Vol. 34: 253–258, 2007
doi: 10.3354/cr00634

CLIMATE RESEARCH
Clim Res

Published September 18

Historical emissions, by country, of N_2O from animal manure management and of CH_4 from enteric fermentation in domestic livestock

Maria Silvia Muylaert de Araujo*, Christiano Pires de Campos, Luiz Pinguelli Rosa

International Virtual Institute of Global Change and Energy Planning Program of the Coordination of Post-Graduation Programs in Engineering of the Federal University of Rio de Janeiro (COPPE/UFRJ), Cidade Universitária, Ilha do Fundão, Centro de Tecnologia, Bloco I, Sala 129, CEP:21.945-970, Rio de Janeiro – RJ, Brazil

ABSTRACT: Human activities have always led to the emission of greenhouse gases; atmospheric concentrations have been increasing during the last century; and present-day climate change is a result of past emissions. This paper presents historical emissions (1890–1998) by country due to CH_4 enteric fermentation and N_2O animal manure management from domestic livestock (excluding animals grazing). Two indicators are compared: cumulative emissions and concentrations. Further research is necessary to improve the inventory of N_2O and CH_4 emissions and concentrations, by using other country-level historical datasets and emission factors. Inventories were taken from historical databases of emissions from domestic livestock, including cattle, buffalos, pigs, sheep, goats, horses, mules and asses. Emission factors for each animal and gas in each country were based on Intergovernmental Panel on Climate Change methodologies. Developed countries and countries with large populations of domestic animals are responsible for most N_2O and CH_4 emissions. In addition, emissions depend on animal sizes, and on quantity and quality of the feed.

KEY WORDS: Greenhouse gas inventories · Historical emissions · Methane · Nitrous oxide · Climate change

1. INTRODUCTION

Historical CO_2 emissions and concentrations, mainly from the energy sector (Rosa & Ribeiro 2001) and changes in land use (Rosa et al. 2004), are quite well understood, sometimes at the country level (de Campos et al. 2005). The historical methane (CH_4) and nitrous-oxide (N_2O) emissions due to human activities are not well inventoried by country. CH_4 emissions due to enteric fermentation of cattle, buffalos, pigs, sheep, goats, horses, mules and asses by country and N_2O emissions due to animal manure management (N_2O emissions from grazing animals are not included in the present analysis) of the above domestic livestock from 1890–1998 have been estimated in this study. The level of emission is calculated using a simple formula: the emission factor (EF) per animal × their population. The specific country populations of domestic livestock were obtained from the history database of the global environment (HYDE 2003). Calculation of the EFs was based on data of the Intergovernmental Panel on Climate Change (IPCC 1996). It should be mentioned that other methodologies have been developed (Stern & Kaufmann 1998). The latter authors estimated the CH_4 emissions from livestock farming for each year as a function of human population, assuming that per capita emissions declined linearly over time. A comparison among different methodologies will be the subject of further research.

Inventories of worldwide historical greenhouse-gas (GHG) emissions are important in evaluating countries' contributions to the present atmospheric con-

*Email: muylaert@ppe.ufrj.br

centrations, in calibrating model decay times of the gases and in analyzing the different development patterns by region over time (Muylaert et al. 2005). Several climate-policy proposals are currently being discussed in regard to burden-sharing; these proposals use different indicators of climate change, such as temperature increase and GHG concentrations (see den Elzen et al. 2005). The choice of one indicator or another has implications in political decision-making both for the debate about burden-sharing among nations or sectors and for the issue of GHG-emissions mitigation. Table 1 shows the concentrations of CH_4 and N_2O before the Industrial Revolution and in 1998.

2. METHODOLOGY

2.1. Methane

Ruminants are one of the most important sources of anthropogenic CH_4 emission. CH_4 is produced naturally in their digestive systems, and this process is called enteric fermentation. 'Methane is produced in herbivores as a by-product of enteric fermentation, a digestive process by which carbohydrates are broken down by micro-organisms into simple molecules for absorption into the bloodstream. Both ruminant animals (e.g. cattle, sheep) and some non-ruminant animals (e.g. pigs, horses) produce CH_4, although ruminants are the largest source since they are able to digest cellulose, a type of carbohydrate, due to the presence of specific microorganisms in their digestive tracts. The amount of CH_4 that is released depends on the type, age, and weight of the animal, the quality and quantity of the feed, and the energy expenditure of the animal' (IPCC 1996). The higher the feed intake, the higher the CH_4 emission. In many, if not most, cattle-management systems, the principal driving factors that affect feed intake are: weight, milk production and feed digestibility.

In the 1990s ruminants were responsible for about 28% of all CH_4 anthropogenic emissions (TAR-WGI 2001). According to Yamaji et al. (2004), the emissions factors for Asia are quite similar to the IPCC (1996) estimates in terms of magnitude.

Table 1. N_2O and CH_4 concentrations before the Industrial Revolution (IR) and in 1998. Source: Muylaert et al. (2005), based on data from IPCC (2001, Table 6.7)

	Before IR (ppb)	In 1998 (ppb)	Lifetime in the atmosphere (yr)
N_2O	~270	314	114
CH_4	~700	1745	12

We calculated the CH_4 emissions due to enteric fermentation of cattle, buffalos, pigs, sheep, goats, horses, and mules, using the HYDE (2003) domestic-livestock population by country since 1890, according to the inventory methodology from the IPCC (1996):

$$E_{CH_4}\ (\text{Gg yr}^{-1}) = f_{CH_4}\ (\text{kg ind.}^{-1}\ \text{yr}^{-1}) \times P \times 10^{-6}\ (\text{kg Gg}^{-1})$$

where E_{CH_4} = emissions, f_{CH_4} = EF and P = population and Gg = Gigagram.

The quantity produced depends on the animal and region of the world, as explained above. The most important ruminants in terms of CH_4 emissions ind.$^{-1}$ are buffalo, as shown in Table 2, and cattle as shown in Table 3. The reference value adopted was the EF per animal, according to the IPCC (1996). It is estimated that there is an uncertainty of 20% in these values.

In the case of cattle, the average including both dairy and non-dairy cattle was used, since the HYDE cattle-population database does not discriminate between these categories. The dairy-cattle emissions are much higher in developed than developing countries because of the higher productivity in the former countries (Table 3).

2.2. Nitrous oxide

N_2O is formed when manure nitrogen is nitrified or denitrified, and depends on the system and duration of waste management. The proportion of total nitrogen intake that is partitioned between urine and faeces in

Table 2. CH_4 emission factors by animal (kg ind.$^{-1}$ yr^{-1}) for developed and developing countries. Data from IPCC (1996), Reference Manual (Table 4-3, p. 4.10)

Type	Developed	Developing
Buffalo	55	55
Sheep	8	5
Goat	5	5
Horse	18	18
Mule and ass	10	10
Pig	1.5	1.0

Table 3. Cattle CH_4 emission factor (kg ind.$^{-1}$ yr^{-1}) by selected regions of the world. Data from IPCC (1996), Reference Manual (Table 4-4, p. 4.11)

Region	Emission factor		
	Dairy	Non-dairy	Mean
North America	118	47	82.5
Western Europe	100	48	74
Eastern Europe	81	56	68.5
Oceania	68	53	60.5
Latin America	57	49	53
Asia	56	44	50
Africa and Mideast	36	32	34
Indian subcontinent	46	25	35.5

excretion is dependent on the type of animal, the intake of dry matter and the nitrogen concentration of the diet. In general, about 80 to 95% of the total nitrogen taken in is excreted. In animal-production systems, where animal intake of nitrogen is high, more than half of the nitrogen is excreted as urine (IPCC 1996). In 1998 the N_2O emissions due to animal manure management were responsible for 26% of the total anthropogenic emissions of N_2O (Mosier et al. 1998, Olivier et al. 1998, Kroeze et al. 1999).

We calculated the N_2O emissions due to animal manure management (excluding animals grazing) of domestic livestock using the HYDE (2003) domestic-livestock population by country, and the inventory methodologies of the IPCC (1996). The IPCC estimates EF for pigs, sheep and cattle, and we calculated their N_2O emissions based on these estimates. The formula used was:

$$N_2O = n \times EF$$

where N_2O = N_2O emission from the animals (kg N yr^{-1}), n = number of animals and EF = N_2O EF (kg N_2O-N $animal^{-1}$).

The EF is a function of the nitrogen excretion of the animal (IPCC 1996, Table 4.20, p. 4.119–4.121) and the waste-management system in the region (IPCC 1996, Table 4-21, p. 4.101–4.103). The N_2O EF of dairy and non-dairy cattle combined were estimated by averaging. We have used the default values of the IPCC (1996) to calculate the EF, and it is summarized in Table 4.

Table 4. N_2O emission factor (EF) by animal (g $ind.^{-1}$ yr^{-1}) in selected regions of the world. Based on IPCC 1996, Reference Manual (Tables 4.20 & 4.21)

Region	Cattle	Sheep	Pig
North America	952	296	93
Western Europe	596	367	107
Eastern Europe	839	255	159
Oceania	1400	400	86
Latin America	656	240	196
Africa	902	241	299
Near East and Mediterranean	948	240	223
Asia and Far East	319	209	176

3. RESULTS

The complete database of CH_4 emissions per country is very large, including around 200 countries, 108 yr and 8 types of domestic livestock. Table 5 presents

Table 5. Cumulative CH_4 emissions (Gg) due to enteric fermentation by animal and by country from 1890–1998, representing 80% of world total (selected)

Country	Cattle	Buffalo	Sheep	Goats	Horses	Mules	Pigs	Asses	Total	%
USA	1 070 719	0	27 084	1 289	21 086	43	10 390	12	1 130 622	15.1
India	758 899	284 579	19 835	30 296	1 890	52	547	1 323	1 097 421	14.7
Brazil	361 582	1 600	7 397	2 796	8 367	1 151	1 986	905	385 784	5.2
China	217 165	60 241	26 116	22 394	11 613	2 207	13 123	6 312	359 171	4.8
Russian Fed.	267 555	127	34 223	1 709	15 878	0	2 614	23	322 130	4.3
Argentina	245 946	0	21 936	1 464	12 994	202	344	253	283 139	3.8
Australia	129 892	0	101 495	49	2 384	0	244	5	234 068	3.1
Germany	199 520	0	4 482	1 155	5 209	0	3 353	0	213 719	2.9
France	182 713	0	10 479	684	3 610	16	1 317	20	198 838	2.7
Pakistan	77 454	45 372	5 648	6 762	589	25	0	1 125	136 975	1.8
UK	108 725	0	23 845	0	336	0	818	0	133 723	1.8
Ukraine	116 118	0	4 751	327	4 405	0	1 328	20	126 950	1.7
Canada	113773	0	880	7	3 187	2	1 361	0	119 211	1.6
Bangladesh	106 843	2 740	306	4 796	0	0	0	0	114 684	1.5
Italy	81 361	225	8 304	748	1 223	80	765	566	93 272	1.2
Mexico	75 521	0	2 410	3 447	5 860	1 349	657	2 233	91 477	1.2
Poland	75 321	0	2 341	0	5 347	0	1 610	0	84 620	1.1
Colombia	77 247	0	803	362	1 979	305	159	332	81 186	1.1
Kazakhstan	44 571	66	22 331	393	10 214	0	205	47	77 827	1.0
Ethiopia	57 615	0	9 748	4 607	2 679	251	1	2 348	77 249	1.0
Turkey	40 569	4 897	18 875	7 336	2 124	123	1	1 259	75 185	1.0
Uruguay	57 819	0	9 383	7	1 004	2	32	1	68 248	0.9
New Zealand	32 960	0	33 289	58	406	0	74	0	66 788	0.9
Spain	39 950	0	20 798	1 679	988	250	1 095	172	64 933	0.9
South Africa	38 482	0	16 341	3 422	1 130	36	120	457	59 988	0.8
Ireland	50 306	0	2 475	0	698	1	163	23	53 665	0.7
Indonesia	31 216	13 915	1 574	3 310	1 093	0	242	0	51 350	0.7
Romania	37 030	1 136	9 315	282	2 035	0	761	23	50 581	0.7
Sudan	37 387	0	5 521	4 441	42	0	0	360	47 751	0.6
Total selected (80%)	4 734 259	414 898	451 985	103 819	128 369	6 095	43 309	17 818	5 900 554	78.8
Total world	5 832 410	507 834	683 913	169 612	197 117	7 609	59 498	29 599	7 487 593	100

Table 6. CH_4 concentrations (Gg) due to enteric fermentation from all selected animals by country from 1890–1998, representing 80 % of world total

Rank	Country	CH_4	%
1	India	168 940	14.3
2	USA	150 991	12.8
3	Brazil	95 789	8.1
4	China	82 862	7.0
5	Russian Fed.	52 604	4.4
6	Argentina	38 840	3.3
7	Australia	33 561	2.8
8	France	27 102	2.3
9	Pakistan	25 620	2.2
10	Germany	22 959	1.9
11	Mexico	22 244	1.9
12	Ukraine	21 466	1.8
13	UK	18 312	1.5
14	Bangladesh	17 493	1.5
15	Canada	17 28	1.5
16	Colombia	17 210	1.5
17	Ethiopia	15 130	1.3
18	Sudan	12 652	1.1
19	New Zealand	12 106	1.0
20	Kazakhstan	11 323	1.0
21	Italy	11 128	0.9
22	Poland	10 002	0.8
23	Indonesia	9 626	0.8
24	Turkey	9 281	0.8
25	Venezuela	8 767	0.7
26	Spain	8 523	0.7
27	Uruguay	8 188	0.7
28	South Africa	7 901	0.7
29	Nigeria	7 869	0.7
Total selected		945 778	79.9
Total world		1 183 095	100

the cumulative emission (simple sum of emissions of each year of the period) from 1890–1998 by country, and accounts for 80% of worldwide emissions (29 countries).

Cumulative emission is not the only way to express the present CH_4 and N_2O contribution. We present the contribution to the atmospheric CH_4 concentration (Rosa & Ribeiro 2001) in 1998, taking into account a 12 yr exponential decay time (IPCC 2001). CH_4 world cumulative emissions due to enteric fermentation in 1890–1998 were 7.5 million Gg (Table 5) and world concentration due to enteric fermentation in 1998 was 1.2 million Gg (Table 6). N_2O world cumulative emission due to animal manure management in 1890–1998 were 91 000 Gg (Table 7) and world concentration due to animal manure management in 1998 was 63 000 Gg (Table 8).

In order to properly assess each country's responsibility (Muylaert et al. 2004), from Table 6 it can be seen that it is important to estimate the contribution to the atmospheric CH_4 concentration and not just to account for cumulative emissions. The results can be quite different. Ireland and Romania are among the top 29 countries with regard to enteric fermentation cumulative CH_4 emissions in 1890–1998 and but not among the 29 largest contributors to atmospheric CH_4 concentration in 1998. Nigeria and Venezuela are among the top 29 countries with regard to enteric fermentation CH_4 concentration in 1998 but are not among the top 29 largest countries in regard to cumulative emissions for 1890–1998. The relative positions in the top 5 countries also change for the 2 indicators: India is first for concentration, and USA is first for cumulative emissions. This can be understood by considering the different emissions profiles from one country to another over time. A country which had very high emissions in the past can have high cumulative emissions but a lower contribution to the atmospheric concentration than another country with low emissions in the past and high emissions nearer to present.

Table 7 presents the N_2O cumulative emissions for 1890–1998 of the 32 countries which account for 80% of the total worldwide emissions.

However, cumulative emissions are not useful for expressing the present N_2O contribution, as its expo-

Table 7. N_2O cumulative emissions (Gg) from animal manure management 1890–1998, representing 80 % of world total

Rank	Country	Sheep	Pig	Cattle	Total	%
1	USA	1002	644	8639	10285	11
2	Australia	5075	14	2674	7763	9
3	India	831	96	5263	6190	7
4	Brazil	355	390	4164	4909	5
5	China	672	2097	1870	4638	5
6	Russian Fed.	1092	277	2772	4141	5
7	Argentina	1053	68	2832	3953	4
8	New Zealand	1664	4	679	2347	3
9	Turkey	906	0	1068	1974	2
10	Ethiopia	451	0	1461	1912	2
11	UK	1094	59	647	1800	2
12	South Africa	768	26	992	1786	2
13	France	481	94	1088	1663	2
14	Germany	206	240	1188	1634	2
15	Ukraine	152	141	1203	1495	2
16	Spain	954	78	238	1270	1
17	Sudan	255	0	947	1202	1
18	Kazakhstan	712	22	462	1196	1
19	Iran	756	1	393	1149	1
20	Uruguay	450	6	666	1122	1
21	Mexico	116	129	870	1114	1
22	Canada	33	84	918	1035	1
23	Poland	75	170	780	1026	1
24	Colombia	39	31	890	959	1
25	Italy	381	55	485	920	1
26	Romania	297	81	384	761	1
27	Tanzania	66	3	684	753	1
28	Madagascar	9	13	673	695	1
29	Pakistan	121	0	556	678	1
30	Kenya	92	1	571	665	1
31	Nigeria	74	21	567	662	1
32	Bangladesh	5	0	616	621	1
Total selected		20235	4845	47240	72319	80
Total world		24227	7572	58919	90718	100

Table 8. N_2O concentrations (Gg) due to animal manure management emission by country from 1890–1998, representing 80% of world total (selected)

Rank	Country	1998	%
1	USA	6860	11
2	Australia	5302	8
3	India	4220	7
4	Brazil	3699	6
5	China	3618	6
6	Russian Fed.	2947	5
7	Argentina	2653	4
8	New Zealand	1696	3
9	Ethiopia	1400	2
10	Turkey	1325	2
11	South Africa	1219	2
12	UK	1198	2
13	France	1095	2
14	Ukraine	1077	2
15	Germany	1051	2
16	Sudan	908	1
17	Mexico	870	1
18	Kazakhstan	834	1
19	Spain	807	1
20	Iran	805	1
21	Uruguay	742	1
22	Colombia	721	1
23	Canada	706	1
24	Poland	697	1
25	Italy	607	1
26	Tanzania	551	1
27	Romania	527	1
28	Nigeria	521	1
29	Kenya	502	1
30	Madagascar	486	1
31	Pakistan	481	1
32	Bangladesh	429	1
33	Peru	365	1
4	Japan	340	1
Total selected		51254	81
Total world		63499	100

nential decay time is about 114 yr (IPCC 2001). Table 8 presents the contributions to the atmospheric N_2O concentration in 1998 (taking into account the decay time); the 34 countries that account for 80% of the worldwide concentration are included.

In an analysis of each country's responsibility, Tables 7 & 8 show that the results as a whole are not very different. USA, Australia, India, Brazil, China, the Russian Federation, Argentina and New Zealand are the top 8 countries for both cumulative emissions and concentrations; the ranks are almost the same for both indicators. The proportion of cattle N_2O emissions is high in the majority of the countries (Table 7), except for Australia, New Zealand, the UK and Spain. Cattle has a much higher EF than sheep and pigs in all regions, but with great variability: in North America and Oceania the EF for cattle is >3 times higher than for sheep, whereas in Asia the EF for cattle is only 60% higher than for sheep.

4. CONCLUSIONS AND RECOMMENDATIONS

CH_4 emissions due to enteric fermentation and N_2O emissions due to manure management were given for both developed and developing countries. The historical-emissions inventory is important in estimating accurately the contribution of anthropogenic emissions by country (Figs. 1 & 2); in analyzing the different development patterns by region over time; and in refining the calibration of the decaytime models of the gases.

In Tables 5 & 7 it can be seen that cattle represent the most important type of animal in terms of CH_4 enteric fermentation emissions and N_2O manure management emissions. Cattle should be estimated separately for dairy and non-dairy per country, as their EFs vary a lot. The present work did not separate the diary and non-diary data, because the animal population data for all countries are not available in such categories.

Developed countries and the countries with bigger population are the larger emitters of both N_2O from manure management and CH_4 from enteric fermentation related to domestic livestock. Beyond the

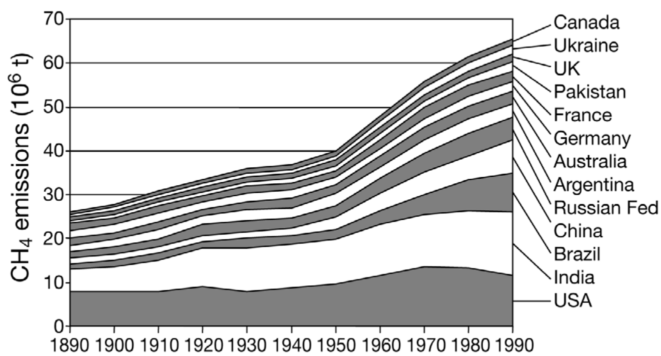

Fig. 1. CH_4 historical emissions due to enteric fermentation in the top 13 countries

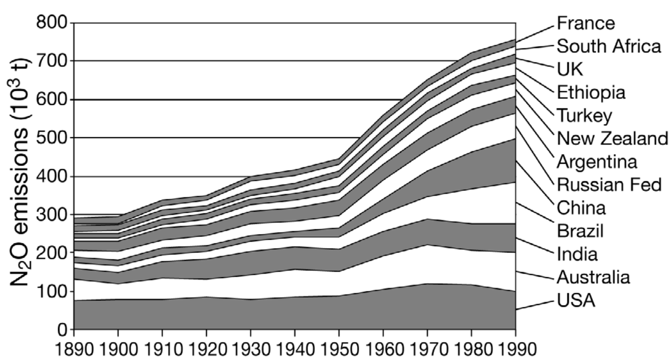

Fig. 2. N_2O historical emissions due to manure management in the top 13 countries

animals' population sizes, the results can be explained by the higher CH_4 and N_2O emissions factors for some types of animals in developed countries, mainly cattle. Since feed intake is positively related to animal size, growth rate and production (e.g. milk production, wool growth or pregnancy), CH_4 emissions due to enteric fermentation are much higher than for developing countries. The same can be concluded for N_2O from manure management, since it is proportional to the intake of dry matter and the nitrogen content of the diet.

EFs related to each period of time were not taken into account, meaning that from 1890 to 1998 they were considered constant for each country and each animal. The present work considered emissions factors to be constant over time (1890–1998), due to the absence of past references on this topic. However, it is recognized that EF by animal have changed during the evolution of technologies and management practices, as stated by Yamaji et al. (2004).

Another important issue to be addressed is that cumulative emissions are not the best indicator of climate-change contributions, due to the decay time of the gases. The concentration is considered to be a better indicator, as it is a better expression of the reality. In terms of responsibility, it was shown that concentrations compared with cumulative emissions present different rankings among the countries, but the difference is not too relevant.

Although it does not matter for the atmosphere which sector emits a ton of Carbon Equivalent, it can be associated with different consumption patterns. CH_4 enteric fermentation emissions and N_2O manure management emissions result from important economic, socio-cultural and religious activities, which involve much greater subjectivity and efforts to reduce emissions than the energy sector, for example.

Acknowledgements. The authors thank the Minister of Science and Technology, ELETROBRÁS Environment Department, K. K. Goldewijk from RIVM, and A. S. Oliveira, L. da S. Ribeiro, L. C. Monteiro and R. M. Henriques from IVIG.

Editorial responsibility: Nils Chr. Stenseth, Oslo, Norway

LITERATURE CITED

de Campos CP, Muylaert MS, Rosa LP (2005) Historical CO_2 emission and concentrations due to land use change of croplands and pastures by country. Sci Total Environ 346:149–155

den Elzen M, Fuglestvedt J, Höhne N, Trudinger C and 5 others (2005) Analysis countries' contribution to climate change. Environ Sci Policy 8:614–636

HYDE (2003) History database of the global environment. www.mnp.nl/hyde/

IPCC (1996) Revised guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Vol 3. Available at www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

IPCC (2001) Climate change 2001: Working Group I: the scientific basis. Intergovernmental Panel on Climate Change. Available at www.grida.no/climate/ipcc_tar/wg1/index.htm

Kroeze C, Mozier A, Bouwman L (1999) Closing the N_2O budget: a retrospective analysis. Global Biogeochem Cycles 13:1–8

Mosier A, Kroeze C, Nevison C, Oenema O, Seitzinger S,van Cleemput O (1998) Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle – OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology. Nutr Cycling Agroecosyst 52:225–248

Muylaert MS, Cohen C, Rosa LP, Pereira AS (2004) Equity, responsibility and climate change. Clim Res 28:89–92

Muylaert MS, de Campos CP, Rosa LP (2007) GHG historical contribution by sectors, sustainable development and equity. Renew Sustain Energ Rev 11:988–997

Olivier JGJ, Bouwman AF, van der Hoek KW, Berdowski JJM (1998) Global air emission inventories for anthropogenic sources of NO_x, NH_3 and N_2O in 1990. Environ Pollut 102: 135–148

Rosa LP, Ribeiro SK (2001) The present, past, and future contributions to global warming of CO_2 emissions from fuels. Clim Change 48:289–308

Rosa LP, Ribeiro SK, Muylaert MS, de Campos CP (2004) Comments on the Brazilian proposal and contributions to global temperature increase with different climate responses – CO_2 emissions due to fossil fuels, CO_2 emissions due to land use change. Energy Policy 32:1499–1510

Stern DI, Kaufmann RK (1998) Annual estimates of global anthropogenic methane emissions: 1860–1994. Trends online: a compendium of data on global change. Carbon Dioxide Information Analysis Centre, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN

Yamaji K, Ohara T, Akimoto H (2003) A country-specific, high-resolution emission inventory for methane from livestock in Asia in 2000. Atmos Environ 37:4393–4406

Submitted: September 7, 2005; Accepted: May 29, 2006
Proofs received from author(s): August 9, 2007