
THE PROCEEDINGS OF THE
NEW ZEALAND SOCIETY
OF
ANIMAL PRODUCTION
VOLUME 62 2002

ISSN 0370-2731/2002 *Proceedings of the New Zealand Society of Animal Production 62:* 206-210

Ruminant methane emission measurements and estimates - from gut to globe

H. CLARK

AgResearch Grasslands, Palmerston North, New Zealand.

ABSTRACT

Methane emissions from ruminants are New Zealand's largest source of greenhouse gas emissions. As a signatory to the United Nations Framework Convention on Climate Change and the Kyoto Protocol, New Zealand is committed to producing an accurate inventory of its methane emissions. Official estimates of methane emissions from ruminants have declined since 1990 but because of a failure to take account of changes in agricultural productivity these figures may be misleading. In comparison to Australia, the United Kingdom and the United States of America the methods used in New Zealand to calculate methane emissions comply less well with guidelines published by the Intergovernmental Panel on Climate Change although new methodologies are under development. Estimated errors in methane inventories are large (20-80%) and although some of these errors can be reduced, large biological variation in the processes being quantified places a limit on this.

Keywords: ruminants; methane; inventory.

INTRODUCTION

Signatories to the United Nations Framework Convention on Climate Change and the Kyoto Protocol are committed to producing regular, detailed and accurate inventories of all sources and sinks of greenhouse gases (GHG). Globally, methane is second only in importance to carbon dioxide as a GHG. Having an accurate method for calculating methane emissions is therefore an essential component of an accurate national GHG inventory. It is especially important for New Zealand which has the majority of its GHGs emitted as methane.

Global estimates of CH_4 emissions from all sources are in the order of 500-600 Tg/year (Ehhalt *et al*., 2001). Of this total 80-115 Tg/year arises from ruminants. New Zealand's methane emissions in 1998 were estimated to total 1.6 Tg/year, less than 0.5% of the world's total (Ministry for the Environment, 2000b). However New Zealand is unusual in that methane emissions are greater than CO_2 emissions and that over 85% of our emissions arise from ruminant livestock.

Although data are available on the quantity of methane emitted there are questions as to its accuracy. This is especially true when it comes to enteric methane emissions where values estimated from microbial processes occurring in the fore and hind gut of individual ruminants are scaled to the national and global scale. Animal scientists have studied methane emissions from the rumen for many years and, as a percentage of the gross energy intake, losses as methane can be as low as 2% and as high as 12%, depending on the diet, level of performance, age and type of ruminant (Johnson & Ward, 1996). Many countries do not have accurate inventories of livestock numbers, let alone accurate data on levels of animal performance and the type of diets consumed.

This paper, will describe how enteric methane emissions are measured in grazing ruminants, outline the *good practice* guidelines prepared by the Intergovernmental Panel on Climate Change (IPCC) for national methane inventory estimates, detail how New Zealand compiles its national methane inventory, compare the New Zealand method with other countries and outline changes being made in the New Zealand inventory methodology to improve its accuracy.

Methods for measuring methane from ruminants

The traditional method for measuring methane emissions from ruminant animals is respiration calorimetry. Many different designs have been used but the basic principle behind all of them is measurement of the change in methane concentration of ambient air brought about by contact with methane released by the animal. Data obtained from experiments using respiration calorimetry form the basis of all the common empirical equations used to predict methane emissions from ruminants (e.g. Blaxter & Clapperton, 1965; Moe & Tyrell, 1979). The disadvantage from a New Zealand perspective is that the data may not be readily applicable to grazing ruminants because of the type of diets fed (concentrates and dried forages) and the behavioural constraints imposed.

The main alternative to respiration calorimetry for measuring methane emissions by individual animals is the use of sulfur hexafluoride gas (SF_6) as an inert tracer. This technique, developed by Johnson *et al*. (1994) in the USA, involves inserting a calibrated source of SF_6 gas into the rumen and sampling air continuously from around the mouth and nose. Methane emissions are then calculated from a knowledge of the SF_6 release rate and the ratio of SF_6 to methane in the sample collected, after adjusting for the natural levels of SF_6 and CH_4 in the atmosphere. The technique was originally developed for cattle but in New Zealand has been successfully extended for use in both grazing sheep and cattle (Lassey *et al*., 1997; Woodward *et al*., 2001). In New Zealand, experiments to measure methane using the SF_6 tracer technique usually last for between three and five days and breath samples are collected for separate 24 hours periods in evacuated plastic yokes fitted around the animal's neck. A full description of the technique can be found in Ulyatt *et al*. (1999).

A second alternative for measuring methane emissions from free grazing ruminants is the use of micrometeorology techniques that measure methane at the paddock scale from groups of animals. Basically these methods work by estimating the flux of methane downwind of paddocks grazed by animals using a combination of direct sampling, measurements of wind speed and temperature and models of gas and heat diffusion in the atmosphere (see Judd *et al.*, 1999 for a detailed description of the method).

Compared to respiration calorimetry the SF_6 tracer technique has not been around for very long and a lack of published data makes it difficult to comprehensively compare results obtained by the two methods. Johnson *et al.* (1994) found in cattle that SF_6 emission values were 93% of those obtained using respiration chambers. Ulyatt *et al.* (1999) quote a figure of 95% for SF_6 derived emission values compared to respiration chamber measurements in sheep. A possible source of the difference between respiration calorimetry and SF_6 measurements is that measurements obtained using respiration calorimetry include methane expelled in the flatus. Murray *et al.* (1976) found with sheep that 98% of the enteric methane produces was expelled in the breath. Comparative estimates for cattle are not available.

The micrometeorological techniques have the advantage of being non-intrusive, less labour intensive and capable of averaging over larger numbers of animals. The disadvantages are that the ability to obtain estimates of methane emissions at any point in time depends crucially on factors such as consistency of wind direction and absence of rainfall. Experiments in New Zealand by Judd *et al.* (1999) indicate that when conditions are favourable estimates of average methane emission per animal obtained using micrometeorological can compare well with those obtained using the SF_6 technique.

An important issue with methane measurements is that no matter how accurate the technique used to measure methane emissions, a large source of the variance is animal to animal variance (e.g. Ulyatt *et al.*, 1999). Thus for inventory purposes, where emissions are being estimated for the 'average' animal, there will always be considerable error attached to the values. For example, in experiments conducted by AgResearch, coefficients of variation (cv) for treatment means have ranged between 10 and 25%. In a hypothetical national inventory, calculated from methane output per head and the total number of animals present, if the population data is measured without error and the cv of the methane output per head is assumed to be 12.5%, the cv of the total inventory is 12.5%. Therefore in a methane inventory totalling 1.5 million tonnes, the 95% confidence limits are approximately 1.13 – 1.87 million tonnes.

International *good practice* guidelines for national estimates enteric methane emissions

The IPCC provides detailed advice and guidelines for the calculation and reporting of anthropogenic greenhouse gas emissions (IPCC, 1996; IPCC, 2000). A key element of the recommended methodologies is the adherence to *good practice* guidelines which support the development of inventories that are 'transparent, documented, consistent over time, complete, comparable, assessed for uncertainties, subject to quality control and quality assurance, and efficient in the use of resources'.

The recommended first step in inventory preparation is the identification of *key source categories*. These are emission categories that have a significant influence on the total inventory of GHG's in terms of the absolute level of emissions and/or the trend in emissions. The aim is for'*key source categories* to account for 95% of total emissions. A further breakdown into sub-source categories is recommended to determine which of these sub-categories have a 'significant' influence on the total for each *key source category*. A sub-category is regarded as being 'significant' if it accounts for 25-30% of the emissions from the *key source category*.

An important aspect of *good practice* guidelines is the concept of *Tier 1* and *Tier 2* methods. Basically, *Tier 2* methods are more detailed than *Tier 1* methods and have a requirement for more comprehensive data. For *key source categories* it is recommended *good practice* to use *Tier 2* methods.

For enteric methane emissions the *Tier 1* method involves using standard methane *emission factors* for each class of livestock (dairy, beef cattle sheep etc) in conjunction with annual estimates of the number of livestock in each class. These standard *emission factors* can be country specific or published IPCC defaults values.

Tier 2 methods for enteric methane estimations involve obtaining information on total numbers for each class of livestock from national sources and developing a so called *enhanced* characterisation of population numbers within each livestock class. For example, in the sheep livestock category, potential sub-categories would be mature ewes, other mature sheep and lambs. A further important recommendation is that livestock population numbers should be adjusted to reflect seasonal birth, death and slaughter patterns. The *Tier 2* method also requires an estimate of the feed intake for the typical animal within each livestock sub-category. Detailed equations and data requirements for the estimation of intake are presented by the *IPCC* but it is recommended *good practice* to use country-specific methods where these are well documented and recognised. For all livestock sub-categories the method adopted to estimate feed intake should take into account factors such as weight, weight change, feeding situation, milk production, calving/ lambing percentage, wool production and feed characteristics. It is also recommended *good practice* to estimate intake on a seasonal basis where seasonal differences in the factors influencing intake occur. To estimate methane emissions from the intake data, the IPCC publish standard values for cattle and sheep (range 4% - 7% of gross energy intake lost as methane energy) although it is recommended *good practice* to develop country specific values.

A crucial point with regard to *good practice* guidelines is that those countries ratifying the Kyoto protocol are obligated to develop inventory methodologies that conform to these guidelines.

New Zealand's inventory methodology

Official estimates of enteric methane emissions in New

Zealand are calculated by multiplying annual estimates of the number of animals in each livestock class (dairy, beef, sheep, deer, goats) by a constant annual *emission factor* per head for each class of livestock (Ministry for the Environment, 2000b). The population data are obtained from Statistics New Zealand annual surveys supplemented by industry information. The methane *emission factors* are derived from the detailed methane inventory for 1990 compiled by Ulyatt *et al*. (1991).

In the Ulyatt *et al*. (1991) study, New Zealand was divided into four climatic regions and grasslands within each region classified as improved, unimproved or tussock. Stock numbers were allocated to these grassland types based on typical farming practice. Animals were classified into breeding and growing stock and models developed to adjust populations on a monthly basis taking into account births, deaths and time of slaughter. Performance levels for different classes of animals were based on those typical of the industry. The energy needed to meet these levels of production were calculated using data obtained under New Zealand conditions. Herbage intakes were then calculated using typical New Zealand values for the energy concentration of ingested herbage. These energy concentration values varied according to climatic zone, grassland type, livestock class and time of year. Methane production from the ingested herbage was estimated using a mathematical model of rumen digestion (Baldwin *et al*., 1987). Specific *emission factors* were calculated by dividing the total methane emissions for each class of livestock by the total number of animals in that class.

Official estimates of New Zealand's enteric methane emissions for 1990-1999 are presented in Table 1. The principal features are the large drop in emissions from sheep, a rise in the emissions from dairy cattle and an overall fall of almost 10% in total emissions between 1990 and 1999.

In terms of IPCC categorisation the approach adopted in New Zealand is *Tier 1*. However, because of the size of methane emissions in New Zealand *good practice* guidelines suggest that methane should be regarded as a *key source category* and a *Tier 2* approach adopted.

The use of a *Tier 1* as opposed to a *Tier 2* is not simply an issue of semantics, it does have important implications for the magnitude of New Zealand's GHG emission estimates. This is principally because the current *Tier 1* method uses fixed *emissions factors* to develop the time series, meaning that the inventory can only reflect changes in livestock numbers over time and not changes in farming practice. This is potentially a serious issue when productivity is changing relatively rapidly. Data from the Meat and Wool Board Economic Service of New Zealand (2000) and the Livestock Improvement Corporation (2000) show that over the 1990 – 1999 period, lambing percentages have increased by 12%, lamb slaughter weights by 12%, sheep slaughter weights by 11%, beef carcase weights by 4.5% and dairy cow milk yields by 20%. If a–*Tier 2* method had been used to compile the inventory time series these increases in animal performance would have increased herbage intakes and hence methane output per head. If the changes in farming practice in the 1990 – 1999 period are factored into the estimates by increasing the *emission factors* values, total methane emissions from New Zealand ruminants show little change between 1990 and 1999 (Clark, 2001).

TABLE 1. Enteric methane emissions (000's tonnes/annum) in New Zealand 1990-2000. Source: Ministry for the Environment.

Year	Total	Dairy	Beef	Sheep	Deer	Goats
1990	1,474	263	312	854	31	15
1991	1,440	266	316	814	34	11
1992	1,417	273	322	781	35	8
1993	1,416	286	332	757	35	6
1994	1,421	302	338	741	36	5
1995	1,420	315	337	727	37	5
1996	1,406	323	325	714	40	4
1997	1,394	330	314	702	44	4
1998	1,389	334	308	697	47	4
1999	1,399	342	309	691	53	3
2000	1,398	342	317	680	56	3

The notion that methane emissions are unlikely to have fallen since 1990 accords with industry statistics. Sheep livestock numbers may have fallen since 1990 and beef numbers remained static but, between 1990 and 1999, total meat production increased from 971,000 tonnes to 1,080,000 tonnes (Meat and Wool Board Economic Service of New Zealand, 2000). Total dairy cow numbers increased by 40% and factory milk production increased from 6868 million litres to 10168 million litres (Livestock Improvement Corporation, 2000) over the same period. Against this background of rising production it would be surprising if enteric methane production had fallen substantially between 1990 and 1999.

International approaches to enteric methane inventories

As a generalisation, developed countries are more likely to adopt a *Tier 1* approach to the estimation of enteric methane emissions because they are usually a minor component of total GHG emissions. This is not always true however and an examination of inventory methodologies used by the UK, USA and Australia reveals that a mix of *Tier 1* and *Tier 2* approaches have been implemented within each country.

Australia

Enteric methane emissions make up approximately 13% of Australia's total CO_2 equivalent GHG emissions and are therefore an important source of GHG's (Australian Greenhouse Office, 2002). The methodology for estimating enteric methane emissions has been developed by an expert committee and extensively peer reviewed by scientists and industry bodies (National Greenhouse Gas Inventory Committee, 1998). It has been designed specifically to be consistent with IPCC guidelines while taking into account special Australian conditions. In contrast to the present New Zealand approach, a *Tier 2* method has been adopted for all the major livestock classes (beef, dairy, sheep, pigs). A *Tier 1* approach is used for minor livestock classes (goats, buffalo, camels, horses, donkeys, deer, alpacas, emus). Calculations are generally on a state basis. The major livestock classes are disaggregated by sex, age, breeding and non-breeding animals. Feed intake estimates for the various categories of livestock are based upon liveweight, level of performance, stage of lactation and type of feed available. The approach adopted to estimate methane production per animal from intake and feed quality data varies according to the class of livestock. For example, in dairy cattle and non-feedlot beef the Blaxter & Clapperton (1965) algorithm is used but in feedlot beef, which are fed diets with a high concentrate component, the Moe & Tyrell (1979) equation, developed in North America from studies on dairy cows fed high concentrate rations, is used.

The approach adopted by Australia conforms far better with IPCC *good practice* guidelines than does the present New Zealand approach. It is a *Tier 2* method tailored specifically to the Australian situation and, in comparison with many other countries, estimates of enteric methane emissions are likely to be very accurate.

USA

In 1999, enteric fermentation from livestock in the USA was responsible for 1.9% of the total CO_2 equivalent greenhouse gas emissions (Environmental Protection Agency, 2002). Because enteric methane is such a small proportion of total GHG emissions a *Tier 1* approach could be justified under the *good practice* guidelines but in fact a mix of *Tier 1* and *Tier 2* methods have been adopted.

A *Tier 1* approach based on national estimates of livestock numbers per annum and standard IPCC emission factors per livestock type is used for all livestock classes other than cattle. A *Tier 2* approach has been adopted for cattle, the major source of enteric methane. In this method cattle populations are categorised as either beef or dairy and then disaggregated under these two main headings. Population data are taken from the US National Agricultural Statistics Service. Categorisation of livestock populations is on a monthly basis and takes into account births, deaths, parturition dates and slaughter patterns. Energy calculations for each class of livestock are carried out on a regional basis using the equations published by the IPCC (IPCC, 2000), regional livestock performance data and diets typical of those found in each region. The method used to estimate methane emissions from energy intake depends upon the cattle sub-category. For dairy cows an updated version of the Baldwin model (Donovan & Baldwin, 1999), used to compile the original New Zealand *emissions factors*, is used.

In common with Australia the methods adopted by the USA conform well to IPCC *good practice* guidelines.

United Kingdom

Enteric methane production in the United Kingdom accounts for 2.9% of total emissions (National Air Quality Information Archive, 2002a). The approach adopted is a mixture of *Tier 1* and *Tier 2* methods and given the relative size of enteric methane emissions appears to confirm well with *good practice* guidelines. Sheep and beef cattle emissions are estimated from annual census data and standard IPCC *emissions factors*. A *Tier 2* approach is used for dairy cows with emissions per head a function of cow size, level of milk production and quality of diet. Methane emissions are assumed to be 6% of gross energy consumption.

How accurate are national emission estimates?

The IPCC in their *good practice* guidelines state that the *emission factors* used in *Tier 1* methods are unlikely to be known more accurately than ± 30%. Livestock populations are also unlikely to be measured without error, indicating that total errors in *Tier 1* methods are likely to be in excess of ± 30%. Many countries publish error estimates but without details of their derivation. New Zealand and the United Kingdom both claim errors of ± 20% but neither give a justification for the figure (Ministry for the Environment, 2000b; National Air Quality Information Archive, 2002b). The USA does not attempt to quantify the error in its enteric methane emissions.

IPCC suggest that errors in *Tier 2* approaches are likely to be ± 20%. Australia, which uses a *Tier 2* approach for almost all of its livestock categories, publishes error ranges rather than exact values (National Greenhouse Gas Inventory Committee, 1998). All livestock categories, with the exception of dairy cattle, are categorised as being estimated with 'medium' levels of confidence (uncertainty range 20-80%). Uncertainty estimates for dairy cattle are thought to be less than 20%.

The four countries examined in this paper are all developed countries with access to accurate data sources. They have also attempted to construct inventories that reflect their own circumstances. The size of the errors in their inventories are therefore likely to be a conservative estimate of the general size of the error in national methane inventories.

An important point regarding error estimates in national methane inventories is that, irrespective of the methods are used to calculate them, there is a limit to how far errors can be reduced. More accurate data on animal numbers, animal performance and diet composition will reduce the errors involved. However, a major component of the error is likely to comprise biological variation in the processes being quantified and this cannot be reduced. For example, the energy needed to meet a given level of animal performance and the amount of methane lost per unit of energy intake vary considerably from animal to animal and this variation will always be reflected in national methane inventory error estimates.

Developments in the New Zealand inventory methodology

The New Zealand government has signalled its intention to ratify the Kyoto protocol and to adhere to *good practice* guidelines needs to develop a *Tier 2* inventory methodology. The Ministry of Agriculture and Forestry has the responsibility for GHG inventory development for agricultural sources, and has already made a start on this for methane and nitrous oxide. The detailed 1990 inventory compiled by Ulyatt *et al*. (1991) was in almost all respects a *Tier 2* methodology and provides an excellent starting point for any new methodology. Areas presently being examined include the energy requirements of grazing ruminants, estimates of diet quality and methane prediction algorithms. An area that needs particular scrutiny is the prediction of methane output per unit of intake. When Ulyatt *et al*. (1991) compiled the 1990 inventory, measurements of enteric methane output by grazing ruminants were not available. A complex ruminant digestion model, the Baldwin model (Baldwin *et al*., 1987), was used to predict methane output per animal from a knowledge of herbage intake and the chemical composition of the diet. Subsequent examinations of results obtained using the Baldwin model show that the model tends to overestimate methane production compared with experimental data by 15%-30% (Benchaar *et al*., 1998; Clark, 2001). This, combined with the failure to include changes in animal productivity in the present methane inventory estimates, means that there is no guarantee that once a *Tier 2* methodology is used to construct a time series the magnitude and direction of emissions will be the same as that currently published in official documents. Although a new *Tier 2* methane methodology for New Zealand may help to reduce errors in emissions estimates, because there is biological variation in the processes being estimated these errors will not disappear. Realistically an error estimate of ±20% may well be as good as it gets.

Irrespective of the methods used to estimate methane emissions, the present forecasts are that they will be above 1990 levels by the first commitment period of the Kyoto Protocol (2008 – 2012). New Zealand will need to take responsibility for these excess emissions and this could mean the possibility of having to purchase emission credits to offset any increases, or offsetting them against carbon sinks. However the major challenge facing scientists is not enumeration but mitigation. We need to move on from arguing about the absolute size of emissions and concentrate on methods to reduce them.

REFERENCES

Australian Greenhouse Office 2002: www.greenhouse.gov.au/inventory/facts

Baldwin, R.L.; Thornley, J.H.M.; Beever, D.E. 1987: Metabolism of the lactating cow. II Digestive elements of a mechanistic model. *Journal of dairy research 54*: 107-131

Benchaar, C.; Rivest, J.; Pomar, C.; Chiquette, J. 1998: Prediction of Methane Production from Dairy Cows Using Existing Mechanistic Models and Regression Equations. *Journal of animal science 76*: 617-627

Blaxter, K.L.; Clapperton, J.L. 1965: Prediction of the amount of methane produced by ruminants. *British journal of nutrition 19*: 511-522

Clark. H. 2001: Ruminant methane emissions: a review of the methodology used for national inventory estimations. A report prepared for the Ministry of Agriculture and Fisheries by AgResearch

Donovan, K.; Baldwin, L. 1999: Results of the AAMOLLY model runs for the Enteric Fermentation Model. University of California, Davis

Ehhalt, D.; Prather, M.; Dentener, F.; Derwent, R.G.; Dlugokencky, E.J.; Holland, E.; Isaksen, I.; Katima, J.; Kirchoff, V.; Matson, P.; Midgley, P.; Wang, M. 2001: Chapter 4. Atmospheric chemistry and greenhouse gases. *In*. Houghton, J.T. & Ding, Y. *ed*. Climate Change: The Scientific Basis. Cambridge, Cambridge University Press

Environmental Protection Agency 2002: Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1999. www.epa.gov/globalwarming/publications/emissions/index.html

IPCC 1996: Revised IPCC Guidelines for National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Inventories Programme. Published for the IPCC by the UK Meteorological Office, Bracknell

IPCC 2000: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Inventories Programme. Published for the IPCC by the Institute for Global Environmental Strategies, Japan

Johnson, D.E.; Ward, G.M. 1996: Estimates of animal methane emissions. *Environmental monitoring and assessment 42*: 133-141

Johnson, K.A.; Huyler, M.T.; Westburg, H.H.; Lamb, B.K.; Zimmerman. P. 1994: Measurement of methane emissions from ruminant livestock using a SF_6 tracer technique. *Environmental science and technology 28*: 359-362.

Judd, M.J.; Kellier, F.M.; Ulyatt, M.J.; Lassey, K.R.; Tate, K.R.; Shelton, I.D.; Harvey, M.J.; Walker, C.F. 1999: Net methane emissions from grazing sheep. *Global change biology 5*: 647-657

Lassey, K.R.; Ulyatt, M.J.; Martin, R.J.; Walker, C.F.; Shelton, I.D. 1997: Methane emissions measured directly from grazing livestock in New Zealand. *Atmospheric environment 31*: 2905-2914

Livestock Improvement Corporation 2000: 1999/2000 Dairy Statistics.

Meat & Wool Economic Service of New Zealand 2000: Annual Review of the New Zealand Sheep and Beef Industry 1999-00

MfE 2000a: New Zealand Greenhouse Gas Inventory 1990-1998: Common Reporting Format 1990-1998. As reported April 2000. Ministry for the Environment, Wellington, New Zealand

MfE 2000b: New Zealand Greenhouse Gas Inventory 1990-1998: As reported April 2000. Ministry for the Environment, Wellington, New Zealand

Ministry for the Environment 2000: New Zealand Greenhouse Gas Inventory 1990-1998: Common Reporting Format 1990-1998. As reported April 2000. Ministry for the Environment, Wellington, New Zealand

Moe, P.W.; Tyrrell, H.F. 1979: Methane production in dairy cows. *Journal of dairy science 62*: 1583-1586

Murray, R.M.; Bryant, A.M.; Leng, R.A. 1976: Rates of production of methane in the rumen and large intestine of sheep. *British journal of nutrition 36*: 1-14

National Air Quality Information Archive 2002a: www.aeat.co.uk/netcen/airqual/reports/ghg

National Air Quality Information Archive 2002b: www.aeat.co.uk/netcen/airqual/naei/annreport/annrep99

National Greenhouse Gas Inventory Committee 1998: Agriculture, Workbook 6.1 with Supplements. Internet publication, www.greenhouse.gov.au/inventory/index.html

Ulyatt M.J.; Betteridge, K.; Costall, D.; Knapp, J.; Baldwin, R.L. 1991: Methane Production by Ruminants. A report prepared for the Ministry of the Environment by DSIR Grasslands, June 1991

Ulyatt, M.J.; Baker, S.K.; McCrabb, G.J.; Lassey, K.R. 1999: Accuracy of SF_6 tracer technology and alternatives for field measurements. *Australian Journal of agricultural research 50*: 1329-1334.

Woodward, S.L.; Waghorn, G.C.; Ulyatt, M.J.; Lassey, K.R. 2001: Early indications that feeding Lotus will reduce methane emissions from ruminants. *Proceedings of the New Zealand Society of Animal Production 61*: 23-26