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Enteric fermentation and ruminant eructation: the role (and control?) of methane in the climate change debate

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Abstract Anthropogenic processes are responsible for between 55% and 70% of the estimated 600 Tg of methane that is released annually into the atmosphere, with enteric fermentation a major contributor to emissions in a number of countries. This paper therefore reviews current levels of CH_4 discharges by both animal type and country, and shows how the growth or decline in national herds over the last 20 years has significantly altered the global composition of enteric emissions. As developing countries are now responsible for almost three-quarters of such emissions, this has important implications in terms of mitigation strategies—particularly as such countries are presently outside the remit of the Kyoto Protocol.

1 Introduction

In 2007 the Intergovernmental Panel on Climate Change reported that the global average surface temperature had increased by around 0.74 ± 0.18°C over the twentieth century[1] (probably the largest centennial increase over the last thousand years), with 11 of the last dozen years (1995–2006) ranking among the warmest since records began in 1850 (IPCC 2007:2). Moreover, a series of long-term emissions scenarios developed by the same organisation suggested that temperatures could rise between 2.4°C and 6.4°C by 2090–2099 (IPCC 2007:8 [high scenario]). The root cause of this (recent) past and projected climate change is now recognised to be the warming potential of a number of *greenhouse gases* [GHG] that, by absorbing terrestrial infrared radiation, raise the temperature of the troposphere and with it, global surface temperatures. The increased atmospheric concentrations of these GHG are largely anthropogenic in origin—chlorofluorocarbons [CFC], for example, only

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[1] This compares to the 0.6 ± 0.2°C cited by the prior IPCC (2001) report.

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established an atmospheric presence following their first synthesis in 1928, reaching concentrations of between 307 [case of CFC-11] and 533 [CFC-12] parts per trillion volume by the mid-1990s (Mangani 1999:263), before their production/consumption was gradually phased out under the terms of the Montreal Protocol.[2] While the anthropogenic generation of other GHG has not been banned, recognition of their deleterious environmental effects did historically lead governments to consider curbing emission levels. In 1989, for example, the Dutch government decision to set CO_2 emission reduction targets in the National Environmental Policy Plan caused energy distributors to sponsor the development of renewable energy sources (Agterbosch et al. 2004:2054ff), while European preoccupations about reducing emissions of sulphur dioxide and oxides of nitrogen underpinned the 1988 Large Combustion Plant Directive (EEC 1988).

The emission reduction process gained a greater momentum following the drafting of the Kyoto Protocol in December 1997. The Protocol, presently ratified by 179 countries, formally entered into force on 16 February 2005 and obliged the 39 states inscribed in Annex B of the Protocol (the industrialised economies plus countries in transition to a market economy) to reduce aggregate emissions of the six main GHGs by ‘at least 5% below their 1990 levels in the [First] commitment period 2008 to 2012’ (Protocol, Article 3).[3] Individual targets differed—the pre-2004 EU members plus a clutch of other countries (including Bulgaria, Monaco, Romania and Switzerland) were set an 8% reduction target, New Zealand, the Russian Federation and the Ukraine were expected to peg emissions to their 1990 levels, while Australia and Iceland were granted special dispensation to increase emissions by 8% and 10% respectively over and above the 1990 base-line figure (UNFCC ND).

Countries responded by formulating their own post-Kyoto national emission reduction strategies—Australia approved a A$400 million GHG Abatement Program in 1999 to encourage large-scale cost-effective abatement of emissions (http://www.greenhouse.gov.au/ggap, accessed 23 March 2006), the ‘central pillar of Swiss climate policy’ is the CO_2 Law of 2000 which is designed to reduce heating and motor fuel consumption by either voluntary or fiscal means (SAEFL ND) and, while New Zealand (2005) and Japan (2007) subsequently dropped plans to introduce carbon taxes, the Canadian province of British Columbia is currently intent on introducing a fully revenue-neutral carbon tax of C$10/tonne from July 2008 (Government of British Columbia 2008). Even President Bush, while reiterating his opposition to the Kyoto Protocol, announced that his administration intended to implement measures to slow the growth of US greenhouse gas emissions—and unveiled a *Clear Skies Initiative* expected to cut air pollution by 70% (White House 2002).

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[2] Production of CFCs was banned in the developed countries in 1996, with developing countries scheduled to follow suit by 1 January 2010 under the terms of the Montreal Protocol. The Protocol also establishes similar phasing-out periods for other ozone depleting substances such as halons, hydrochlorofluorocarbons and methyl bromide for example (http://www.undp.org/seed/eap/montreal/montreal.htm).

[3] Only one–the United States–of the 39 states inscribed in Annex B has not yet ratified the Protocol. US ratification has not taken place on the grounds that the agreement itself is flawed (as it fails to include the developing economies—which are responsible for 45%+ of global GHG emissions) and that the domestic changes needed to meet the US emissions target will be too costly (Hathaway-Zepeda 2004:30).

One particular proposal, the New Zealand government's July 2003 proposition to introduce a (livestock) levy to fund research into ways to reduce methane gas produced by livestock as a contribution to tackling climate change, provoked much mirth in the popular press.[4] Scatological headlines like 'Kyoto Flatulence Plan causes turbulence in New Zealand', 'New Zealand tries to cap gaseous sheep burps', 'New Zealand's belching animals' and 'Getting the Cows to Cool it' (National Geographic News 2002, 13 May; LA Times 2003, 7 June; New Zealand Farmers 2003, 2 July; CNS News 2003, 3 July) in their own idiosyncratic way have helped to extend awareness that methane (CH_4) is one of the six GHG covered by the Kyoto Protocol, and ruminant eructation is one of the largest—albeit somewhat overlooked until recently—sources of anthropogenic methane emissions (IPCC 2001). This oversight is now in the process of being remedied through the activities of the LEARN (Livestock Emission Abatement Research Network, www.livestockemissions.net/AboutUs/tabid/55/Default.aspx, accessed 28 May 2008) initiative,[5] which was established in November 2007—following comments made at side events during the May 2007 IPCC Bonn meeting. Its activities are complemented by the outputs of the Greenhouse Gases and Animal Agriculture [GGAA] Conferences, the third and most recent—in New Zealand in November 2007—resulted in a selection of papers being published in a special double issue of the *Australian Journal of Experimental Agriculture* (AAJEA) in 2008.

This paper is intended to contribute to these efforts, outlining the role of ruminant eructation in the global warming process and discussing how (and whether) such emissions might be controlled given current national and international regulatory frameworks. The following section of the paper examines methane's role in global radiative forcing, and how ruminant digestive processes [enteric fermentation] contribute to the same. Section three then estimates global methane emission levels attributable to ruminant eructation—and identifies the main enteric CH_4 producing nations. Section four discusses mitigation strategies and the likelihood of their adoption in the light of Kyoto, while the final section presents some concluding remarks.

2 Methane, climate change and enteric fermentation

Climate change occasioned by global warming was attributed to 'the greenhouse effect' by Jean-Baptiste Fourier as early as 1827. The effect is triggered by incoming solar infra-red radiation being absorbed by the earth, a thermal blackbody radiator. The infra-red thermal energy irradiated in turn by the earth is, however, primarily long-wave (peaking at around 10 μm—as opposed to the 500 nm peak of solar infra-

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[4] The proposal was subsequently shelved, following discussions with the NZ livestock industry, in favour of funding the research through existing mechanisms.

[5] The Network's objectives are "to improve understanding, measurement and monitoring of non-CO_2 greenhouse gas emissions from animal agriculture at all scales, and to facilitate the development of cost-effective and practical greenhouse gas mitigation solutions (http://www.livestockemissions.net/AboutUs/tabid/55/Default.aspx).

Table 1 Tropospheric concentrations, emission rates and lifetimes of GHG cited by the Kyoto protocol

GHG	Formula	Abundance		Trend	Annual emission (late1990s)	Lifetime (years)	GWP
		1750	1998				
Carbon dioxide	CO_2	280	367	2.0	7 GtC	5–200	1
Methane	CH_4	700	1745	7.0	600 $TgCH_4$	8.4	23
Nitrous oxide	N_2O	270	314	0.8	16.4 TgN	120	296
Hydrofluoro-carbons	CHF_3	0	14	0.55	~ 7 Gg	260	12,000
	CF_3CH_2F	0	7.5	2.0	~ 25 Gg	13.8	1,300
	CH_3CHF_2	0	0.5	0.1	~ 4 Gg	1.4	120
Perfluorocarbons	CF_4	40	80	1.0	~ 15 Gg	$> 50,000$	5,700
	C_2F_6	0	3	0.08	~ 2 Gg	10,000	11,900
Sulphur hexafluoride	SF_6	0	4.2	0.24	~ 6 Gg	3,200	22,200

Abundance and trends are in parts per trillion (10^{12}) volume p.a., with the exception of methane and nitrous oxide which are in parts per billion (10^9) and carbon dioxide (parts per million—10^6). Annual emission data for carbon dioxide relates to anthropogenic fossil fuel combustion only (all other figures show anthropogenic and natural emissions)—where GtC are gigatonnes of carbon, Tg are teragrams ($10^{12)}$ and Gg are gigagrams (10^9). GWP (global warming potential) measures the radiative forcing of the gas over a time horizon standardized at 100 years relative to that of the same mass of CO_2. Source: Harding (1998), IPCC (2001: Table 4.1[a]), Blasing and Jones (2005)

red radiation)[6]—and is largely trapped within the atmosphere, a good absorber of long-wave infra-red radiation. This causes the earth's surface temperature to rise—the 'greenhouse effect'—with suggestions that, in the absence of this effect, global temperatures would be around 33°C lower than they presently are (Lindzen 1990).[7] Research moreover suggests that the extent of the greenhouse effect is umbilically linked to the concentration of both natural and synthetic GHG in the atmosphere (IPCC 2001). While the emission of a number of synthetic GHG were to be gradually phased out via the 1987 *Montreal Protocol on Substances that Deplete the Ozone Layer* (UNEP ND), the Kyoto Protocol demanded action regarding a further six GHG (Table 1).

Although carbon dioxide is the second most abundant GHG (behind water vapour) in the atmosphere, the recent and continuing increase in atmospheric CO_2 has been attributed to anthropogenic CO_2 emissions—most crucially fossil fuel burning (IPCC 2001). Nevertheless, the 31% growth in CO_2 atmospheric concentrations over the past 250 years was matched by a substantive increase (149%) in methane emissions, a GHG that has both a higher global warming potential and a longer atmospheric lifetime. As a consequence, it has been calculated that methane, whose presence in the atmosphere was first detected by Migeotte (1948), has been

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[6] This is explained by Wien's displacement law, which states that the wavelength distribution will peak at a value that is inversely proportional to absolute temperature. As the earth has a markedly lower temperature than the sun, earth infra-red thermal wavelengths will be correspondingly longer.

[7] A good, comprehensive scientific account of the greenhouse effect can be found in IPCC (2001, Chapter 1).

responsible for about 20% of the global radiative forcing[8] since 1750 (carbon dioxide accounts for slightly more than 60%, the halocarbons 14% and nitrous oxide 6%). Currently, between 55% and 70% of methane emissions result from anthropogenic activities (Fung et al. 1991; Lelieveld et al. 1998; IPCC 2001), with studies suggesting (Table 2) that ruminant eructation is one, if not the main anthropogenic source.

Globally, while ruminant eructation is estimated to account for between one-quarter and one fifth of anthropogenic emissions, national emission levels are determinant upon ruminant population and the presence (or lack) of alternative methane emitters. In the EU, for example, approximately two-thirds of annual regional methane emissions—amounting to some 6.8 million tonnes—have been attributed to enteric fermentation in ruminants (Moss et al. 2000:235). Even more strikingly, in New Zealand, where grazing ruminants dominate the agrarian landscape and paddy-fields are conspicuous by their absence, enterically generated methane accounts for 97.6% of CH_4 emissions from the agricultural sector—and 85.6% of all anthropogenic CH_4 discharges (see http://ghg.unfccc.int/tblxy.htm?fv1=cntr&fv2=src&time=03%253A45%253A43%2BPM).

Eructation, and with it methane emission, is actually caused by the process of intestinal fermentation. Ingested food is broken down in the digestive tract by enzymes and microbes, ruminants being particularly blessed by having, in addition, a large fore-stomach [the rumen] at the beginning of the tract which, by acting as a ‘fermentation vat’ (Freeman 2008:968), expedites the digestion of carbohydrates. Methane is one by-product of this process, with around 90% of methane produced in the rumen and around 98% of enterically produced methane released through the nose and mouth (Johnson et al. 2000). While larger ruminants (cattle, buffaloes and camels) emit greater masses of methane than smaller ruminants (goats, sheep, alpacas etc.), ruminants in turn have higher emission rates (per unit of feed intake) than non-ruminants (horses, pigs etc.)—thanks to their highly functional rumens (Crutzen et al. [henceforth CAS] 1986:272; Moss et al. 2000:236ff), as the following section discusses.

3 Enteric fermentation and the global ruminant methane budget

Research into enteric fermentation has tended to focus on domestic/domesticated animals for three reasons. First, as the rationale for compiling an emissions inventory is generally to assess the *anthropogenic* impact on atmospheric methane. Second, as assessing emissions by wild animals is frustrated by the poor information base. Third, because emissions from domestic/domesticated animals account for around 94% of total annual methane emissions by animals (Milich 1999:189). CAS (1986:277ff), however, do attempt to estimate likely CH_4 production by different types of wild ruminants in both temperate northern regions and the Serengeti in Africa.

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[8] The term “radiative forcing” denotes an externally imposed perturbation in the radiative energy budget of the Earth’s climate system and is standardly employed in IPCC assessments of climate change (see Ramaswamy et al. 2001, for elaboration on the concept and its use).

Table 2 Annual contributions to global methane budget, by source (Tg)

Author	Fung et al. (1991)	Hein et al. (1997)	Lelieveld et al. (1998)	Houweling et al. (1999)	Mosier et al. (1998)	Olivier et al. (1999)	Cao et al. (1998)
Base year	1980s	–	1992	–	1994	1990	–
Natural sources							
Wetlands	115	237	225	145			92
Termites	20	–	20	20			
Oceanic	10	–	15	15			
Hydrates	5	–	10	–			
Anthropogenic sources							
Energy	75	97	110	89		109	
Landfills	40	35	40	73		36	
Ruminants	80	90	115	93	80	93	
Rice Agri.	100	88	–[a]	–	25–54	60	53
Biomass Burning	55	40	40	40	34	23	
Other			25	20	29		
Total	500	587	600				

[a] Rice agriculture included under wetlands. Totals not computed for the last four studies as they fail to include one (or other) main emission sources. Source: Constructed from reports/research cited in IPCC (2001)

The earliest empirical work on ruminant emission, by Ritzman and Benedict in 1938 (cited by CAS 1986), computed the methane yields[9] of horses and three domestic ruminants (cattle, sheep and goats). Their findings, and subsequent work by Blaxter and Clapperton (1965), Van der Honing et al. (1981), Krishna et al. (1978), Murray et al. (1978), Kempton and Leng (1979), also highlighted how both management practices and feeding schemes could have substantive impacts on rates of methane discharge. Johnson and Johnson (1995) and Johnson et al. (2000), for example, have suggested that methane yields in cattle may vary from 2% to 3% (if fed a high-concentrate diet) to 10% (when fed a very poor quality diet), with most diets at most feeding levels producing methane yields in the range 6–7%.

CAS (1986) synthesised the findings of this earlier research to produce 'emission factors'—annual per capita masses of methane production for various animal types—which allowed for the calculation of national, regional and global enteric fermentation budgets. Lerner and Matthews (1988) subsequently applied the CAS methodology and emissions factors (EFs) to provide geographic information on the source of enteric CH_4. The IPCC then re-evaluated EFs for various ruminants (most particularly cattle) using regional livestock population characterisations and productivity data to produce a series of EF Tier 1 default values[10] (IPCC 1996—updated 2006), with only minor EFs developed by CAS (mules, asses, pigs) retained by the IPCC for inventory assessment purposes. These EFs have subsequently been incorporated into a series of papers (see Anastasi and Simpson 1993; Johnson and Ward 1996; Mosier et al. 1998; Scheehle et al. 2002; Lassey 2008, for example) which estimate national, regional and/or global enteric fermentation budgets. What sets this paper apart from these others is that we do not just focus on the aggregate increase in enteric emissions over time. We also highlight the marked change since the CAS study in the geographic distribution of such emissions—and then relate current national enteric emission levels to the emission reduction commitments espoused in, and demanded by, the Kyoto Protocol.

Cattle remain the main contributors to the global enteric methane budget. However, a multiplicity of EFs have been applied to compute emissions reflecting the different types of cattle production [dairy/beef—and the accompanying difference in energy intake required to support each], the different types of animal [Angus, Hereford, Brahman, Shorthorn etc.] and the differing quality of dietary regimes. While the original CAS paper, for example, noted that feed differentials across the US herd translated into distinctive gross energy uptakes and with it, sharp differences in annual methane production rates (54 kg for range cattle, 65 kg for fed cattle, and 84 kg for dairy cattle), it also calculated that cattle subsisting on near maintenance diets in India and other parts of the developing world discharged around 35 kg CH_4 annually per head. Currently, the IPCC (2006) recommend the application of different emission factors depending on region (eight) and cattle type (two) when

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[9] Methane yields express the energy lost through methane generation as a percentage of the gross energy intake. In the case of Ritzman and Benedict, these ranged from 3% to 7%.

[10] These 'Tier 1' default values are applied when local EF data is unavailable. EFs are reviewed regularly—a modification to calculating local sheep EFs was made in the IPCC Good Practice Guidance Manual (2000, Section 4.2.1.2) for example.

local EF data is unavailable—dairy cattle rates varying from 118 kg (USA) to 46 kg CH_4 (Indian sub-continent), while non-dairy cattle rates extend from 25 kg (Indian sub-continent) to 56 kg CH_4 (Eastern Europe), although even these disaggregated EFs are not beyond reproach (IPCC 1996, Appendix A, Page 4.29ff). Table 3 identifies the countries with the largest cattle populations (national herds ascending to 20 million or more head in 2004) and, by applying the regional EF recommended in the CAS and IPCC studies,[11] shows how annual national emissions levels have changed over the 20-year period.

Although the most dramatic growth in cattle populations over the period 1984–2004 was posted by smaller countries such as Gabon (up 463% to 35,000 head), Djibouti (249% to 297,000), Egypt (123% to 3.9 million) and Cambodia (108% to three million), the largest absolute increases in national herds were recorded by Brazil (up 64.3 million), China (47.5 million), and the Sudan (17.3 million). In contrast, led by the US (down 18.5 million) and the EU—following reform of the Common Agricultural Policy (Gugele et al. 2002)—herd numbers in many developed economies fell. Thus, by 2004, over three-quarters of the global herd were to be found in the developing world (up from 66%), although the region's contribution to international methane emissions was slightly less due to more widespread reliance upon 'maintenance' feeding regimes. Applying the revised IPCC regional EFs—as opposed to the original CAS estimates—suggests that enteric emissions from cattle were 6.6% higher at 61.3 Tg CH_4 p.a., and accounted for 74% of global enteric CH_4 discharges in 2004.

Water buffalo are primarily found in southern Asia where they are used as both draft and dairy animals. Over half the global buffalo population of 172.7 million presently resides in India (Table 4), with three countries (India, Pakistan and China) accounting for 85%, and ten countries contributing 97% of the global total. The greatest growth in buffalo populations over the last 20 years has occurred in Pakistan (up 99%), Iran (67%—to 560,000), Brazil (49%—to 1.2 million), Egypt (50%), Nepal (41%) and India (33%)—while absolute numbers have fallen in Malaysia, Thailand, and Sri Lanka where agrarian mechanisation has ousted the draft buffalo.[12] While CAS (1986) calculated that a buffalo discharges 50 kg CH_4 of methane annually, and the current recommended IPCC Tier 1 default EF is 55 kg CH_4 per head, Singhal and Madhu Mohini (cited by Sirohi and Michaelowa 2004:19) have suggested EFs are probably a little higher (varying from 56 to 77 kg CH_4 for females, 66 kg CH_4 for working males). As Table 4 shows, buffalo herd growth over the last 20 years has seen a sharp rise in methane discharges (currently 9.5 Tg p.a. if the IPCC recommendation

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[11] Our intent here is to show both the magnitude of the increase in enteric emissions (hence the application of 1984 CAS EFs to 2004 population data) and how changes in the EFs applied can alter—in some cases substantially—computed CH_4 emission levels (computed 2004 emissions under the CAS and IPCC Tier 1 default scenarios). Livestock numbers are taken from the FAOSTAT statistical database maintained by FAO and cover all domestic animals irrespective of their age and the place or purpose of their breeding.

[12] China has seen its buffalo herd grow below trend (18.7%) over the period—while there is a strong expectation that buffalo numbers will decline as industrialisation proceeds apace (Simpson et al. 1994).

of 55 kg per animal is applied), and the contribution of buffalo eructation to the enteric methane budget has increased accordingly—from 8.8% to 10.3%.

Sheep are more widely distributed than buffaloes, 131 countries reporting sheep flocks in 2004. Nine countries, headed by China (157.3 million head), have national flocks of over 25 million animals, these accounting for 52% of the global population. While sheep numbers in the developed economies have fallen 35% over the last 20 years, in large part due to the steep decline in sheep flocks in those countries that were formerly part of the USSR (down 90.7 million head—62%) or under Soviet influence in Eastern Europe, Australia (32%), and New Zealand (43%), flocks in the developing world have grown by 106 million head to 691.8 million (up 18%)—with the biggest percentage increases in China, Sudan, Iran and India (see Table 4). In this instance the IPCC have retained the original CAS EFs—8 kg CH_4 per head in developed countries, 5 kg CH_4 per head in the developing world—as the best defaults available in the absence of local data. Consequently, while there has been a notable aggregate decline (7.2%) in global sheep stocks over the last 20 years and a greater portion of the flock are now located in developing countries, the impact on the global methane budget is slight.[13]

Goat herds are largely concentrated in the developing world (96%) where they provide hides, milk, meat and mohair, having similar energy intakes—and hence enteric profiles—to sheep (which is why CAS/IPCC apply an identical annual EF of 5 kg CH_4 per head). While the sharp increase in the global goat herd (+297 million—up 62%) is, once again, largely attributable to a substantive increase in Chinese (169%), Bangladeshi (154%), Pakistani (91%) and Indian (21%) stocks, many African countries[14] have seen a doubling in their goat herds—aided in part by non-governmental organisations such as Farm Africa (2005), OXFAM (ND) and CAFOD (ND) promoting the acquisition of goats as a means of consolidating food security and livelihoods in the region. While annual CH_4 emissions have risen to 3.9 Tg (Table 4), the contribution of goats to the global methane budget nevertheless remains fairly marginal (4.7%—up from 3.2% in 1984).

Horse herds have also fallen over the intervening 20 years since Lerner and Matthews (1988) completed their study, with the absolute decline in the developing world matching that recorded in the developed (circa two million head). The sharpest declines have been in China (27%)—where the horse has been increasingly supplanted by the petrol motor—in the states which were formerly part of the USSR (down 1.3 million—23%), Poland (one million—64%), and Ethiopia (one million—44%), although growing recreational use has seen numbers rise slightly in North Europe. As methane yields for horses are lower than those for ruminants due to the differential nature of digestive processes, the recommended annual EF is correspondingly lower (18 kg CH_4 per head). Estimated equine emissions of CH_4 in 2004 were therefore of the magnitude of one Tg annually (Table 4). *Camel* herds, almost exclusively located in the developing world, have experienced

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[13] The computed reduction of 0.83 Tg (Table 4) represents around 1% of the 2004 global enteric budget.

[14] These include Nigeria (up to 28 million from 15.9 million), Sudan (14 to 42 million), Tanzania (6.5 to 12.6 million), Malawi (0.7 to 1.7 million) and Ghana (1.6 to 3.6 million).

restrained growth since 1984, increases in the Sahel countries of Mali (115%), Mauritania (66%), Chad (60%) and Niger (29%) due to growing desertification being largely offset by reductions in Chinese (53%), Indian (39%) and Ethiopian (60%) stockholdings (Table 4). As camels are essentially large foraging ruminants, CAS originally proposed an EF of 58 kg CH_4 per capita, although the IPCC subsequently scaled the Tier 1 default EF back to 46 kg CH_4 per head. Camel emissions equated to around 0.87 Tg in 2004, just over 1% of the annual enteric fermentation budget.

Mules and asses are also largely to be found in the developing world, with the largest herds in China (24% of global total). Although Egypt (up 72%) and Pakistan (54%) have posted substantive increases in their national herds over the last 20 years, the trend is, by and large, downwards, with sizeable falls in the Chinese herd (11%) and the sharpest percentage declines recorded in Turkey (64%) and Greece (70%). In contrast, the tractor stock in Greece and Turkey grew by 40% and 75% respectively (FAOSTAT, http://faostat.fao.org/, accessed 13 July 2005) over the same period, and with lightweight manoeuvrable three-wheeled trucks such as the Reliant Ant displacing mules on Greece's mountainous roads (Lockton 2005:6), the demand for draft animals in these two countries has slumped. Applying the 10 kg CH_4 per head figure employed in both the CAS and subsequent IPCC studies suggests current enteric emissions from this group amount to around 0.53 Tg p.a., a figure similar to that reported in the CAS study 20 years earlier (Table 4).

Pigs, as non-ruminants, are much less prone to eructation. Producing an estimated 1.5 kg CH_4 per head annually in the developed world and 1 kg in the developing world, emission rates in China—where half the global herd is currently located—are moving towards the developed country norm as the traditional system of 'backyard' pigs is swiftly giving way to the development of specialised pig-fattening enterprises (Verburg and Denier van der Gon 2001:34). This growing emphasis on the commercial rearing of pigs has seen the Chinese herd expand by 168 million head (up 55%) since 1984 and, with large absolute increases in Vietnamese (11.7 million—100%), Korean (7 million—207%), and Filipino (4.9 million—64%) stocks, the proportion of the global herd resident in the developing world has risen from 56% to 70% during the last 20 years (Table 4). Aggregate enteric emissions, however, remain relatively low—at around 1 Tg per annum.

Although China, as the above analysis shows, has the largest herds in five of the eight categories examined, it is not the major national source of enteric CH_4 emissions (Table 5). This 'honour' falls to India, given the dominance of cattle and buffalo in the ruminant eructation stakes. Similarly, the dramatic expansion of cattle-ranching in the Amazonian basin—80% of the growth in the Brazilian cattle herd over the period 1990–2002 occurred in this region (Kaimovitz et al. 2005; Margulis 2004)—has seen Brazil consolidate its position as the second major enteric emitter of CH_4. Chinese, Sudanese and Australian emissions are less bovine driven—sheep producing 39% of Australian enteric discharges, and goats, pigs and sheep accounting for around one-third of the Chinese and Sudanese totals. Emissions have become more concentrated over time too, the top eight states producing 57.5% of total emissions in 2004, compared to 50% in 1984. More significantly however, while aggregate emissions have grown by just 10.4% to 83.53 Tg over the last 20 years, there has been a pronounced shift in the source of these emissions. Emissions emanating from the developing world are estimated to have increased by 33%

over the period—and now account for almost three-quarters of global enteric CH_4 emissions. Conversely, the estimated contribution of the developed world to the global enteric budget has declined sharply. These trends have important implications in terms of formulating strategies to regulate/restrict enteric emission of this second most important GHG.

4 Methane mitigation strategies

Although a number of enteric methane mitigation strategies exist, following Clemens and Ahlgrimm (2001), such strategies can be broadly divided into preventative and 'end of pipe' options.[15]

Preventative measures reduce carbon/nitrogen inputs into the system of animal husbandry, generally through dietary manipulation and, while a reduction in the volume of CH_4 emitted per animal may result, this is often secondary to the (primary) objective of improved productive efficiency (Ulyatt and Lassey 2000:123; GIA 2008:4). More intensive feeding regimes can have a marked impact on CH_4 emissions (Lerner and Matthews 1988), while carefully tailored feed and forage management practices can equally result in substantive cuts in enteric methane production. van Caeseele (2002), for example, cites research suggesting that high quality forage can reduce per capita emissions by up to 50%; cattle grazing on mixed alfalfa-grass pasture produce lower emissions per head than those grazing on grass-only pastures; and rotational grazing is superior to continuous grazing via-a-vis methane production, Moss (1992) found that augmenting the volume of [rumen resistant] starches in the diet curtailed CH_4 discharges, while Grainger et al. (2008) suggest that whole cottonseed also appears to be a promising dietary supplement in this regard. Equally, improving metabolic efficiency through the enforced ingestion of growth promoting hormones produces comparable reductions in methane releases (Bauman et al. 1985), although the effect may only be temporary as there is evidence to suggest that the rumen ecosystem adapts to the new feed environment.

Alternatively, '*end of pipe*' options reduce—or inhibit—the production of methane (methanogenesis) within the system of animal husbandry. Such options include the application of ionophores, propionate enhancers, methane oxidisers, halogenated methane analogues, defaunating agents, and probiotics as feed additives (Moss et al. 2000:242ff; McAllister and Newbold 2008), although concerns have been expressed that the volumes required to effectively curb emission levels are likely to prove toxic to the animal, interfere materially with digestive processes and/or be uneconomic to apply (Ulyatt and Lassey 2000:124). A different strategy, highlighted by Shu et al. (1999) and Baker (cited by Moss et al. 2000), involves immunising livestock using antimethangenic vaccines, although such research is currently in its infancy.

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[15] It is not our intention to provide a detailed synthesis of mitigation strategies here, simply an overview of the general approaches available. Readers interested in a more in-depth discussion of mitigation strategies should consult Mosier et al. (1998), Boadi et al. (2004), the Clemens and Ahlgrimm (2001) article—which identifies 20 such strategies—and the special issue of the Australian Journal of Experimental Agriculture (2008) which presents a variety of strategies.

Indeed, the problem with many of these preventative and ‘end of pipe’ strategies is that they are relatively novel and, sometimes, difficult to implement in practice. Equally, methods that are found to work on laboratory or pilot scales may be unsuccessful or unsustainable at a farm, regional or national level. In the case of ‘end of pipe’ strategies to manipulate rumen microfauna, for example, techniques that work in vitro may not translate to in vivo success.

Consequently, *herd reduction* is probably the most straightforward strategy to reduce enteric emission levels and three factors have contributed to herd downsizing across the developed world over the last 20 years. First, increased public awareness about links between meat consumption and increasing antibiotic immunity, allergic reactions, cancers, diabetes and reduced fitness levels (Fiddes 1991; Mennell et al. 1992).[16] Second, environmental concerns over the nature of meat production—it takes 7 kg of grain to produce 1 kg of beef (Horrigan et al. 2002:445), for example—have affected the demand for livestock products.[17] Third, periodic food scares, such as the UK BSE crisis—which saw 3.3 million cattle slaughtered and estimated economic losses of around £3.7 billion to the beef industry (Beck et al. 2005:396)—have also impacted upon consumption habits. Consequently, in the US cattle herds have fallen by 18.5 million (16.3%), in France by 5.3 million (19.7%) and by 2.7 million (20.5%) in the UK. Sheep herds are down by 44.7 million (32%) in Australia, 29.7 million (43%) in New Zealand and 5.5 million (47.3%) in the US, while pig herds have dropped by ten million (27.4%) in Germany and 2.7 million (34.5%) in the UK. Unfortunately, these declines have been more than offset by herd growth in the developing countries—goat herds have grown by 64%, pig herds by 49%, and buffalo, cattle and sheep herds by 30%, 23% and 18% respectively. Consequently, global herd figures for five of the top six enteric emitters (the exception is sheep) are currently at an all term high (Tables 3 and 4).

Equally, with enteric emissions also at all time highs (Table 5), the question is begged as to whether there is indeed any political will to control/curb CH_4 emissions emanating from enteric sources?

This paper contends that the likelihood of countries adopting CH_4 mitigating strategies will depend upon both the national stance towards the Kyoto Protocol, and the contribution of enteric emissions to the national methane budget. Developing countries, for example, are not compelled to reduce emissions in line with Kyoto recommendations, and voluntary adherence to the spirit of the Protocol is compromised by two factors. First, the diminution in developed country herds has been supplanted by a surge in meat imports from the developing world[18]—the ‘hamburger connection’ (Myers 1981)—with meat exports becoming a lucrative exchange-earner for a number of developing countries. Brazilian beef exports, for example, increased

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[16] A recent longitudinal study of 478,040 individuals aged 35 to 70 years across ten European countries, for example, found that those who consumed more than 160 g of red or processed meat a day were 35% more likely to develop bowel cancer than those who consumed below 20 g a day (Norat et al. 2005).

[17] Equally, while increased livestock productivity would allow meat/dairy production to be maintained from a smaller herd, this typically calls for an increased use of feed supplements (usually grain-based).

[18] US bovine meat imports (net) rose 122% to 1.35 million metric tonnes (MT) between 1984 and 2004, for example (FAOSTAT).

Table 3 Enteric emissions of CH_4 from cattle, main emitting countries (over 20 million head of cattle in 2004)

	Population (millions)		Percent	Percent of global	Annual CH_4 emissions (Tg)		
	1984	2004	change	population 2004	1984	2004	IPCC2004
Brazil	127.7	192	50.3	14	6.90	10.37	9.6
India	195.2	185.5	(5.0)	14	6.83	6.49	8.6
China	59.0	106.5	80.5	8	2.07	3.73	4.7
USA	113.4	94.9	(16.3)	7	6.58	5.50	5.1
Argentina	54.6	50.8	(7)	4	2.95	2.74	2.5
Sudan	21.0	38.3	82.4	3	0.74	1.34	1.2
Ethiopia	N/A	35.5	N/A	3	N/A	1.24	1.2
Mexico	30.5	30.8	1.0	2	1.07	1.08	1.6
Australia	22.1	26.4	19.5	2	1.19	1.43	1.4
Colombia	23.4	25.3	8.1	2	0.82	0.89	1.3
Russia	N/A	24.8	N/A	2	N/A	1.36	1.6
Bangladesh	21.9	24.5	11.9	2	0.77	0.86	1.1
Pakistan	16.4	23.8	45.1	2	0.57	0.83	1.1
Developing	827.7	1,018.4	23.0	76.3	32.43	39.82	43.76
Developed	426.1	316.1	(25.8)	23.7	23.77	17.67	17.55
Total	1,253.8	1,334.5	6.4		56.2	57.49	61.31

1984 and 2004 Annual CH_4 emissions are calculated using the EF originally applied by CAS in their 1986 paper. The IPCC2004 emissions are calculated using the regional IPCC Tier 1 Default values—and for this reason may differ slightly from the figures shown in national inventory tables. Source: FAOSTAT

five-fold in volume terms (1.2 million MT) and three-fold in value terms (US$1.5 billion) between 1995 and 2003 alone (Kaimovitz et al. 2005:3; Margulis 2004). Second, domestic economic growth allied to positive income elasticities for red and white meats (FAO 2005) produced an enlarged internal market for animal proteins in the developing world. Brazilian per capita meat consumption more than doubled between 1975 and 1997, while Chinese meat consumption exhibited a similar rate of growth during the 1990s (Kaimovitz et al. 2005:3, Horrigan et al. 2002:445). Consequently, there seems little immediate likelihood of a marked reduction in developing country CH_4 emissions—indeed, with Rosegrant et al. (1999:226) calculating that Chinese per capita meat consumption is likely to grow by 8.2% to 60 kg a head by 2020, there is every prospect that enteric emissions originating from the developing world will actually continue to increase.[19]

In the case of developed countries bound by the Kyoto recommendations (the Annex B countries), the willingness to introduce mitigation strategies is likely to be conditioned by the enteric contribution to the national methane budget (Table 6) and the country-specific obligations laid out in the Protocol.

Although enteric emissions account for 40% plus of CH_4 emissions in 11 of the Annex B countries—and as much as 85.5% in the case of New Zealand—total aggregate emissions (if we exclude Liechtenstein, Poland and the Russian Federation which have no comparable data for 1990) have declined by 11.9% since 1990. This decline is principally attributable to sharp reductions in fugitive CH_4 emissions levels

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[19] The exception is likely to be in the case of buffalo, as mechanical power sources continue to replace 'relatively inefficient and time consuming draft animal power' (Sirohi and Michaelowa 2004:32).

Table 4 Population statistics for other animals and associated enteric CH_4 emissions, by major emitting country 2004

	Population (millions)		Percent change	Percent of global population (2004)	Annual CH4 emissions (Tg)	
	1984	2004			1984	IPCC2004
Buffaloes (50 kg CH_4 per head p.a.)						
India	73.4	97.7	33.1	57	3.67	4.89
Pakistan	12.8	25.5	99.2	15	0.64	1.28
China	19.2	22.8	18.8	13	0.96	1.14
Nepal	2.7	3.8	40.7	2	0.14	0.19
Egypt	2.4	3.6	50	2	0.12	0.18
Developing	132.7	172.0	29.6	99.6	6.64	8.6
Developed	0.5	0.7	40	0.4	0.03	0.04
Total	133.2	172.7	29.7		6.67	8.64
Sheep (8 kg in developed/5 kg in developing, CH_4 per head p.a.)						
China	98.9	157.3	59.0	15	0.50	0.79
Australia	139.2	94.5	(32.1)	9	0.70	0.47
India	47.5	62.5	31.6	6	0.24	0.31
Iran	38.0	54.0	42.1	5	0.19	0.27
Sudan	20.0	47.0	135.0	5	0.10	0.24
N. Zealand	69.7	40.0	(42.6)	4	0.56	0.32
Developing	585.1	691.8	18.2	66.6	2.93	3.46
Developed	534.0	347	(35.0)	33.4	3.85	2.49
Total	1,119.1	1,038.8	(7.2)		6.78	5.95
Goats (5 kg CH_4 per head p.a.)						
China	68.2	183.3	168.8	24	0.34	0.92
India	99.4	120.0	20.7	15	0.50	0.60
Pakistan	28.7	54.7	90.6	7	0.14	0.27
Sudan	14.1	42.0	197.9	5	0.07	0.21
Bangladesh	13.6	34.5	153.7	4	0.07	0.17
Developing	455.4	748.0	64.3	95.9	2.28	3.74
Developed	27.2	32.0	18.5	4.1	0.14	0.16
Total	482.6	780.0	61.6		2.42	3.90
Horses (18 kg CH_4 per head p.a.)						
China	10.8	7.9	(26.9)	14	0.19	0.14
Mexico	6.1	6.2	1.6	11	0.11	0.11
Brazil	5.4	5.9	9.3	11	0.10	0.11
USA	5.1	5.3	3.9	10	0.09	0.10
Argentina	3.0	3.6	20.0	7	0.05	0.06
Developing	42.4	40.5	(4.5)	73.2	0.76	0.73
Developed	17.0	14.8	(12.9)	26.8	0.31	0.27
Total	59.4	55.3	(6.9)		1.07	1.00
Camels (58 kg CH_4 per head p.a.)						
Sudan	2.8	3.3	17.9	17	0.16	0.19
Mauritania	0.8	1.3	62.5	7	0.05	0.08
Kenya	0.8	0.8	–	4	0.05	0.05
Pakistan	0.9	0.8	(11.1)	4	0.05	0.05
Chad	0.5	0.7	40.0	4	0.03	0.04
Developing	17.7	18.6	5.1	98.4	1.03	1.08
Developed	0.3	0.3	–	1.6	0.02	0.02
Total	18.0	18.9	5.0		1.05	1.10

Table 4 (continued)

	Population (millions)		Percent change	Percent of global population (2004)	Annual CH4 emissions (Tg)	
	1984	2004			1984	IPCC2004
Mules/asses (10 kg CH_4 per head p.a.)						
China	14.0	12.4	(11.4)	24	0.14	0.12
Mexico	6.3	6.4	1.6	12	0.06	0.06
Pakistan	2.8	4.3	53.6	8	0.03	0.04
Ethiopia	N/A	3.7	N/A	7	N/A	0.04
Egypt	1.8	3.1	72.2	6	0.02	0.03
Developing	51.5	51.2	(0.5)	97	0.52	0.51
Developed	2.3	1.6	(30.4)	3	0.02	0.02
Total	53.8	52.8	(1.9)		0.54	0.53
Pigs (1.5 kg in developed/1 kg in developing, CH_4 per head p.a.)						
China	304.9	472.9	55.1	50	0.31	0.47
USA	56.7	60.3	6.3	6	0.09	0.09
Brazil	32.3	33.0	2.2	3	0.03	0.03
Germany	36.5	26.5	(27.4)	3	0.06	0.04
Spain	12.0	24.0	100.0	3	0.02	0.04
Developing	448.7	666.9	48.6	70.1	0.45	0.67
Developed	339.5	284.9	(16.1)	29.9	0.50	0.43
Total	788.2	951.7	20.7		0.95	1.10

Source: FAOSTAT

in Eastern Europe (c.f. Czech Republic, Estonia and Hungary) and herd downsizing in the agricultural sector of a number of Annex B countries. Nevertheless, in nine countries CH_4emission levels were above Kyoto-adjusted baseline values.[20] In five of these countries (Denmark, Italy, Norway, Portugal, and the US) the difference is marginal (<10%)—and in only one of these (Denmark) does the enteric contribution to the annual budget perhaps merit contemplating livestock-specific methane mitigation strategies.

Irish emissions were 15.4% above the Kyoto-adjusted baseline value, largely occasioned by a substantive increase in landfill emissions (up 47% to 81 Gg) and growth in the cattle (17.1% to seven million) and pig (58.8% to 1.8 million) herds over the 1990–2002 period. Moreover, as enteric emissions are responsible for almost three-quarters of the national CH_4 budget, action on the enteric front is clearly necessary. The Irish response was enunciated in the *National Climate Change Strategy* (NCCS 2000) and more recently via the *Fourth National Communication under the UNFCCC* (UNFCCC-Ireland 2007) and, in the case of CH_4 enteric emissions, will largely be driven by reforms to the EU Common Agricultural Policy (CAP). Changes in the Extensification Premia, Special Beef Premium and Disadvantaged Areas Compensatory Allowance, allied to the introduction of premia for slaughtering cattle

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[20] The Kyoto commitments are based on aggregate CO_2-equivalent emissions, and do not demand identical reductions in the emissions of each of the six GHG. Hence, a country can meet its Kyoto commitments despite registering an increase in CO_2-equivalent emissions of one (or more) of the GHG—providing this increase is offset by reduced CO_2-equivalent emissions of other GHGs. Our paper presumes that countries intent on meeting their Kyoto commitments are likely to seek an across-the board reduction in GHG emissions, *taking especial interest* in those gases whose current emission levels exceed their Kyoto-adjusted 1990 baseline targets.

Table 5 Top ten enteric CH_4 emitting countries—and emissions by source, 2004 (Tg p.a.)

	Cattle	Buffalo	Sheep	Goats	Other animals	Total IPCC 2004	Total 1984
India	8.6	4.89	0.31	0.6	0.08	14.48	11.33
Brazil	9.6	0.06	0.07		0.16	10.33	7.23
China	4.7	1.14	0.79	0.92	0.77	8.32	4.53
USA	5.1	0	0.05	0.01	0.2	5.36	6.85
Argentina	2.5	0	0.06	0.02	0.07	2.65	3.16
Pakistan	1.1	1.28	0.12	0.27	0.10	2.87	1.56
Australia	1.2	0	0.76	0	0	1.96	2.36
Sudan	1.4	0	0.24	0.21	0.19	2.04	1.07
Russia	1.6	0	0.12	0	0.05	1.77	N/A
Ethiopia	1.2	0	0.06	0.05	0.07	1.38	N/A
Total developing	43.76 (32.43)	8.60 (6.63)	3.46 (2.93)	3.74 (2.28)	2.99 (2.75)	62.55	47.02
Total developed	17.55 (23.77)	0.04 (0.03)	2.49 (3.85)	0.16 (0.14)	0.74 (0.86)	20.98	28.65
Total	61.31 (56.2)	8.64 (6.66)	5.95 (6.78)	3.9 (2.42)	3.73 (3.61)	83.53	75.67

Figures given in parentheses in the first five (total) columns are the equivalent figures from 1984. Source: FAOSTAT

Table 6 CH_4 emission sources—annex B countries, 2002 (Gg CH_4)

	Fuel comb.	Fugit. emiss.	Indust. process	Total agric.	(of which—Enteric)	Land use change	Total waste	Nat. total. 2002	Nat total 1990	Reduct. needed	Enteric as % of total
Australia	99	1,129	3	3,672	3,059	205	810	5,918	5,807	Nil	51.7
Austria	15	14	0.39	190	148		135	355	446	Nil	41.7
Belarus	15	122	1.61	312	277	22	136	609	666	Nil	45.5
Belgium	11	20	1.73	325	198	5	72	435	519	Nil	45.5
Bulgaria	3	125	2	95	69		222	446	1,164	Nil	15.5
Canada	252	1,856		1,165	897	136	1,066	4,475	3,500	1,185	20.0
Croatia	5	62	0.26	42	35		54	163	182	Nil	21.5
Czech R.	15	261	3	105	76	3	107	494	798	Nil	15.4
Denmark	29	6		179	133		54	268	259	19.7	49.6
Estonia	5	29		21	18		36	90	208	Nil	20.0
Finland	24	1.36	0.68	84	74		134	244	302	Nil	30.3
France	183	160	2	2,057	1,376	(22)	562	2,941	3,306	Nil	46.8
Germany	55	782	0.1	2,554	1,276		574	3,965	6,743	Nil	32.2
Greece	22	80		172	143	0.38	270	545	428	151.2	26.2
Hungary	33	101	0.76	105	80	0.31	226	466	624	Nil	17.2
Iceland	0.17			12	11		13	25	22	0.8	44.0
Ireland	5	4		519	454		81	609	567	87.4	74.5
Italy	79	246	6	787	526	1.18	516	1,635	1,771	5.7	32.2
Japan	25	28	6	646	319		225	930	1,181	Nil	34.3
Latvia	13	8		32	28	5	50	108	174	Nil	25.9
Liechtenstein								N/A	0.82		
Lithuania	11	20	0.06	67	58		72	169	340	Nil	34.3
Luxembourg	0.78	3		16	15		3	22	24	Nil	68.2
Monaco	0.04							0.04	0.03	Nil	

Table 6 (continued)

	Fuel comb.	Fugit. emiss.	Indust. process	Total agric.	(of which—Enteric)	Land use change	Total waste	Nat. total. 2002	Nat total 1990	Reduct. needed	Enteric as % of total
Netherlands	32	120	2	389	306	1.81	346	891	1,302	Nil	34.3
New Zealand	11	36	5	1,150	1,123	4	106	1,313	1,218	Nil	85.5
Norway	14	31	1.5	95	80		185	327	307	17	24.5
Poland								N/A	3,141		
Portugal	24	14	0.58	198	120	17	144	398	402	28.2	30.2
Rumania	31	522	0.91	334	248	0.49	270	1,158	2,464	Nil	21.4
Russian Fed.								N/A	26,190		
Slovakia	6	62		59	49	0.66	92	220	310	Nil	22.3
Slovenia	4	13	0.24	41	33		51	109	121	Nil	30.2
Spain	47	104	3	1,129	701		676	1,959	1,440	634.2	35.8
Sweden	27		0.33	157	136		86	271	317	Nil	50.2
Switzerland	5	12	0.45	136	117		49	203	238	Nil	57.6
Ukraine	42	6,424	94	896	667		1,359	8,815	9,402	Nil	7.6
United Kingdom	98	634	3	905	806	1.13	457	2,098	3,362	Nil	38.4
USA	529	9,588	120	7,688	5,450		10,557	28,482	30,603	21.2	19.1
Total	1,768	22,617	259	26,336	19,104	380.81	19,797	71,158	110,146		26.8

The *Reduction needed* (penultimate column) indicates the extent to which 2002 emissions exceed 1990 (as amended by Kyoto) CH_4 emission levels. In the case of Spain, for example, Kyoto demands an 8% reduction in GHG emissions by the First Commitment Period 2008–2012. The Kyoto-adjusted methane baseline is therefore 92% of 1,440 Gg [1990 emissions level], or 1,324.8 Gm. Currently Spanish emissions (1,959 Gm) are 634.2 Gm above this. Nil signifies current emission levels are below the 1990 Kyoto-amended baseline level. Source: http://ghg.unfccc.int/tblxy.htm?fv1=cntr\&fv2=src\&time=03{%}253A45{%}253A43{%}2BPM

at an earlier age, will all help reduce stocking densities (NCCS 2001:20) and this, combined with the development of Ireland-specific feeding regimes (NCCS 2000; Drennan 2002), is projected to see enteric emissions drop 11% between 2003 and 2012 (UNFCCC-Ireland 2007:60).

Although *Greek* emissions were even further above the Kyoto-adjusted 1990 baseline value (+27.7%) than Ireland's, the volume of enteric emissions (and their contribution to the national methane budget) is lower. Equally, there are fewer references in the Greek 188 page *Fourth National Communication to the UNFCC* (UNFCCC-Greece 2007:117) beyond recognising that projected changes in herd/flock sizes (sheep account for 50% of Greek enteric emissions) will cause enteric emissions to rise by 3% over their 1990 baseline values by 2020, while the Hellenic Ministry for the Environment, Physical Planning and Public Works web-site (http://www.minenv.gr/frame.html?2\&1\&2\&/4/41/e4100.html, accessed 20 January 2006) makes no reference to any national mitigation plans/strategies. Much the same applies in *Spain*. Here CH_4 emissions were 32.4% above the Kyoto-adjusted baseline, with enteric emissions contributing around one-third of the national total. However, although Spain's *Third National Communication* does acknowledge that reducing emissions is intrinsically related to herd reduction (UNFCCC-Spain 2007, p.7) and changes in dietary feeding regimes (p.78), it admits that a lack of knowledge regarding the extent to which such dietary regimes have presently been taken up prevents any meaningful comment upon enteric emission trends. Equally, while the Ministry of Agriculture, Food and Fisheries (MAPA 2008) web-site recognises that enteric emissions of methane 'contaminate' the atmosphere—and provides a chart to enable livestock owners to compute their aggregate emissions levels—the site remains silent on remedial strategies.

Canada has seen the greatest absolute increase in methane emissions since 1990 (1,185 Gg, 26.4% above the Kyoto-adjusted baseline)—a consequence of sustained growth in enteric, fuel combustion and landfill emissions over the 1990–2002 period—and has also been the most active in developing policy responses. *Action Plan 2000* (Government of Canada 2000) and the *2002 Climate Change Plan for Canada* (Government of Canada 2002) were followed by the *2005 Moving Forward on Climate Change* (Government of Canada 2005, which propounded C$10 billion of strategies designed to reduce GHG CO_2-equivalent emissions by around 270 Mt p.a. over the 2008–2012 First Commitment Period) and the 2008 *Turning the Corner: Taking Action to Fight Climate Change* (Government of Canada 2008; which put in place one of the 'toughest regulatory regimes' in the world to cut GHG emissions) documents. Although the documents make little reference to enteric emissions and their reduction, the *2007–2009 Sustainable Development Strategy: Making Progress Together* (Government of Canada 2006) acknowledges that improved management practices can reduce methane emissions (although provides no details of measures).

Elsewhere, mitigation strategies have been most to the fore in the rest of Europe—although herd downsizing occasioned by CAP reform has been more a consequence of EU cost-cutting considerations than a determined attempt to reduce enteric emissions—and Australasia where enteric emissions account for a substantive element of the annual CH_4 budget in both New Zealand and Australia. In New Zealand, NZ$16 million has been invested through the Pastoral Greenhouse Gas Research Consortium (PGGRC) since 2002 in research intent on reducing national agricultural GHG emissions by 20% by 2012 (Leslie et al. 2008; NZIER 2005:24). Australia has experimented with vaccines to inhibit methane production in the rumen (although initial results were not overly encouraging) and has instituted emission-reducing grazing management tools and established the propensity of certain feed additives to reduce livestock methane emissions (AGO 2002:26; Wright et al. 2004). These developments notwithstanding however, the decline in enteric emissions in both countries over the last decade is more explicable to herd downsizing as a consequence of drought and the reduced profitability of sheep farming than any overt CH_4 mitigation strategy.

5 Conclusion

Ruminant eructation is an important contributor to anthropogenic CH_4 emissions—the average New Zealand dairy cow produces around 80 kg of methane p.a., a herd of 200 cows producing annual emissions equivalent (in energy terms) to 21,400 l of gasoline, enough to propel a conventional family car 180,000 km (NZCCP 2002:4). Yet, to date, the GHG discourse has been dominated by debate about the most prolific of the GHG—CO_2—and methane and enteric emissions have only belatedly begun to receive the due attention they deserve in the literature. This oversight is particularly pertinent as ongoing research by NASA's Goddard Institute for Space Studies (amongst others) suggests that methane emissions may in fact be responsible for one-third of all global warming over the last 250 years, the real contribution of methane to climate change being double the amount previously reported by the IPCC.[21] If this is so, "control of methane emissions turns out to be a more powerful lever to control global warming than would be anticipated (Shindell et al. 2005)".

Our paper seeks to contribute to a widening of the GHG debate by reviewing contemporary enteric emission patterns and the mitigation strategies that exist—and have presently been applied—to curb such discharges. In particular, we trace how the global enteric emissions profile has evolved since the pioneering work of CAS and Lerner and Matthews during the early 1980s. Although India and Brazil remain the top enteric emitting countries, the dramatic expansion of livestock herds across much of the rest of the developing world has reduced the developed world's share of enteric CH_4 discharges to barely one-quarter of the global total (Table 5). However, the national methane budgets of some developed countries—most notably New Zealand, Ireland, Luxembourg, Switzerland, Australia and Sweden (Table 6)—are still dominated by enteric emissions.

Yet, while this importance/dominance has precipitated scientific research oriented to more precisely quantifying enteric emissions at the national level (c.f. Singhal et al. 2005—case of India, and CCFIA (2005) in Canada) and/or reducing CH_4 emission levels by inhibiting methanogenesis in the gut (c.f. Moss et al. 2000; McAllister and Newbold 2008) or through changes/improvements in dietary regime (van Caeseele 2002; Grainger et al. 2008), national implementation of (enteric) methane mitigating strategies has lagged and potentials remain 'uncertain' (Smith

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[21] The Second IPCC (1996) Assessment originally estimated methane's 100 year global warming potential (GWP) at 21 kg (CO_2)/kg (CH_4)—the accepted value at the time the Kyoto Protocol was formulated, but was subsequently revised to 23 kg (CO_2)/kg (CH_4) in the Third IPCC (2001) Assessment and thence 25 kg (CO_2)/kg (CH_4) in the Fourth IPCC (2007) Assessment.

et al. 2007:531). This is perhaps attributable to the fact that research relating to climate change in the agricultural field is not only a relatively new area of study (CCFIA 2005:i), but also because national obligations to curb GHG (including CH_4 emissions) are in part conditioned by the terms of the Kyoto Protocol. As developing countries are currently exempted from the emission limitation or reduction commitments laid down in the Protocol, there is presently little incentive for such countries to sacrifice foreign exchange earnings and/or enhanced domestic per capita consumption of meat by herd downsizing.

While others (the Annex B countries) are obliged to conform to the emission limitations laid out in the Protocol, only nine of these countries exceeded CH_4 target emissions levels—and in the case of five the overshoot was marginal (Table 6). Hence, the stimulus to pursue enteric methane mitigating strategies in order to comply with Kyoto commitments is presently weak. Moreover, even if the Protocol were to be extended to include the developing countries—as George Bush has frequently re-iterated (c.f. CNN 2005, 1 July)—and tightened in the light of emerging evidence on the real contribution of CH_4 to climate change (Shindell et al. 2005), the most likely mitigation strategy will be herd down-sizing,[22] a strategy that raises two further considerations. *First*, if policy leads to a reduction in the global pool of animals (principally water buffalo, asses/mules and other animals to a lesser extent) providing draught power, the alternative power source is likely to be oil-based, with a concomitant rise in CO_2 emissions. *Second*, while consumption-switching away from a ruminant-rich diet will lead to reduced enteric emission levels, it could not only prove disastrous for already overfished aquatic populations (Thorpe and Bennett 2001: FAO 2004—particularly if consumers respond to the advice of the Norat et al. study cited earlier), but also lead to enhanced anthropogenic CH_4 wetland emissions. If India and China, two of the top three emitting nations—accounting for over one-quarter of global enteric emissions—shifted away from ruminant consumption to a pulse-based diet, the chief regional pulse produced is rice, the global production of which is estimated to potentially release as much CH_4 into the atmosphere annually (88–100 Tg—Table 2) as enteric fermentation does. The control of agrarian methane emissions, like the supposed proposal to 'charge a tax on flatulence released by livestock' in New Zealand, may then be rather more difficult to accomplish than it at first appears.

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[22] Milich (1999:195), for example, notes that improved feeds are not an option - while methane inhibition strategies are costly and offer no discernible payback in productivity terms – for much of the developing world.

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