Methane and Nitrous Oxide Emissions from Grazed Grasslands

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Key points

1. Emissions of methane (CH_4) and nitrous oxide (N_2O) from grasslands make a substantial contribution to total agricultural emissions of these two gases.
2. At present practical mitigation options that relate to grazing ruminants and grazed pastures are limited.
3. Research into agricultural greenhouse gas emissions is of low priority in most developed countries.
4. Direct manipulation of the rumen ecosystem provides the best opportunity for large reductions in CH_4 in the long term.
5. Reducing the amount of nitrogen (N) excreted by grazing animals is a priority in N_2O research, as this source of N_2O constitutes almost 90% of the total global N_2O emissions from grasslands.

Keywords: greenhouse gas, climate change, ruminant, grassland mitigation

Introduction

In its third assessment report, the Inter Governmental Panel on Climate Change (IPCC) stated "The earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities" (IPCC, 2001a). Human activities have increased the atmospheric concentrations of greenhouse gases (GHG) and the key anthropogenic gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20) and tropospheric ozone (O_3)), reaching their highest ever-recorded levels in the 1990's (IPCC 2001a). At the same time there is increasing evidence that the world's climate is getting warmer and that, judged from the 1861-2000 instrumental record, the 1990's were the warmest decade in recent history (IPCC 2001a). Faced with this situation there is now a major international effort to reduce anthropogenic GHG emissions to the atmosphere through such mechanisms as the United Nations Framework Convention on Climate Change (UNFCCC) and, most notably, the Kyoto Protocol. The latter treaty, which at present covers only the developed nations, is a landmark treaty in that those countries ratifying have agreed to legally binding reductions in GHG emissions compared to a 1990 baseline.

The principal agricultural GHGs are CH_4 and N_2O, and it is estimated that agriculturally derived emissions account for >55% and >75% of the world's anthropogenic CH_4 and N_2O emissions respectively (IPCC, 2001b). On a mass basis, global anthropogenic emissions of CH_4 and N_2O are small compared to CO_2 emissions, but because their global warming potentials are greater than CO_2 (CO_2 =1, CH_4 = 23 and N_2O = 296) they play an important role in the radiactive balance of the atmosphere (IPCC, 2001b).

Since agriculture is an important source of GHG there has been considerable focus in the last decade on methods to mitigate CH_4 and N_2O emissions associated with agricultural activity. Ruminant livestock production systems have received particular attention since ruminant animals directly emit CH_4 *via* the breath, and provide the substrate for CH_4 and N_2O

emissions arising from stored and pasture deposited animal excreta. In addition, nitrogenous fertiliser applications, a further source of N_2O emissions, have been a focus of mitigation studies as they are a feature of ruminant livestock production systems in many countries.

In this paper, we will concentrate on the particular problem of mitigating GHG emissions from grazing animals and from extensively grazed pastures. In these situations mitigation options have to be appropriate to systems where, in many cases, animals are handled infrequently, where there may be limited opportunities to manipulate or supplement the diet, where manipulations of the soil are constrained by terrain and accessibility and where synthetic nitrogenous fertiliser inputs are low or non-existent.

Sources of methane and nitrous oxide from grazed livestock

Methane

The principle source of CH_4 from ruminants is enteric methane arising as a by-product of the fermentation of feed in the rumen and, to a lesser extent, the large intestine. The rumen contains a large and diverse population of microorganisms and these break down feed to produce volatile fatty acids (VFA's), CO_2 and CH_4. The VFA's produced in the rumen are absorbed and used as an energy source, but most of the CO_2 and CH_4 are removed from the rumen by eructation. Typically >80% of the CH_4 is produced in the rumen and the rest in the lower digestive tract (Immig, 1996; Murray *et al.,* 1976). In sheep 98% of the CH_4 produced is released via the mouth and 2% via the flatus (Murray *et al.,* 1976). The microorganisms responsible for the production of CH_4 synthesise it from hydrogen, although they do have the ability to use other substrates (Miller, 1995). The removal of hydrogen by methanogens helps maintain a low partial pressure of hydrogen in the rumen without which microbial growth and forage digestion are inhibited (Wolin *et al.,* 1997). As a percentage of the gross energy consumed, 2 - 15% can be lost as CH_4 (Johnson & Ward, 1996), although in temperate forages the range is typically 3.5 – 7.5% (O'Hara *et al.,* 2003).

A secondary source of CH_4 is that arising from voided faecal material. In grazing animals where faecal material is deposited directly onto pastures, only small amounts of CH_4 arise from this source. For example, in New Zealand pastoral agriculture, 99% of CH_4 emissions arise from enteric sources and only 1% from faecal material (New Zealand Climate Change Office, 2004). In this paper only enteric sources of CH_4 will be considered.

Nitrous oxide

Nitrous oxide emissions from agricultural soils arise from nitrification and denitrification processes (Figure 1). Denitrification is the stepwise reduction of soil nitrate (NO_3) (to gaseous nitrogen compounds, with N_2O being one of the intermediate products (Haynes & Sherlock, 1986). It is an anaerobic process that requires a NO_3 substrate, a restricted oxygen supply and suitable pH and temperature conditions (Firestone, 1982; Mosier *et al.,* 1996). Nitrification is an aerobic process, and in most soils is controlled by the availability of ammonium (NH_4) (Schmidt, 1982).

Nitrous oxide
↑
Ammonia →Nitrite→Nitrate→Nitrite→Nitric oxide→Nitrous oxide→Nitrogen
(gas) (gas) (gas)

Figure 1 The production of nitrous oxide by nitrification and denitrification (adapted from O'Hara *et al.,* 2003)

There are two principle sources of nitrogen (N) substrate in grazed pastoral systems; recycled dietary N and applied synthetic fertilisers. Ruminants are relatively poor converters of ingested dietary N into products, and the retention of N in meat, wool or milk ranges from 3 - 25% of the N ingested (Whitehead, 1995). As a result large quantities of N are re-cycled via excreta deposited directly onto pastures by grazing livestock. The relative importance of these two sources of N substrate to nitrous oxide production is likely to vary markedly from country to country. In New Zealand pastoral agriculture, where there is a strong reliance on the biologically fixation of N by forage legumes rather than synthetic fertiliser N, approximately 90% of N_2O emissions arise from excreta N deposited by grazing animals (New Zealand Climate Change Office, 2004). This may well be typical of many developing countries, although not necessarily northern Europe where N fertiliser use is much higher.

How much agricultural methane and nitrous oxide are produced by the world's grasslands?

The IPCC publish estimates of global agricultural emissions of N_2O and CH_4, and data on a country-by-country basis are available from the UNFCCC (IPCC, 2001b; UNFCCC, 2004). In this section we present a 2003 inventory of CH_4 and N_2O emissions that relates solely to the grassland component of ruminant livestock diets.

Methane

Estimated CH_4 emissions from grasslands for the year 2003 are shown in Table 1.

Table 1 Estimates of methane production by ruminant livestock from grassland forage intake (Tg CH_4/yr)

Regions[1]	OECD	O Dev	EE+CIS	CSA	WANA	SSA	ASIA	Total
Dairy cows	2.0	<0.1	2.1	1.8	0.3	0.4	2.3	8.9
Other cattle	6.4	0.4	1.2	11.6	0.2	1.6	5.0	26.3
Buffalo	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	3.2	3.3
Sheep and goats	1.3	0.2	0.4	0.5	0.3	0.5	1.5	4.6
Camelids	<0.1	<0.1	<0.1	<0.1	0.1	0.6	0.1	0.9
Total	9.7	0.6	3.6	14.0	0.9	3.0	12.2	44.0

[1] Regions: OECD, Organisation for Economic Cooperation and Development; O Dev, other developed countries (e.g. South Africa); EE+CIS, Eastern Europe and former URSS countries; CSA, Central and South America; WANA, West Asia and North Africa; SSA, Sub-Saharan Africa.

The methodology adopted to arrive at these estimates is consistent with IPCC good practice guidelines (IPCC, 2000). Feed intake for different classes of livestock was estimated from performance and population data (FAOSTAT, 2003; GLIPHA, 2003) and converted into a CH_4 output using a CH_4 yield factor (% of gross energy (GE) lost as CH_4). The methods adopted were a combination of those of Wheeler *et al.* (1981); Hendy *et al.* (1995) and USEPA, (1995). Briefly, livestock production systems were separated into nine different types, and the world into seven different geographical regions as described by Seré & Steinfeld, (1996). Daily feed intake for each animal class was assumed to be a fixed proportion of liveweight. The proportions used ranged from 1.4 – 3.6% depending on species, type of husbandry system and geographic region (Hendy *et al.,* 1995). To make the CH_4 emissions specific to grasslands, non-grassland derived feed intake was subtracted from total feed intake. The proportions of non-grassland derived feeds (e.g. crop residues, forage crops and concentrates) were taken from Bouwman *et al.,* (2004). The assumed gross energy (GE) content of forages ranged between 18.0 and 18.4 MJ/kg DM (Andrieu *et al.,* 1988). Methane emissions were derived from the forage feed energy intake, assuming that in free ranging animals between 6.5 and 8% of the GE consumed is lost as CH_4 (Johnson & Ward, 1996; McCaughey *et al.,* 1997; Lassey *et al.,* 2002; De Ramus *et al.,* 2003), and that concentrate supplementation below 40% of the diet does not greatly influence CH_4 yield (Vermorel, 1995; Boadi *et al.,* 2002). The global estimate of 44 Tg CH_4/yr from grassland derived feeds implies that compared to IPCC estimates (IPCC, 2001b) approximately 20% of all agricultural CH_4 emissions, and between 40 and 55% of the total ruminant CH_4 emissions, arise from grasslands. For comparison with other IPCC estimates the methods used here estimated enteric CH_4 emissions from feed sources to be 70.5 T g/yr.

Nitrous oxide

Estimating global N_2O emissions from pastoral agricultural soils worldwide is extremely difficult as it requires detailed dietary information (quantity of feed consumed and protein content of feed), detailed information on manure management systems, the quantity of nitrogenous fertiliser used, and information on such things as the quantity of animal dung collected and burnt or used as a building material. A lack of data ruled out a complex methodology and we adopted an IPCC Tier 1 approach. This involved using the grassland feed intake data, calculated from the CH_4 inventory, along with estimates of the N% in the diet (1.6 - 2.4%) and the N% retained in animal products (7 - 20%), to obtain an estimate of excreta N arising from grasslands. Default IPCC emission factors (IPCC, 1996; 2000) were then used to estimate direct and indirect N_2O emissions. This estimate makes no attempt to differentiate between manure deposited directly onto pastures or managed in manure management systems, and uses the IPCC default emission factor of 2% of N deposited. It also does not account for manure removed from pastures and used for other purposes. Nitrous oxide emissions from N fertilisers were estimated using the grassland N fertiliser use estimates of the United Nations Food and Agriculture Organisation (FAO) (FAO, 2001) and IPCC default values.

Estimated N_2O emissions from grasslands for the year 2003 are shown in Table 2. These data indicate that between 16 and 33% of the total estimated agricultural N_2O emissions (IPCC 2001b) arise from grasslands.

Table 2 Estimates of nitrous oxide (N_2O) production by ruminant livestock from grassland forage intake (Tg N_20/year)

	N input to soil	Direct N_2O losses	Indirect N_2O losses from:		Total N_2O losses
			volatislised N	leached N	
	(Tg N/yr)	(Tg N_2O-N/yr)			
Nitrogen fertiliser	4.331	0.049	0.004	0.029	0.082
Excreta nitrogen	34.812	0.696	0.070	0.261	1.027
Total	39.143	0.745	0.074	0.290	1.109

Mitigating methane and nitrous oxide emissions from grazing ruminants

Mitigating CH_4 and N_2O emissions from grazing ruminants poses a particular challenge since solutions requiring frequent manipulation of the grazing animal, or changes in pasture and soil conditions, are likely to be difficult to implement in many livestock systems. A second, more generic issue is that in the developed world, emissions from agriculture are generally minor compared to total CO_2 equivalent emissions. For example, in the EU in 2000 (and accepting that there are substantial differences between states), enteric CH_4 emissions from the agricultural sector comprised 3.2% of total CO_2 equivalent emissions (UNFCCC, 2004), down from 3.4% in 1990. The situation is similar for N_2O where emissions from agricultural soils in 1990 and 2000 comprised only 4.6% of total CO_2 equivalent emissions (UNFCCC, 2004). There is therefore little incentive to give high priority to the agricultural sector when funding research into GHG mitigation.

Methane mitigation

Improving efficiency of the animal production system

Improving the efficiency of livestock production as a route to reducing CH_4 emissions from livestock systems is an area that has the capability to cause considerable perplexity. Farmers continue to strive for improvements in the efficiency of production in order to survive in a competitive global market and, although improved production efficiency can influence CH_4 output, it is unlikely that efficiency increases by themselves will solve the CH_4 problem. For the purposes of this paper we will define improvements in efficiency as equating to increasing the amount of milk, meat or wool produced per unit of feed ingested. Defined in this way, efficiency is closely related to the partitioning of feed intake between that required for maintenance and that required for production. Viewed simplistically there will be a fixed CH_4 output associated with the maintenance portion of the diet, and a variable CH_4 emission that is associated with the production portion of the diet. As feed intake, and hence production increases, the proportion of total CH_4 output associated with maintenance goes down, and CH_4 output per unit of product declines (Table 3). Thus for a fixed amount of product, it will be beneficial in terms of CH_4 emissions to produce this from a smaller number of high producing animals than a large number of low producing animals.

Unfortunately, although improvements in efficiency will reduce the amount of CH_4 emitted per unit of product, they will not necessarily reduce the amount of CH_4 produced in total. A reduction in the total will only occur if the amount of product produced is static or rises at a slower rate than the rate of decline in CH_4 emitted per unit of product. For example, in New

Zealand the quantity of CH_4 produced per unit of product has declined since 1990 for beef and milk, but CH_4 emissions have increased in both sectors because of increases in the quantity of product produced (Clark & Ulyatt, 2002). Methane emissions from the sheep sector have fallen, principally because sheep number declined by 30% between 1990 and 2000, and increases in the quantity of sheepmeat and wool produced were small (Clark & Ulyatt, 2002).

Table 3 An estimation of the proportion of methane (CH_4) emission attributable to maintenance or milk production, in a 450kg grazing dairy cow at various levels of digestible DM intake (DDMI)

DDMI (kg/d)	Milk yield (kg/d)	CH_4 (kg/d)	% CH_4 associated with		CH_4/milk (g/kg)
			Maintenance	Production	
4.0	0	105	100	0	
7.9	12	206	51	49	17.2
10.5	20	272	39	61	13.6
11.7	24	305	34	66	12.7

Source: O'Hara *et al.,* (2003)

Improving herbage quality

One of the principle aims of grassland management is to increase the quality of the forage ingested by grazing ruminants. Methane production is highly correlated with fibre digestion in the rumen (Kirchgessner *et al.,* 1995), and so it would be logical to assume that decreasing the fibre content of forages would reduce CH_4 emissions. Empirical evidence to support this comes from the work of Blaxter & Wainman (1964), who found with hay based diets fed at twice maintenance intake levels, that CH_4 emissions increased from 3.5 to 7.0% of GE intake, as the crude fibre in the diet increased from 2.2 to 33.8%. In a summary of 339 experiments with sheep and cattle (Blaxter & Clapperton, 1965), it was found that at intakes above twice maintenance, the percentage of GE lost as CH_4 was reduced as digestibility increased. Since fibre content and digestibility of forages are negatively correlated, and are responsive to management manipulation, at first site it appears that increasing the digestibility of forages could be an effective CH_4 mitigation option for grazing livestock. However, this may not be the case in many situations.

Recent work using animals fed fresh, as opposed to dried, forage diets suggests that in C3 grasses at least the percentage of GE lost as CH_4 may be relatively insensitive to forage quality over the range of intakes found in grazing systems. Pinares-Patiño *et al.* (2003a), working with *Phleum pratense* L. (timothy grass) at four stages of maturity spanning an organic matter digestibility of 56 – 78% and a neutral detergent fibre (NDF) content of 52–76%, could find no relationship between digestibility or NDF and the percentage of GE intake lost as CH_4 in cattle fed at 1 - 1.5 above maintenance. Similarly Molano *et al.* (2003) working with *Lolium perenne* L. (perennial ryegrass) at two stages of growth and four levels of feeding, found no relationship between CH_4 emissions per unit of DM intake and digestibility (Table 4).

Table 4 Methane (CH_4) emission by sheep at four levels of voluntary feed intake, consuming *Lolium perenne* L. (perennial ryegrass) harvested at the vegetative and reproductive stage of growth

	Reproductive				Vegetative				
Apparent digestibility (%)	61.5	62.5	61.1	65.1	74.5	76.9	74.1	75.9	*P<0.001*
DMI kg/d	0.57	0.73	0.91	1.37	0.78	0.95	1.15	1.54	*P<0.001*
CH_4 g/day	11.5	17.7	24.3	31.9	15.6	22.7	27.4	35.9	*P<0.001*
CH_4 g/kg DMI	20.5	24.2	26.6	23.3	20.1	24.1	24.0	23.5	*NS*

Source: Molano *et al.,* (2003)

A second issue related to forage quality is that even if it does not influence the CH_4 yield, it can indirectly reduce CH_4 emissions since it affects how much feed is needed to achieve a given level of production. Increasing forage quality, could be used to decrease emissions per head simply because less feed is processed in the rumen to achieve a given level of production. However, in practice, if feed quality is increased without any reduction in the quantity of feed available, the intake of individual animals and/or the number of animals kept per unit area will increase. These would both tend to increase CH_4 production either per animal or per unit area. Therefore reductions in CH_4 could only be guaranteed if the number of stock kept, or the amount of product produced was also controlled.

Forage plants with low methane yield

Forage species have been shown to influence CH_4. Waghorn *et al*. (2002) found in sheep, that legumes generally reduced the quantity of CH_4 produced per unit of feed intake compared to C3 grasses. The data of Kurihara *et al*. (1999) and O'Hara *et al*. (2003) suggests that C4 grasses have a higher CH_4 yield than C3 grasses. However, some caution needs to be exercised since, with the exception perhaps of C4 grasses, the differences between forage species in CH_4 emissions may in practice be small. In an experiment with *Trifolium repens* L. (white clover) fed at varying proportions in the diet (Lee *et al.,* 2004), it was reported that even when incorporated at 60% of a grass:clover diet (a quantity only likely to be achieved for short periods in grazed swards), the reduction in CH_4 was only 16%. When *Trifolium repens* was included at 15% of the diet (a more realistic figure in many practical situations), the reduction was only 4%.

The difficulties surrounding plant solutions to CH_4 mitigation are perhaps best exemplified by condensed tannin (CT) containing plants. Plants containing CT have been found to reduce CH_4 emissions in cattle (Woodward *et al.,* 2001), and sheep (Waghorn *et al.,* 2002; Pinares-Patiño *et al.,* 2003b). In addition they have been found to increase liveweight gains and decrease the severity of gastrointestinal worm infestations (Min *et al.,* 2003). The disadvantage of CT containing plants in temperate pastures is that they do not compete well with other temperate species. As pointed out by O'Hara *et al.,* (2003), the benefits of CT containing plants have been recognised for over 30 years but to date we still do not have a competitive CT containing pasture plant.

Manipulation of the rumen microbial ecosystem

A number of strategies for influencing CH_4 production by direct manipulation of the rumen ecosystem have been promulgated (for a review see McAllister *et al.,* 1996). Some of them, notably the use of halogenated CH_4 compounds such as chloroform and bromochloromethane, have been shown to be highly effective at suppressing CH_4 production (van Nevel & Demeyer, 1996; McCrabb *et al.,* 1997), but they are in many cases also unstable compounds which are potentially toxic to ruminants (Lanigan *et al.,* 1978). Similarly the control of protozoa (which live in symbiosis with methanogens), which can be responsible for up to 25% of rumen CH_4 emissions (Newbold *et al.,* 1995), can only be achieved by the use of potentially toxic chemicals. Other strategies such as the manipulation of methanogens by bacteriophage and bacteriocins, and the promotion of acetogenesis as an alternative hydrogen sink are at an early stage. Two strategies are much closer to being available and these are discussed in more detail below.

Scientists working for CSIRO in Australia have developed animal vaccines that reduce methanogenesis by stimulating the production of antibodies in the host animal, which restrict the activity of rumen methanogens (Baker, 1999). This work has progressed to the stage where vaccines have been tested *in-vivo*. The limited data available show no clear evidence that the current formulations can consistently reduce CH_4 emissions (Table 5). However, the promising aspect of the Australian trial is that both vaccine formulations were able to boost antibody titres (IGa and IGg) in blood and saliva compared to control animals. Clearly considerably more work is needed to develop a vaccine with proven efficacy but the approach is one that is highly attractive in grazing animals, since it holds out the promise of an effective mitigation technology allied to an infrequent and simple delivery mechanism.

Table 5 Percentage changes in the quantity of methane (CH_4) emitted per unit feed intake, compared to adjuvant only controls following vaccination with three different anti-methanogenic vaccine preparations (AMG-v). All data non-significant except for *, where *P=0.51*

	Post-primary vaccination			Post-booster vaccination		
	AMG-v1	AMG-v2	AMG-v3	AMG-v1	AMG-v2	AMG-v3
Australia[1]	-6	Not used	-1	-7.7*	Not used	+0.8
New Zealand[2]	-4	+2	Not used	+2	+9	Not used

Source: [1]Wright *et al.,* (2004); [2]Clark *et al.,* (2004)

Ionophores, particularly monensin, have been used routinely in animal production systems for many years as growth promoters. There is evidence to suggest that they can reduce CH_4 through a combination of reduced voluntary intake, reduced acetate production and the inhibition of H_2 release from formate (Goodrich *et al.,* 1984; van Nevel & Demeyer, 1996; Tedeschi *et al.,* 2003). Slow release delivery devices are available, thus monensin is potentially suitable for use in grazing animals. There are two principle issues surrounding its use as a CH_4 mitigation tool. First, there are doubts as to the duration of the direct CH_4 suppressing effect (Tedeschi *et al.,* 2003). However O'Kelly & Spiers (1992), working with steers fed Lucerne hay, found that 55% of the reduction in CH_4 was attributed to the anorectic effect (reduced intake) and 45% to the direct effect on rumen fermentation. This implies that even in the absence of a direct effect on rumen methanogenesis, CH_4 production would still be reduced in situations where ionophores reduce herbage intakes. A second issue is that ionophores are classed as antibiotics and there is a strong move to phase out the routine use of antibiotics in livestock production systems. Hence even if the efficacy of monensin as a long-term CH_4 inhibitor could be conclusively demonstrated, its routine use may not be readily acceptable to both consumers and regulatory authorities.

Exploiting animal to animal variation in methane production

Since the development of the SF_6 tracer technique for estimating CH_4 production in unconfined ruminants (Johnson & Johnson, 1995), it has been possible to simultaneously measure emissions from groups of animals consuming the same diet. The vast majority of work with grazing animals fed fresh forage has been carried out in New Zealand. A common finding is that there are large differences in emissions per unit of feed intake (Ulyatt *et al.,* 2002). This phenomenon has been confirmed recently in a single experiment when CH_4 emissions were measured from 302 grazing dairy cows over a four-week period (Table 6). In addition in sheep, differences between individual animals have been found to persist for up to five months (Pinares-Patiño *et al.,* 2003c).

Table 6 Methane (CH_4) emissions from a herd of 302 Friesian x Jersey dairy cows measured between January 12 and February 6, 2003

	Min	Max	Mean	St. Dev	Lower quartile	Upper quartile
CH_4 g/day	213.9	478.8	332.1	38.1	285.6	381.0
CH_4 kg DMI/day^{-1}	11.0	31.1	19.3	2.9	16.1	23.1

Source: C. Pinares-Patiño & H. Clark (*unpublished data*).

Since CH_4 is produced by microbial fermentation in the rumen, the existence of animal-to-animal variation suggests that there is an interaction between the animal and its microbes. This leads onto issues of whether this interaction is genetically based, and if it is a heritable trait? In New Zealand, cows of a US genetic background have been found to have lower CH_4 emissions per unit of dry matter intake than cows of a New Zealand genetic background (O'Hara *et al.,* 2003). Similarly Ferris *et al.* (1999) found that the percentage of GE lost as CH_4, was lower for high genetic merit than for medium genetic merit Holstein cows. These two studies indicate that it may be possible to breed animals that have inherently low CH_4 emissions. Although work on exploiting animal variation in CH_4 emissions is at a preliminary stage, breeding low CH_4 producing animals does offer an extremely attractive solution. It has applicability across all types of production systems, exists for the life of the animal and is open to continuous improvement.

Nitrous oxide mitigation

Improving efficiency of the animal production system

In a similar manner to that already discussed for CH_4, improving the efficiency of production can reduce N_2O emissions in situations where constraints are placed on product output. If the productivity of each animal is increased, less total dry matter intake is needed to produce a given amount of product (see Table 3). This in turn leads to a reduction in the total N being recycled through the grazing animal for a given amount of product. The quantity of N_2O emitted per animal is therefore likely to be higher, but fewer animals are needed to obtain the quantity of product required. Mitigating N_2O (and CH_4) by improving the efficiency of production does however imply that product output is restricted to some extent.

Diet manipulation

Decreasing either the total N content and/or the N degradability of ruminant diets will reduce the amount of N excreted during the grazing process (Kebreab *et al.,* 2001). This solution is most applicable to the dairy sector where there are more opportunities to manipulate the diet. Optimising fertiliser applications has an important role here since the N content of plants is directly related to N supply (Whitehead, 1995). The replacement of high N content grass, with low N content high-energy feeds such as maize silage is a possibility in some circumstances. For example, in New Zealand maize silage is commonly given as a supplement to grazing dairy cows. Modelling studies by de Klein & Ledgard (2005), have shown that substituting fertilised grass with fertilised maize silage can reduce N_2O emissions from the typical New Zealand dairy farm by 27% (Table 7).

Table 7 Estimated nitrogen (N) fertiliser use, N excretion rates and nitrous oxide (N_2O) emissions from an average dairy farm in New Zealand, under a 'business-as usual' scenario and when replacing fertilized grass with maize silage

	Business-as usual	Maize silage supplement
N fertiliser use		
On farm (t N/yr)	7.4	0
Off-farm (t N/yr)	0	1
N excreted (kg N/ha/yr)	345	318
N_2O emissions (t CO_{2equiv}/yr)	218	159 (-27%)

Adapted from de Klein & Ledgard (2005)

The quantity of N voided by grazing ruminants can also be influenced by the protein: carbohydrate ratio of the diet (van Vuuren & Meijs, 1987; Kebreab *et al.,* 2001). Studies at the Institute of Grassland and Environmental Research (IGER) in Wales have shown that feeding beef cattle, silage made from grass cultivars containing elevated concentrations of water soluble carbohydrates, increased the N use efficiency for microbial growth in the rumen from 46 to 68% (Merry *et al.,* 2003). Similarly, studies with dairy cows suggested that high sugar grasses reduced N excretion rates and, under some conditions, increased milk yield and milk protein yield (IGER, 2001). However, recent New Zealand research suggests that the effectiveness of these grasses as a N_2O mitigation strategy might be limited to cooler climates, as a warm-temperate climate may limit grass expression of high sugar content (Parsons *et al.*, 2004).

Plants containing CT's have already been discussed in relation to CH_4 mitigation. They also have the potential to influence N_2O emissions from grazed pastures because of their ability to influence protein breakdown and absorption in ruminants (Min *et al.,* 2003). Unfortunately, as already discussed, the inferior agronomic characteristics of these plants limit their usefulness at present. Similarly, the ionophore monensin, which can reduce CH_4 evolution from ruminants, can also influence N retention (Tedeschi *et al.,* 2003). This can be directly through increased N retention or indirectly through its anorectic effect. However, as discussed previously, the widespread use of monensin to mitigate GHG emissions may not be readily acceptable in practice.

Management of fertilisers and excreta deposited during grazing

In general, practices that increase the efficiency of use of applied N will reduce emissions of N_2O from soils. Likewise, the timing, quantity and type of N fertilisers have all been shown to influence N_2O emissions (for a review see O'Hara *et al.,* 2003). Slow release fertilisers, formulated to achieve a better synchrony between the demand and supply of N, have been shown to be effective at reducing N_2O emissions (Smith *et al.,* 1997). Similarly, fertilisers containing, or applied in conjunction with, nitrification inhibitors such as dicyandiamide (DCD) have also proved to be effective at reducing N_2O emissions by as much as 60% (Belastegui Macadam *et al.,* 2003; Williamson & Jarvis 1997).

Although improved management of synthetic fertilisers can help to reduce N_2O emissions from grasslands, a more pressing problem is that of reducing emissions from animal wastes deposited directly onto pastures by grazing animals. Options here are very limited. A field study by de Klein *et al.* (2005) suggests that the strategic use of a feed pad can reduce total N_2O emission by avoiding urine and dung being deposited during wet conditions when N_2O emissions are likely to be high. Their results suggested that for a typical dairy farm in the southern part of New Zealand, N_2O emissions could be reduced by about 10%. In addition, small reductions can be achieved by altering soil conditions e.g. liming, improving drainage and avoiding soil compaction (Clark *et al*., 2001). However, the general applicability of these methods is limited. Work with nitrification inhibitors to reduce N_2O emissions from animal urine does however hold some promise. Williamson & Jarvis (1997) reported reductions of over 70% in N_2O emissions from urine applied to pasture in conjunction with DCD, compared to urine alone between 6 – 21 days after application. In lysimeter studies Di & Cameron (2002, 2003) found that DCD reduced N_2O emissions from urine treated grassland by about 80% following spring and/or autumn applications of urine with or without DCD. The addition of a nitrification inhibitor directly into the urine stream from an animal mounted dispenser has also been advocated, although no results are available to attest to the efficacy of this approach (Quin, 2004). The research conducted so far does indicate that applying DCD to grazed pastures could be used as a practical method of reducing N_2O from urine patches, although issues of toxicity (DCD has been shown to be exhibit phytotoxic effects to *Trifolium repens* (Belastegui Macadam *et al.,* 2003), timing and longevity of the effect need to be assessed. Additionally research needs to be conducted at the system level to determine the long-term effects of nitrification inhibitors on N cycling dynamics in the soil, plant, and atmosphere system. For example, Belastegui Macadam *et al.* (2003), showed that DCD increased the N concentration in *Trifolium* plants, and this will influence the quantity of excreta N cycled through the animal.

Conclusions

Grassland ecosystems are major contributors to agricultural emissions of CH_4 and N_2O. Options do exist to mitigate emissions from grazed systems, but in general they do not have universal applicability and for many situations practical methods of reducing emissions do not exist at present. Research into GHG emissions from agriculture is low priority in most developed countries, and this will need to be addressed if more rapid progress is to be made. Priority research areas need to be those that have high efficacy, and cost effective and simple delivery mechanisms. For the long term direct manipulation of the rumen ecosystem provides the best opportunity for large reductions in CH_4 emissions. This is a neglected area of research in most countries. Breeding low CH_4 emitting animals is an exciting prospect but more work is needed on the fundamental basis of animal-to-animal variation before breeding programmes are contemplated. For N_2O emissions the research priorities are two-fold. Firstly, studies should be conducted that focus on providing experimental evidence of the effectiveness of mitigation options. In particular on options which focus on reducing the amount of N excreted by grazing animals, as this source of N_2O constitutes almost 90% of the total global N_2O emissions (Table 2). Secondly, the development of accurate models is important. Due to the high spatial and temporal variability of N_2O emissions, accurate measurements at a whole systems level are near impossible. Therefore, the development of systems models that utilise and link the experimental evidence of component studies to evaluate the effect of mitigation strategies at a systems level is a priority area.

Such models should also have the ability to collectively assess all major GHG emissions. In this paper, as in most others, N_2O and CH_4 have been considered separately. In reality they are both emissions from the same production system and, in the short term at least, manipulations of the system as a whole may offer the best hope of reducing net GHG emissions from pastures. This also means looking at both sources and sinks of GHG. Modelling studies by Lambert & Clark, (2005) have demonstrated that for beef and sheep farms in NZ it is possible to maintain farm incomes and reduce GHG emissions by a combination of the intensification of animal production and the planting of trees. It would be surprising if opportunities for this type of system manipulation didn't exist in other countries.

Finally, although the aim of GHG mitigation technologies is to reduce actual emissions to the atmosphere, international treaty obligations mean that countries also have to be able to demonstrate in their GHG accounts that they have done so. This means that national inventories capable of accounting for mitigation technologies need to be developed alongside measurement systems that can verify claimed emission reductions.

References

Andrieu, J., C. Demarquilly & D. Sauvant (1988). Tables de la valeur nutritive des aliments. In: R. Jarrige (ed.) Alimentation des bovins, ovins et caprins (Feeding of cattle, sheep and goats*)*, INRA, Paris, 351–464.

Baker, S.K. (1999). Biology of rumen methanogens and stimulation of animal immunity. In: P.J. Reyanga & S.M. Howden (eds.) Meeting the Kyoto Target. Implications for the Australian livestock industries. Bureau of Rural Sciences, 31-40.

Belastegui Macadam, X.M.B., A. del Prado, P.Merino, J.M. Estavillo, M.Pinto & C. Gonzalez-Murua (2003). Dicyandiamide and 3,4-dimethyl pyrazole phosphate decrease N_2O emissions from grassland but dicyandiamide produces deleterious effects in clover. *Journal of Plant Physiology*, 160, 1517-1523.

Blaxter, K.L. & J.L. Clapperton (1965). Prediction of the amount of methane produced by ruminants. *British Journal of Nutrition*, 19, 511-522.

Blaxter, K.L. & F.W. Wainman (1964). The utilization of the energy of different rations by sheep and cattle for maintenance and for fattening. *Journal of Agricultural Science, Cambridge*, 63, 113-128.

Boadi, D.A., K.M. Wittenberg & W.P. McCaughey (2002). Effects of grain supplementation on methane production of grazing steers using the sulphur (SF_6) tracer gas technique. *Canadian Journal of Animal Science*, 82, 151-157.

Bouwman, A.F., K.W. Van der Hoek, B. Eickhout & I. Soenario (2004). Exploring changes in world ruminant production systems. *Agricultural Systems,* (In press).

Clark H., C. de Klein & P. Newton (2001). Potential management practices and technologies to reduce nitrous oxide, methane and carbon dioxide emissions from New Zealand agriculture. Report to Ministry of Agriculture and Forestry - Oct 2001, Wellington, New Zealand, 81pp.

Clark, H. & M.J. Ulyatt (2002). A recalculation of enteric methane emissions from New Zealand ruminants 1990-2000 with updated emission predictions for 2010. A report prepared for the Ministry of Agriculture and Forestry, Wellington, New Zealand, 38pp.

Clark, H., A.D. Wright, K. Joblin, G. Molano, A. Cavannagh & J. Peters (2004). Field testing an Australian developed anti-methanogen vaccine in growing ewe lambs. *Proceedings of the workshop on the science of atmospheric trace gases, 2004*. NIWA Technical Report 125, Wellington, New Zealand, 167pp.

de Klein, C.A.M. & S.F. Ledgard (2005). Nitrous oxide emissions from New Zealand agriculture – key sources and mitigation strategies. *Nutrient cycling in AgroEcosystems.* (in press).

de Klein, C.A.M., L.C. Smith & R.M. Monaghan (2004). Restricted autumn grazing to reduce nitrous oxide emissions from dairy pastures in Southland, New Zealand. *Agriculture, Ecosystem and Environmen,* (in press).

DeRamus, H.A., T.C. Clement, D.D. Giampola & P.C. Dickison (2003). Methane emissions of beef cattle on forages: efficiency of grazing management. *Journal of Environmental Quality*, 32, 269-277.

Di, H.J. & K.C. Cameron (2002). The use of a nitrification inhibitor, dicyaniamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland. *Soil Use and Management*, 18, 395-403.

Di, H.J. & K.C. Cameron (2003). Mitigation of nitrous oxide emissions in spay-irrigated grazed grassland by treating the soils with dicyaniamide, a nitrification inhibitor. *Soil Use and Management*, 19, 284-290.

FAO (2001). Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land. Report by the international fertilizer industry association and the Food and Agriculture Organisation of the United Nations, Rome, 58pp.

Available from <http:www.fao.org/DOCREP/004/Y2780E/y2780e00.htm#P-10>

FAOSTAT (2003). FAO Statistical Databases. Food and Agriculture Organization of the United Nations, Rome. Available from <http://faostat.fao.org/faostat>

Ferris, C.P., F.J. Gordon, D.C. Patterson, M.G. Porter & T. Yan (1999). The effect of genetic merit and concentrate proportion in the diet on nutrient utilisation by lactating dairy cows. *Journal of Agricultural Science, Cambridge*, 132, 483-490.

Firestone, M.K. (1982). Biological denitrification. In: F.J. Stevenson (ed.) Nitrogen in agricultural soils. ASA-CSSA-SSA, Madison, Wisconsin, U.S, 289-326.

GLIPHA (2003). Global Livestock Production and Health Atlas. Food and Agriculture Organization of the United Nations, Rome. Available from<http://www.fao.org/ag/aga/glipha/index.jsp>

Goodrich, R.D., J.E. Garrett, D.R. Ghast, M.A. Kirich, D.A. Larson & J.C. Meiske (1984). Influence of monensin on the performance of cattle. *Journal of Animal Science*, 58, 1484-1498.

Haynes, R.J. & R.R. Sherlock (1986). Gaseous losses of nitrogen. In: R.J. Haynes (ed.) Mineral nitrogen in the plant-soil system. Orlando, Academic Press, 242-302.

Hendy, C.R.C., U. Kleih, R. Crawshaw & M. Phillips (1995). Interactions between livestock production systems and the environment: impact domain: concentrate feed demand. FAO Consultancy Report for Livestock and Environment Study, 147pp.

IGER (2001). <http://www.IGER.bbsrc.ac.uk/igerweb/AnnRep2000/arasciadv.htm#Sweet>

Immig, I. (1996). The rumen and hindgut as source of ruminant methanogenesis. *Environmental monitoring and assessment*, 42, 57–72.

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.

IPCC (2001a). IPCC Third Assessment Report: Climate Change 2001: Synthesis Report, R.T. Watson & the Core Writing Team (eds.), IPCC, Geneva, Switzerland, 34pp.

IPCC (2001b). IPCC third assessment report: climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (eds.), Cambridge University Press, UK, 881pp.

Johnson, D.E. & G.M. Ward (1996). Estimates of animal methane emissions. *Environmental monitoring and assessment*, 42, 133–141.

Johnson, K.A. & D.E. Johnson (1995). Methane emissions from cattle. *Journal of Animal Science*, 73, 2483-2492.

Kebreab, E., J. France, D.E. Beever & A.R. Castillo (2001). Nitrogen pollution by dairy cows and its mitigation by dietary manipulation. *Nutrient Cycling in AgroEcosytems*, 60:275-285.

Kirchgessner, M., W. Windisch & H.L. Muller (1995). Nutritional factors for the quantification of methane production. In: W. von Engelhardt, S. Leonhard-Marek, G. Breves & D. Gieseke (eds.) Ruminant physiology: digestion, metabolism, growth and reproduction. Ferdinand Enke Verlag, Stuttgart, 333-348.

Kurihara, M., T. Magner, R.A. Hunter & G.J. McCrabb (1999). Methane production and energy partition of cattle in the tropics. *British Journal of Nutrition*, 81, 227-234.

Lambert, M.G. & H. Clark (2005). A systems approach to managing greenhouse gases on New Zealand sheep & beef farms. In: *Proceedings of the XX International Grassland Congress*, Dublin, offered paper (in press).

Lanigan, G.W., A.L. Payne & J.E. Peterson (1978). Antimethanogenic drugs and *Heliotropium europaeum* poisoning in penned sheep. *Australian Journal of Agricultural Research*, 29, 1281-1291.

Lassey, K.R., C.S. Pinares-Patiño & M.J. Ulyatt (2002). Methane emission by grazing livestock: some findings on emission determinants. *Proceedings of the third International Symposium on non-CO2 Greenhouse Gases (NCGG-3),* Maastricht, The Netherlands, 95-100.

Lee, J.M., S.L. Woodward, G.C. Waghorn & D.A. Clark (2004). Methane emissions by dairy cows fed increasing proportions of white clover (*Trifolium repens*) in pasture. *Proceedings of the New Zealand Grassland Association*, 66, 151-155.

McAllister, T.A., E.K. Okine, G.W. Mathison & K.J. Cheng (1996). Dietary, environmental and microbial aspects of methane production in ruminants. *Canadian Journal of Animal Science*, 76, 231-243.

McCaughey, W.P., K. Wittenberg & D. Corrigan (1997). Methane production by steers on pasture. *Canadian Journal of Animal Science*, 77, 519-524.

McCaughey, W.P., K. Wittenberg & D. Corrigan (1999). Impact of pasture type on methane production by lactating beef cows. *Canadian Journal of Animal Science*, 79, 221-226.

McCrabb, G.J., K.T. Berger, T. Magner, C. May & R.A. Hunter (1997). Inhibiting methane production in Brahman cattle by dietary supplementation with a novel compound and the effects on growth. *Australian Journal of Agricultural Science*, 48, 323-329.

Merry R.J., M.R.F. Lee, D.R. Davies, J.M. Moorby, R.J. Dewhurst & N.D. Scollan (2003). Nitrogen and energy use efficiency in the rumen of cattle fed high sugar grass and/or red clover silage. *Aspects of Applied Biology*, 70, 87-92.

Miller, T.L. (1995). Ecology of methane production and hydrogen sinks in the rumen. In: W. von Engelhardt, S. Leonhard-Marek, G. Breves & D. Gieseke (eds.) Ruminant physiology: digestion, metabolism, growth and reproduction. Ferdinand Enke Verlag, Stuttgart, 317-331.

Min, B.R., T.N. Barry, G.T. Attwood & W.C. McNabb (2003). The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: a review. *Animal Feed Science and Technology*, 106, 3-19.

Molano, G., T. Renard & H. Clark (2003). The effect of level of feeding and forage quality on methane emissions by wether lambs. *Proceedings of the 2nd joint Australia and New Zealand forum on Non-CO2 greenhouse gas emissions from Agriculture*, R. Eckard & B. Slattery (eds.). Cooperative research centre for greenhouse gas accounting. Canberra, Australia, F14.

Mosier, A.R., J.M. Duxbury, J.R. Freney, O. Heinemeyer, K. Minami & R. Merckx (1996). Nitrous oxide emissions from agricultural fields: assessment, measurement and mitigation. *Plant and Soil*, 181, 95-108.

Murray, R.M., A.M. Bryant & R.A. Leng (1976). Rates of production of methane in the rumen and large intestine of sheep. *British Journal of Nutrition,* 36, 1-14.

New Zealand Climate Change Office (2004). National inventory report. Greenhouse gas inventory 1990 - 2002. The national inventory report and common reporting format Tables, April 2004. Wellington, New Zealand, 155pp.

Newbold, C.J., B. Lassalas & J.P. Jouany (1995). The importance of methanogens associated with ciliate protozoa in ruminal methane production *in vitro*. *Letters in Applied Microbiology*, 21, 230-234.

O'Hara, P., J. Freney & M. Ulyatt (2003). Abatement of agricultural non-carbon dioxide greenhouse gas emissions. A study of research requirements. A report prepared for the Ministry of Agricultue and Forestry on behalf of the Convenor, Ministerial Group on Climate Change, the Minister of Agriculture, and the Primary Industries Council. May 2003, New Zealand Ministry of Agriculture and Forestry, Wellington, 171pp. <www.govt.nz/publications>

O'Kelly, J.C. & W.G. Spiers (1992). Effect of monensin on methane and heat production of steers fed lucerne hay either *ad libitum* or at the rate of 250 g/hour. *Australian Journal of Agricultural Research*, 43, 1789-93.

Parsons A.J., S. Rasmussen, X. Hong, C.B. Anderson & G.P. Cosgrove (2004). Some 'high sugar grasses' don't like it hot. *Proceedings of the New Zealand Grassland Association,* 66, (in press).

Pinares-Patiño, C.S., R. Baumont & C. Martin (2003a). Methane emissions by charolais cows grazing a monospecific pasture of timothy at four stages of maturity. *Canadian Journal of Animal Science*, 83, 769-777.

Pinares-Patiño, C.S., M.J. Ulyatt, C.W. Holmes, T.W. Barry & K.R. Lassey (2003c). Persistence of the between-sheep variation in methane emission. *Journal of Agricultural Science, Cambridge*, 140, 227-233.

Pinares-Patiño, C.S., M.J. Ulyatt, G.C. Waghorn, C.W. Holmes, T.N. Barry, K.R. Lassey & D.E. Johnson (2003b). Methane emission by alpaca and sheep fed on lucerne hay or grazed on pastures of perennial ryegrass/white clover or birdsfoot trefoil. *Journal of Agricultural Science, Cambridge*, 140, 215-226.

Quin, B. (2004). Nitrification inhibitors: N-sense or nonsense? FertScience, the science of soil fertility. The Official Newsletter of Summit-Quinphos (NZ) Ltd. (Autumn 2004), 10pp.

Schmidt, E.L. (1982). Nitrification in soil. In: Stevenson, F.J. (ed.) Nitrogen in agricultural soils. ASA-CSSA-SSA, Madison, Wisconsin, U.S, 253-288.

Seré, C. & H. Steinfeld (1996). World livestock production systems: current status, issues and trends. FAO Animal Production and Health Paper 127. Food and Agriculture Organization of the United Nations, Rome, Italy, 92pp.

Smith, K.A., I.P. McTaggart, H. Tsuruta & K. Smith (1997). Emissions of N_2O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. *Soil Use and Management*, 13, 296-304.

Tedeschi, L.O., D.G. Fox & T.P. Tylutki (2003). Potential environmental benefits of ionophores in ruminant diets. *Journal of Environmental Quality*, 32, 1591-1602.

Ulyatt, M.J., H. Clark & D.K.R. Lassey (2002). Methane and climate change. *Proceedings of the New Zealand Grassland Association*, 64, 153-157.

UNFCCC (2004). Greenhouse gas inventory database.
<http://ghg.unfccc.int/default1.htf?time=05%3A02%3A54+AM>

USEPA (1995). Global impact domain – methane emissions. Consultant report for the livestock and the environment study. USEPA, Washington D.C. Available from
<http://www.fao.org/WAIRDOCS?LEAD?X6116E/x6116e05.htm#5.%20Exhibits>

van Nevel, C.J. & D.I. Demeyer (1996). Control of rumen methanogenesis. *Environmental Monitoring & Assessment*, 42, 73-97.

van Vuuren, A.M. & J.A.C. Meijs (1987). Effects of herbage composition and supplement feeding on the excretion of nitrogen in dung and urine by grazing dairy cows. In: H.G. van der Meer, T.A. van Dijk & G.C. Ennik (eds.) Animal manure on grassland and fodder crops. Dordrech, The Netherlands, Martinus Nijhof, 17-25.

Vermorel, M. (1995). Productions gazeuses et thermiques résultant des fermentations digestives (Gas and thermal production resulting from digestive fermentation). In: R. Jarrige, Y. Ruckebusch, C. Demarquilly, M.H. Farce & M. Journet (eds), Nutrition des ruminants domestiques, INRA, Paris, 649–670.

Waghorn, G.C., M.H. Tavendale & D.R. Woodfield (2002). Methanogenesis from forages fed to sheep. *Proceedings of the New Zealand Grassland Association*, 64, 167-171.

Wheeler, R.O., G.L. Cramer, K.B. Young & E. Ospina (1981). The world livestock product, feedstuff, and food grain system. Winrock International Livestock Research and Training Center, Arkansas, USA, 85pp.

Whitehead, D.C. (1995). Grassland nitrogen. CAB International, Wallingford, UK, 397pp.

Williamson, J.C. & S.C. Jarvis (1997). Effect of Diccyaniamide on nitrous oxide flux following return of animal excreta to grassland. *Soil Biology and Biochemistry*, 29, 1575-1578.

Wolin, M.J., T.L Miller & C.S. Stewart (1997). Microbe-microbe interactions. In: P.N. Hobson & C.S Stewart (eds.) The rumen microbial ecosystem. Blackie Academic and Professional, London, 467-491.

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

Wright, A.D.G., P. Kennedy, C.J. O'Neill, A.F. Toovey, S. Popovski, S.M. Rea, C.L. Pimm & L. Klein (2004). Reducing methane emissions in sheep by immunization against rumen methanogens. *Vaccine*, (in press).