		19.335
02-Feb	11:40	22808	31.36791	27.99	567.76	Degrees of Freedom	4		27.746
09-Feb	12:22	32930	31.35783	38.07	557.68				37.901
16-Feb	12:53	43041	31.34792	47.98	547.77	X Coefficient(s)	0.001003	mg/min	48.046
23-Feb	11:24	53032	31.33799	57.91	537.84	Std Err of Coef.	5.6E-06	mg/min	58.069

P213 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.50678	(empty)		Constant	4.683705	mg	
17-Jan	15:33	0	31.07708	0.00	570.30	Std Err of Y Est	0.216496	mg	4.684
20-Jan	15:29	4316	31.06830	8.78	561.52	R Squared	0.999890		9.077
27-Jan	15:57	14424	31.05748	19.60	550.70	No. of Observations	6		19.367
02-Feb	11:41	22808	31.04902	28.06	542.24	Degrees of Freedom	4		27.902
09-Feb	12:22	32929	31.03880	38.28	532.02				38.205
16-Feb	12:54	43041	31.02866	48.42	521.88	X Coefficient(s)	0.001018	mg/min	48.499
23-Feb	11:25	53032	31.01850	58.58	511.72	Std Err of Coef.	5.3E-06	mg/min	58.670

P216 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.62335	(empty)		Constant	3.792251	mg	
17-Jan	15:34	0	31.22362	0.00	600.27	Std Err of Y Est	0.206974	mg	3.792
20-Jan	15:30	4316	31.20998	13.64	586.63	R Squared	0.999981		13.887
27-Jan	15:58	14424	31.18600	37.62	562.65	No. of Observations	6		37.527
02-Feb	11:42	22808	31.16631	57.31	542.96	Degrees of Freedom	4		57.136
09-Feb	12:23	32929	31.14270	80.92	519.35				80.807
16-Feb	12:55	43041	31.11907	104.55	495.72	X Coefficient(s)	0.002339	mg/min	104.458
23-Feb	11:26	53032	31.09602	127.60	472.67	Std Err of Coef.	5.1E-06	mg/min	127.825

P225 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.48118	(empty)		Constant	3.581145	mg	
17-Jan	15:35	0	31.08122	0.00	600.04	Std Err of Y Est	0.17258	mg	3.581
20-Jan	15:31	4316	31.07370	7.52	592.52	R Squared	0.999922		7.747
27-Jan	15:59	14424	31.06358	17.64	582.40	No. of Observations	6		17.505
02-Feb	11:43	22808	31.05551	25.71	574.33	Degrees of Freedom	4		25.598
09-Feb	12:24	32929	31.04574	35.48	564.56				35.368
16-Feb	12:56	43041	31.03607	45.15	554.89	X Coefficient(s)	0.000965	mg/min	45.129
23-Feb	11:27	53032	31.02660	54.62	545.42	Std Err of Coef.	4.3E-06	mg/min	54.773

P227 release rate:

Date	Time	Minutes	Mass, g	Loss, mg	Held, mg	Regression Output:			Fit, mg
			30.74448	(empty)		Constant	2.373316	mg	
17-Jan	15:36	0	31.32582	0.00	581.34	Std Err of Y Est	0.15727	mg	2.373
20-Jan	15:32	4316	31.31840	7.42	573.92	R Squared	0.999958		7.542
27-Jan	16:00	14424	31.30591	19.91	561.43	No. of Observations	6		19.647
02-Feb	11:44	22808	31.29625	29.57	551.77	Degrees of Freedom	4		29.688
09-Feb	12:45	32949	31.28402	41.80	539.54				41.833
16-Feb	12:56	43040	31.27190	53.92	527.42	X Coefficient(s)	0.001198	mg/min	53.917
23-Feb	11:27	53031	31.25993	65.89	515.45	Std Err of Coef.	3.9E-06	mg/min	65.883

Table 3. Trial results for 2 cows.

Field Trials: Palmerston North, March 1995

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15-Aug-95

Cow # 223 — Permeation tube # P205 — (=> SF6 release rate = 4.004 mg/day)
(Fresian cow, 6 years old, weighing 620 kg)

Sample #	Capill #	Yoke #	Twin yoke?	Date	Start	Finish	Duration (hr)	Expected Sample Collection: Rate (ml/min)	Expected Sample Collection: Yoke Vol (ml)	Expected Sample Collection: Pressure (atmos)	Actual Pressure (mbar)	Diluted Pressure (mbar)	Dilution Factor	SF6 conc: GC (ppt)	SF6 conc: Sample (ppt)	CH4 conc: GC (ppm)	CH4 conc: Sample (ppm)	CH4 release at mouth: estimate (g/day)	CH4 release at mouth: estimate (L/hr)	CH4 release at mouth: ambient corrctn	CH4 release at mouth: adjust (g/day)	Ambient Backgrounds: Sample ## SF6	Ambient Backgrounds: Sample ## CH4	Ambient Backgrounds: Concs SF6	Ambient Backgrounds: Concs CH4	Comments
1	150	C5		20-Mar	18:28	06:30	12.033	1.8	2823	0.460	418	1880	0.2223	23.5	105.7	9.774	43.96	182	10.7	-0.82%	181	11	11	3.3	1.722	
6	149	C14		21-Mar	06:47	12:22	5.583	3.6	2685	0.449	423	1827	0.2315	29.8	128.7	8.132	35.12	120	7.0	-2.40%	117	11	11	3.3	1.722	
12/1	149	C4		21-Mar	12:25	18:18	5.883	3.6	2317	0.548	892	1818	0.4906	19.0	38.7		0.00	NA	NA	NA	NA	11	11	3.3	1.722	Leaking yoke? Redilution ...
12/2	149	C4		21-Mar	12:25	18:18	5.883	3.6	2317	0.548	522	1576	0.3309		0.0	5.310	16.05	182	10.6	-2.42%	177	11	11	3.3	1.722	... necessary for CH4 meast
16	149	C3		21-Mar	18:38	06:15	11.617	3.6	2286	1.098	796	1839	0.4328	36.9	85.3	9.366	21.64	111	6.5	-4.25%	107	11	11	3.3	1.722	wrong halter: inadvertent
21	149	C1		22-Mar	06:19	12:25	6.100	3.6	2600	0.507	468	1878	0.2492	36.0	144.5	5.523	22.16	67	3.9	-5.67%	63	30	30	3.2	1.720	
26	149	C20		22-Mar	12:50	18:10	5.333	3.6	2573	0.448	425	1783	0.2384	18.9	79.3	9.603	40.29	223	13.0	-0.24%	222	30	30	3.2	1.720	
31	150	C17		22-Mar	18:25	06:05	11.667	1.8	2663	0.473	433	1826	0.2371	16.4	69.2	7.944	33.50	213	12.4	-0.53%	211	30	30	3.2	1.720	
36	149	C18		23-Mar	06:11	12:20	6.150	3.6	2658	0.500	467	1826	0.2558	24.4	95.4	9.538	37.29	172	10.0	-1.43%	169	35	35	3.2	1.752	
43	149	C2		23-Mar	12:27	18:15	5.800	3.6	2505	0.500	465	1797	0.2588	23.1	89.3	8.624	33.33	164	9.6	-1.55%	161	40	40	3.3	1.733	
48	150	C19		23-Mar	18:20	06:15	11.917	1.8	2571	0.501	453	1804	0.2511	20.0	79.6	8.610	34.29	189	11.0	-0.94%	187	40	40	3.3	1.733	
53	149	C21		24-Mar	06:20	12:11	5.850	3.6	2717	0.465	450	1808	0.2489	17.7	71.1	6.383	25.65	158	9.2	-2.41%	154	49	49	3.3	1.772	
Duration-weighted mean:																		165	9.6	-1.57%	162					

Composite sample from samples 12, 16, 21, 26, 31, 36, 43, 48, 53:
delta 13CH4 = -64.4 per mil

"CH4 release at mouth": leftmost estimates are simple ratios with SF6
"ambient adjust" corrects for ambient backgrounds

Field Trials: Palmerston North, March 1995

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15-Aug-95

Cow # 54 — Permeation tube # P216 — (=> SF6 release rate = 3.368 mg/day)
(Fresian cow, 6 years old, weighing 590 kg)

Sample #	Capill #	Yoke #	Twin yoke?	Date	Start	Finish	Duration (hr)	Expected Sample Collection: Rate (ml/min)	Expected Sample Collection: Yoke Vol (ml)	Expected Sample Collection: Pressure (atmos)	Actual Pressure (mbar)	Diluted Pressure (mbar)	Dilution Factor	SF6 conc: GC (ppt)	SF6 conc: Sample (ppt)	CH4 conc: GC (ppm)	CH4 conc: Sample (ppm)	CH4 release at mouth: estimate (g/day)	CH4 release at mouth: estimate (L/hr)	CH4 release at mouth: ambient corrctn	CH4 release at mouth: adjust (g/day)	Ambient Backgrounds: Sample ## SF6	Ambient Backgrounds: Sample ## CH4	Ambient Backgrounds: Concs SF6	Ambient Backgrounds: Concs CH4	Comments
2a	273	C2	1	20-Mar	18:28	06:30	12.033	3.6	2505	0.513	467	1857	0.2515	11.1	44.1	7.424	29.52	247	14.4	1.78%	251	11	11	3.3	1.722	shared yokes
2b	273	C9	-1	20-Mar	18:28	06:30	12.033	3.6	2565	0.513	471	1890	0.2492	11.2	44.9	7.492	30.06	247	14.4	1.74%	251	11	11	3.3	1.722	shared yokes
7	273	C19		21-Mar	06:47	12:22	5.583	3.6	2571	0.469	38		NA		NA		NA	NA	NA	NA	NA	11	11	3.3	1.722	yoke empty
13	273	C6		21-Mar	12:27	18:18	5.850	3.6	2668	0.474	53	1128	0.0470	NA	NA	0.254	5.41	NA	NA	NA	NA	11	11	3.3	1.722	halter tubing damaged
17a	150	C7	1	21-Mar	18:41	06:15	11.567	1.8	2750	0.237	1033	1700	0.6076	7.5	12.3	2.787	4.59	137	8.0	-14.75%	117	11	11	3.3	1.722	shared yokes; wrong halter. Lea
17b	150	C8	-1	21-Mar	18:41	06:15	11.567	1.8	2512	0.237	233	1829	0.1274	5.0	39.2	1.916	15.04	141	8.3	-3.32%	137	11	11	3.3	1.722	shared yokes; wrong halter
22	273	C13		22-Mar	06:22	12:25	6.050	3.6	2619	0.499	26		NA		NA		NA	NA	NA	NA	NA	30	30	3.2	1.720	
27	273	C15		22-Mar	12:50	18:10	5.333	3.6	2619	0.440	20		NA		NA		NA	NA	NA	NA	NA	30	30	3.2	1.720	
32a	273	C22	1	22-Mar	18:25	06:05	11.667	3.6	2591	0.485	31	1102	0.0281	NA	NA	0.068	2.40	NA	NA	NA	NA	30	30	3.2	1.720	shared yokes
32b	273	C12	-1	22-Mar	18:25	06:05	11.667	3.6	2604	0.485	25		NA		NA		NA	NA	NA	NA	NA	30	30	3.2	1.720	shared yokes
37	273	C16		23-Mar	06:11	12:20	6.150	3.6	2517	0.528	18		NA		NA		NA	NA	NA	NA	NA	35	35	3.2	1.752	
44	273	C5		23-Mar	12:28	18:15	5.783	3.6	2823	0.443	20		NA		NA		NA	NA	NA	NA	NA	40	40	3.3	1.733	
47a	273	C9	1	23-Mar	18:20	06:15	11.917	3.6	2565	0.490	1022	1804	0.5665	2.6	4.6	1.575	2.78	224	13.1	35.11%	302	40	40	3.3	1.733	shared yokes; filled with BAA?
47b	273	C14	-1	23-Mar	18:20	06:15	11.917	3.6	2685	0.490	24		NA		NA		NA	NA	NA	NA	NA	40	40	3.3	1.733	shared yokes; QC disconnected
52	273	C10		24-Mar	06:20	12:11	5.850	3.6	2395	0.528	40		NA		NA		NA	NA	NA	NA	NA	49	49	3.3	1.772	

Undetected problemmatic blockage of Capilliary #273 apparent from sample #7 ff

"CH4 release at mouth": leftmost estimates are simple ratios with SF6
"ambient adjust" corrects for ambient backgrounds

Table 4. Trial results for 2 sheep.

Field Trials: Palmerston North, March 1995

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15-Aug-95

Sheep 0036 — Permeation tube # P97 — (=> SF6 release rate = 1.418 mg/day)

(Romney cross wether, 3 years old, weighing 57.8 kg)

Sample #	Capill #	Yoke #	Twin yoke?	Date	Start	Finish	Duration (hr)	Expected Sample Collection: Rate (ml/min)	Expected Sample Collection: Yoke Vol (ml)	Expected Sample Collection: Pressure (atmos)	Actual Pressure (mbar)	Diluted Pressure (mbar)	Dilution Factor	SF6 conc: GC (ppt)	SF6 conc: Sample (ppt)	CH4 conc: GC (ppm)	CH4 conc: Sample (ppm)	CH4 release at mouth: estimate (g/day)	CH4 release at mouth: estimate (L/hr)	CH4 release at mouth: ambient corrctn	CH4 release at mouth: adjust (g/day)	Ambient Backgrounds: Sample ## SF6	Ambient Backgrounds: Sample ## CH4	Ambient Backgrounds: Concs SF6	Ambient Backgrounds: Concs CH4	Comments
4	274	S1		20-Mar	18:28	06:30	12.033	0.9	1746	0.372	392	1888	0.2076	74.8	360.3	10.930	52.64	**22.7**	**1.33**	-2.38%	**22**	11	11	3.3	1.722	
8	274	S14		21-Mar	06:47	12:25	5.633	0.9	837	0.363	676	1897	0.3564	49.4	138.6	7.152	20.07	**22.5**	**1.31**	-6.35%	**21**	11	11	3.3	1.722	halter displaced
14	274	S19		21-Mar	12:31	18:35	6.067	0.9	926	0.354	452	1802	0.2508	121.9	486.0	19.324	77.04	**24.6**	**1.44**	-1.57%	**24**	11	11	3.3	1.722	
18	396	S18		21-Mar	18:36	06:13	11.617	1.2	1723	0.485	449	1794	0.2503	70.2	280.5	12.093	48.32	**26.8**	**1.56**	-2.42%	**26**	11	11	3.3	1.722	
23	396	S5		22-Mar	06:15	12:20	6.083	1.2	840	0.521	476	1815	0.2623	78.9	300.8	12.461	47.51	**24.5**	**1.43**	-2.58%	**24**	30	30	3.2	1.720	
28	396	S13		22-Mar	12:45	18:08	5.383	1.2	883	0.439	425	1825	0.2329	96.1	412.7	10.969	47.10	**17.7**	**1.04**	-2.90%	**17**	30	30	3.2	1.720	
33	396	S2		22-Mar	18:10	06:00	11.833	1.2	1753	0.486	450	1794	0.2508	52.1	207.7	7.746	30.88	**23.1**	**1.35**	-4.09%	**22**	30	30	3.2	1.720	rained o/night
38	396	S0		23-Mar	06:04	12:15	6.183	1.2	963	0.462	223	1828	0.1220	41.5	340.2	3.703	30.35	**13.9**	**0.81**	-4.89%	**13**	35	35	3.2	1.752	filter found blocked
41	394	S14		23-Mar	12:20	18:08	5.800	1.2	837	0.499	1008	3285	0.3068	19.8	64.5	4.668	15.21	**36.6**	**2.14**	-6.60%	**34**	40	40	3.3	1.733	Leaks, 2 dilutions: suspect
45	396	S1		23-Mar	18:16	06:11	11.917	1.2	1746	0.491	464	1825	0.2542	42.9	168.7	8.493	33.40	**30.8**	**1.80**	-3.29%	**30**	40	40	3.3	1.733	
50	396	S9		24-Mar	06:14	12:10	5.933	1.2	894	0.478	451	1841	0.2450	146.7	598.8	16.131	65.85	**17.1**	**1.00**	-2.16%	**17**	49	49	3.3	1.772	
Duration-weighted mean:																		**24.2**	**1.42**	-3.48%	**23.4**					

Composite sample from samples 18, 33, 45 (Sheep # 0036), 19, 34, 46 (Sheep #0038):
delta 13CH4 = -65.9 per mil

"CH4 release at mouth": leftmost estimates are simple ratios with SF6
"ambient adjust" corrects for ambient backgrounds

Field Trials: Palmerston North, March 1995

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15-Aug-95

Sheep 0038 — Permeation tube # P225 — (=> SF6 release rate = 1.390 mg/day)

(Romney cross wether, 3 years old, weighing 69.2 kg)

Sample #	Capill #	Yoke #	Twin yoke?	Date	Start	Finish	Duration (hr)	Expected Sample Collection: Rate (ml/min)	Expected Sample Collection: Yoke Vol (ml)	Expected Sample Collection: Pressure (atmos)	Actual Pressure (mbar)	Diluted Pressure (mbar)	Dilution Factor	SF6 conc: GC (ppt)	SF6 conc: Sample (ppt)	CH4 conc: GC (ppm)	CH4 conc: Sample (ppm)	CH4 release at mouth: estimate (g/day)	CH4 release at mouth: estimate (L/hr)	CH4 release at mouth: ambient corrctn	CH4 release at mouth: adjust (g/day)	Ambient Backgrounds: Sample ## SF6	Ambient Backgrounds: Sample ## CH4	Ambient Backgrounds: Concs SF6	Ambient Backgrounds: Concs CH4	Comments
9	394	S10		21-Mar	06:47	12:25	5.633	1.2	1076	0.377	372	1849	0.2012	98.8	491.1	7.000	34.79	**10.8**	**0.63**	-4.31%	**10**	11	11	3.3	1.722	
15	148	S20		21-Mar	12:28	18:35	6.117	1.2	878	0.502	473	1810	0.2613	65.1	249.1	9.956	38.10	**23.3**	**1.36**	-3.24%	**23**	11	11	3.3	1.722	
19	148	S4		21-Mar	18:36	06:13	11.617	1.2	1687	0.496	477	1795	0.2657	45.1	169.7	6.984	26.28	**23.6**	**1.38**	-4.70%	**22**	11	11	3.3	1.722	
24	148	S11		22-Mar	06:15	12:20	6.083	1.2	859	0.510	502	1811	0.2772	65.0	234.5	6.084	21.95	**14.3**	**0.83**	-6.56%	**13**	30	30	3.2	1.720	
29	148	S7		22-Mar	12:45	18:08	5.383	1.2	878	0.441	420	1827	0.2299	43.8	190.5	5.609	24.40	**19.5**	**1.14**	-5.46%	**18**	30	30	3.2	1.720	
34	148	S3		22-Mar	18:10	06:00	11.833	1.2	1741	0.489	453	1836	0.2467	23.0	93.2	3.236	13.12	**21.4**	**1.25**	-10.03%	**19**	30	30	3.2	1.720	rained o/night
39	148	S8		23-Mar	06:04	12:15	6.183	1.2	851	0.523	512	1832	0.2795	27.4	98.0	2.166	7.75	**12.0**	**0.70**	-20.03%	**10**	35	35	3.2	1.752	
42	148	S6		23-Mar	12:20	18:11	5.850	1.2	885	0.476	477	1840	0.2592	42.7	164.7	3.801	14.66	**13.6**	**0.79**	-10.01%	**12**	40	40	3.3	1.733	
46	148	S17		23-Mar	18:12	06:11	11.983	1.2	1645	0.524	485	1881	0.2578	42.7	165.6	5.172	20.06	**18.5**	**1.08**	-6.78%	**17**	40	40	3.3	1.733	
51	148	S10		24-Mar	06:12	12:10	5.967	1.2	1076	0.399	394	1836	0.2146	24.5	114.2	2.124	9.90	**13.2**	**0.77**	-15.47%	**11**	49	49	3.3	1.772	
Duration-weighted mean:																		**18.0**	**1.05**	-7.77%	**16.6**					

Composite sample from samples 18, 33, 45 (Sheep # 0036), 19, 34, 46 (Sheep #0038):
delta 13CH4 = -65.9 per mil

"CH4 release at mouth": leftmost estimates are simple ratios with SF6
"ambient adjust" corrects for ambient backgrounds

Table 5. Results for samples of background agricultural air.

Field Trials: Palmerston North, March 1995

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15-Aug-95

Background Agricultural Air: time integrated via yokes

Sample #	Capill #	Yoke #	Twin yoke?	Date	Start	Finish	Duration (hr)	Expected Sample Collection: Rate (ml/min)	Expected Sample Collection: Yoke Vol (ml)	Expected Sample Collection: Pressure (atmos)	Actual Pressure (mbar)	Diluted Pressure (mbar)	Dilution Factor	SF6 conc: GC (ppt)	SF6 conc: Sample (ppt)	CH4 conc: GC (ppm)	CH4 conc: Sample (ppm)	Comments
5	148	S2		20-Mar	18:34	06:30	11.933	1.2	1753	0.490			NA		NA		NA	sample discarded
10/1	148	S6		21-Mar	06:47	12:05	5.300	1.2	885	0.431	434	1301	0.3336	1.30	3.90		0.000	Redilution of Sample #10 ...
10/2	148	S6		21-Mar	06:47	12:05	5.300	1.2	885	0.431	308	1194	0.2579		0.00	0.456	1.768	... necessary for CH4 meast
15Z	394	S16		21-Mar	12:35	18:45	6.167	1.2	844	0.526	507	1547	0.3277	1.37	4.18	0.801	2.444	
20b	394	S12	1	21-Mar	18:45	06:18	11.550	1.2	822	0.491	483	1611	0.2998	1.18	3.94	0.802	2.675	shared yokes
20a	394	S15	-1	21-Mar	18:45	06:18	11.550	1.2	872	0.491	489	1629	0.3002	1.20	4.00	0.762	2.538	shared yokes
25	150	C11		22-Mar	06:20	18:00	11.667	1.8	2654	0.475	435	1558	0.2792	0.93	3.34	1.020	3.653	day-time integration

Field Trials: Palmerston North, March 1995

C:\METHANE\ANIMAL\TRIALS.WB1 15-Aug-95

Background Agricultural Air: grab samples via DS cans

Sample #	Cannister	Date	Time	Pumped Pressure (psi)	Conc (GC): SF6 (ppt)	Conc (GC): CH4 (ppm)	Wind conditions
11	DS18	21-Mar	12:08	30	3.30	1.722	10-15 knot wind from 280
30	DS10	22-Mar	13:37	30	3.20	1.720	5 knot wind from 270
35	DS5	23-Mar	06:27	30	3.16	1.752	<5 knot wind from 290
40	DS13	23-Mar	12:48	30	3.31	1.733	10-15 knot wind irom 280
49	DS19	24-Mar	06:29	30	3.28	1.772	<5 knot wind from 300