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Methane and nitrous oxide emissions: an introduction

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Abstract

Methane and nitrous oxide are important greenhouse gases. They contribute to global warming. To a large extent, emissions of methane and nitrous oxide are connected with the intensification of food production. Therefore, feeding a growing world population and at the same time controlling these emissions is a great challenge. Important anthropogenic sources of biogenic methane are wet rice fields, cattle, animal waste, landfills and biomass burning. Important anthropogenic sources of biogenic nitrous oxide are land-use change, fertilizer production and use and manure application. The ultimate objective of the Framework Convention on Climate Change implies a stabilization of greenhouse gas concentrations in the atmosphere. As a small first step towards achieving this objective, the Convention requires the industrialized countries to bring their anthropogenic emissions of greenhouse gases by 2000 back to 1990 levels. It was also agreed that all parties would make national inventories of anthropogenic greenhouse gas emissions and programmes for control (UN, 1992).

In this context, in February 1993 an international workshop was held in Amersfoort in the Netherlands to discuss methods in national emission inventories for methane and nitrous oxide, and options for control (Van Amstel, 1993). A selection of the papers presented in Amersfoort that focus on agricultural sources is published in this volume. This introductory chapter gives background information on biogenic sources and sinks of methane and nitrous oxide and options for their control. The goal of the Climate Convention is described as well as the IPCC effort to develop an internationally accepted methodology for the monitoring of greenhouse gas emissions and sinks. Finally, some preliminary results from country inventories are given. It is concluded that a common reporting framework and transparency of the inventories are important to obtain comparable results that can be used for complying with the requirements of the Climate Convention and for facilitating the international debate about appropriate response strategies.

Framework convention on climate change

The United Nations Framework Convention on Climate Change, signed in Rio de Janeiro in 1992, calls for the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level is to be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. As a first step towards achieving this objective, industrialized countries are required to bring their greenhouse gas emissions back to 1990 levels by 2000. Most OECD countries have adopted national emissions reductions targets that are in line with this requirement. Implicitly, a comprehensive approach is allowed by the Convention, taking into account all sources and sinks of all greenhouse gases, including methane and nitrous oxide. All parties to the Convention will have to report on their national greenhouse gas emissions and on response policies developed or adopted.

Methods for national emission inventories

To facilitate the reporting and report evaluation within the framework of the Climate Convention, comparable results from countries are needed. Therefore, the IPCC in collaboration with the OECD has developed Draft Guidelines for National Inventories of Green-

house Gas Emissions and Sinks (OECD, 1991). These draft guidelines have been widely discussed and tried out by experts of many countries in order to achieve consensus about the methods for estimating national emissions and sinks of greenhouse gases. Currently, revised guidelines are under review among IPCC member states. In 1994 these methods will be recommended to the International Negotiating Committee (INC) or, after entering into force of the Convention, the Conference of Parties. Until now, most attention has been paid to the carbon dioxide emissions, as CO_2 contributed more than 50% to the extra radiative forcing in the eighties and emissions can be quantified relatively easily. But methane and nitrous oxide are important as well with about 13% and 6% of the extra radiative forcing (IPCC, 1992).

Methods for the estimation of CO_2 emissions are relatively straightforward and results are robust. Uncertainties are rather political than scientific, e.g. how marine and aviation bunkers, and carbon embodied in traded products, are dealt with.

For methane and nitrous oxide this is not the case. At the moment, methods are at a relatively early stage of development, especially for N_2O, and results still have wide uncertainty ranges. Part of this problem is associated with the difficulty in translating local measurement results into emissions estimates for larger areas, such as countries. Part of the problem is related to the complexity of processes involved in biogenic production of CH_4 and N_2O, e.g. in soil related anaerobic environments. In soils many processes are involved. Emissions are related to soil types and human interference with the soil system is influencing emissions. For example, flooding is known to have effects on the emissions of methane and nitrous oxide. Emissions are largely related to management of soils. Thus, because of the dependency of emissions on local climate, soil, and management conditions, extrapolation of local emission results is difficult.

Workshop

In February 1993, an International IPCC Workshop was organized in Amersfoort, the Netherlands, to discuss methodologies for national inventories of methane and nitrous oxide emissions and sinks, and options for control. Ten working groups were formed to discuss the most important sources. Experts presented papers on the state of knowledge about the individual sources. Special sessions focused on the IPCC methodologies for national inventories of greenhouse gases from these sources, and on the feasibility of technological options for emissions control.

This special issue of Fertilizer Research presents a selection of those papers from this workshop, that are considered to be relevant to the readers of this Journal. In order to contribute its share to the mitigation of climate change, the agricultural sector should take greenhouse gas emissions into account in its planning activities with respect to production and research. Methane and nitrous oxide are important greenhouse gases released from agricultural activities, such as the application of artificial and animal fertilizer. Therefore, in this volume issues related to soil and livestock were selected. Methodologies are discussed to calculate emissions on a national basis while making use of the best available measurement results. In many respects extrapolation methods will be refined in the future as knowledge increases about the processes active in soils and other environments. Most important bottleneck for national inventories is the absence of supporting data. In many countries statistics simply lack to do detailed calculations. For example, there is a lack of activity data (e.g. the amount of fertilizer types applied, the herd composition, the intake of food by domestic ruminants in a country). Emission calculations can be made for different levels of data availability.

IPCC aims at a consensus about methodologies for calculating national emissions of greenhouse gases tailored to the needs of the Convention and to the capabilities of signatory countries. More detailed inventories can be made, and in fact will be made, e.g. on a grid basis in the Global Emissions Inventory Activity (GEIA) initiative of the International Global Atmospheric Chemistry (IGAC) project (Bouwman, 1993). More experimental research is also necessary to improve the default data set on emission factors as proposed by the IPCC. The set of emission factors is mainly derived from studies in industrialized countries, and can not simply be translated to other environmental conditions, countries or continents.

Atmospheric concentrations, sources and sinks

Methane

Methane has a direct global warming potential (GWP) of 11 (CO_2 = 1), when calculated for a 100 years time horizon, the indirect effect is positive, but unquanti-

fied (IPCC, 1992). It has an atmospheric lifetime of about 10 years. It is the most abundant hydrocarbon in the earth's atmosphere. The atmospheric concentration has more than doubled from 800 ppbv to 1720 ppbv since the industrial revolution. Recently a deceleration of the increase of methane in the atmosphere has been observed. The yearly increase was 20 ppbv in 1978 (1.3% per year), in 1989 it was 10 ppbv (0.6% per year) (Steele *et al.*, 1992). As the sources did not diminish over these years, an increase of the dominant sink for methane, the OH radicals in the troposphere, is suspected (Lelieveld and Crutzen, 1993). Very recently the source strength in the former Soviet Union may have decreased because of the economic recession there and the related reduction of fossil oil and gas production. In Table 1 a recent overview is given of the sources and sinks of methane (IPCC, 1992).

Table 1. Estimated global sources and sinks of methane (Tg CH_4/yr) with ranges in parentheses.

Sources		
Natural		
– Wetlands	115	(100-200)
– Termites	20	(10–50)
– Oceans	10	(5–20)
– Fresh water	5	(1–25)
– Methane hydrate	5	(0–5)
Total natural	155	
Anthropogenic		
– Coal mining	50	
– Natural gas and Petroleum	50	
– Wet Rice	60	(20–150)
– Enteric fermentation	80	(65–100)
– Animal wastes	25	(20–30)
– Domestic sewage	25	?
– Landfills	30	(20–70)
– Biomass burning	40	(20–80)
Total anthropogenic	360	
Total biogenic	415	(280–705)
Total fossil	100	(70–125)
Total natural	155	
Total anthropogenic	360	
TOTAL	515	
Sinks		
Atmospheric removal	470	(420–520)
Removal by soils	30	(15–45)
Atmospheric increase	32	(28–37)

Source: IPCC, 1992.

Wetlands

In wetlands methane is formed under anaerobic conditions by microbial decomposition of organic matter. This occurs in natural wetlands and in wet rice fields. Methane is formed by methanogenic organisms. Aselmann and Crutzen (1989) calculated that 2–7% of the net primary productivity in wetlands is emitted as methane. Whiting *et al.* (1991) found a 5% emission from their measurements.

Anaerobic conditions can be found at different places on earth: in wet soils, in shallow lake bottoms, in peat areas, on the continental shelves. Above the zone of strict anaeroby, an aerobic zone is found. Methane that diffuses upwards is partly oxidized by methanotrophic microbes in this zone. If methane diffuses upwards through a water column, most of it is oxidized. The net budget between methanogenesis and methanotrophy determines whether the site acts as a source or a sink for atmospheric methane. In addition to diffusive processes, methane can escape by bubbling up through the water, or by transport through the stems of reed, and other waterplants in marshes, lakes, shallow lagoons. In swamps most of the net emissions are from bubbles or stem flow (up to 90% of emissions). In salty sediments and in the presence of sulphate, practically no methane is formed. After drainage of wetlands for agriculture oxidation starts. From a source for methane, drained wetlands turn into sinks. Global estimates of emissions have been made by different authors. Aselmann and Crutzen (1989) used average values for wetland methane fluxes in the range of 15–300 mg/m^2 per day and calculated a global emission of 40–160 Tg/yr. Matthews and Fung (1987) used values in the range of 30–200 mg/m^2 per day and found a total of about 110 Tg/yr.

Rice

Methane emissions from rice are dependent on the period that the paddies are flooded, the climate, the soil type, the management and the type, amount and application method of fertilizers. Minami (this issue) reports that emissions increase in all fields with rice straw application. Calculations of the world methane emissions from rice have shown different outcomes

because of a lack of data concerning the area under irrigated, rainfed, deep-water and upland rice. The rainfed and irrigated rice fields have significant emissions. The other types less so. The IRRI (1988) has information on the area of wetland rice. About 80.10^6 million ha harvested wetland rice are potential sources of methane. On the basis of this information and experimental results, Neue *et al.* (1990) assumed average emissions of 200–500 mg/m^2 during an average growing season of 130 days. They estimated a global emission of only 25–60 Tg/yr compared to 40–160 Tg/yr as estimated by Matthews and Fung in 1987.

Soils as a sink for methane

Methane is taken up by methanotrophic bacteria in the aerated parts of the soils. Different authors estimated the total actual sink for methane in oxidative soils (Crill, 1991; Steudler *et al.*, 1989; Striegl *et al.*, 1992; Whalen and Reeburgh, 1990; Whalen *et al.*, 1992; Whalen *et al.*, 1991; Mosier *et al.*, 1991). The IPCC estimated a total sink for methane of 30 Tg CH_4 (IPCC, 1992). Steudler *et al.* (1989) calculated a global total consumption of methane by temperate and boreal forests of 12.4 Tg CH_4 per year. They also found that the uptake rates were significantly decreased by nitrogen additions, implying that nitrogen fertilization may reduce the sink capacity of soils. Striegl *et al.* (1992) estimated the global sink for methane by desert soils at about 7 Tg CH_4 per year.

Enteric fermentation

Methane is formed in the fore-stomach of ruminants by methanogenic bacteria under anaerobic conditions. This process enables ruminants to utilize the energy in low-quality feeds with high cellulose content. Methane is also produced by pseudoruminants like e.g. pigs, but in much smaller quantities. Methane production by insects, e.g. termites is now seen as unimportant on a global scale. Early data on methane yields by cows, sheep, goats, horses and elephants were published by Ritzman and Benedict (1938). They found a range of 4–7% of gross energy intake for ruminants fed at maintenance level. Blaxter and Clapperton (1965) found that methane emissions depended on feeding level and digestibility. The relation they found is used to calculate emissions at a detailed level. In developing countries a large proportion of the feed consists of low-quality straw and fodder. Krishna *et al.* (1978) estimated 9% methane yields in Indian cattle fed at maintenance level with low-quality feeds.

Crutzen *et al.* (1986) estimated the methane emissions from wild and domesticated animals, and humans. They found 80 (range 65–100) Tg CH_4/yr. World herds of domesticated animals have increased since 1950. Crutzen found an increase of methane emissions from domesticated animals of 0.6 Tg/yr or 0.75% per year between 1966 and 1986. Lerner *et al.* (1988) made a global database of methane emissions from livestock per gridcell of $1 \times 1°$. They found emissions of more than 5000 kg/km^2 per year in small regions such as the Benelux, Bangladesh, parts of northern India and New Zealand. They also found that half the global emissions are from only five countries: India, the CIS, Brazil, the USA and China. Gibbs and Johnson (1993) made a recent estimate based on detailed calculations of feed intake and energy requirements for work and lactation. They found a total global emission of 58 Tg/yr, with 30 Tg/yr coming from five countries: the Former Soviet Union: 7.5 Tg/yr; Brazil: 7.0 Tg/yr; India: 5.6 Tg/yr; United States: 5.3 Tg/yr; China: 3.4 Tg/yr and Australia: 1.2 Tg/yr.

Waste

Methane is emitted from different kinds of waste: from anaerobically treated animal, human and industrial liquid wastes and from landfills. The potential amount of methane formed in different waste types and the actual amount of methane emitted from different treatment systems depend on the waste characteristics and the storage temperature. Woodbury and Hashimoto (1993) estimated a total emission of 14 Tg/yr from animal waste, using assumptions about the share of different manure treatment systems per country. Zeeman (this issue) reports on methane emissions from animal manure in the Netherlands. She found that methane emissions are influenced by temperature, storage time and amount of inoculation from waste that remains in the system after emptying. Methane emissions from sewage treatment systems are estimated by Thorneloe (1993) using the BOD_5 values of the waste water and an emission factor of 0.22 kg CH_4/kg BOD_5. Her estimate ranges from 30 to 40 Tg/yr. Industrial waste water treatment is the major contributor. Emissions from landfills are estimated by Bingemer and Crutzen (1987). They calculated emissions from the amount of waste generated, the fraction landfilled, the fraction degradable organic carbon, the fraction dissimilated degradable organic carbon, the fraction methane in the waste gas and the amount recovered. Their estimate was 50 (30–70) Tg/yr. Recently Thorneloe (1993) esti-

mated methane from landfills using a regression model developed from refuse and actual gas recovery data of US landfills. She estimated a world emission of 21 (range 11–32) Tg/yr.

Biomass burning

Biomass burning is a significant source of atmospheric trace gases like methane. Anthropogenic biomass burning is more important than natural fires because of forest destruction (Delmas, this issue). The products of complete combustion of biomass are carbon dioxide and water vapor. The combustion process however is never complete and this prevents some carbon from being oxidized. This generates several carbonaceous products of incomplete combustion, some gaseous and some particulate. Every biomass fire has four phases of combustion: flaming, pyrolysis, smouldering and glowing. These processes co-exist in fires. The magnitude and duration of each of these processes depend on the kind of biomass and the conditions during the fire. Flaming dominates the start of a fire. The heat initiates pyrolysis that provides the fuel gases, including methane, that sustain the visible flaming process. In the smoldering process charcoal is produced. Gaseous products can escape oxidation during this phase. During the glowing of the charcoal no appreciable emissions of volatile compounds occur. Each process has different amounts of resulting products. Methane is released in large quantities especially during the smoldering phase, with emission factors 2–3 times greater than during the flaming phase. The total methane emission from biomass burning in the world is estimated by Delmas (1993) at 34 (range 22–46) Tg/yr. This is lower than the IPCC estimate of 40 (range 20–80) Tg/yr (IPCC, 1992). Three sources dominate this budget: fuel wood burning and tropical forest and savanna fires (Delmas, 1993). Another recent estimate is from Ahuja (1993). His estimate is 48 Tg/yr. It is based on a careful re-evaluation of information and the IPCC/OECD methodology. According to Ahuja (1993) biofuels emit 21 Tg/yr, shifting cultivation 10 Tg/yr, deforestation 8.5 Tg/yr, savanna burning 6 Tg/yr, charcoal production 2.5 Tg/yr and agricultural residues 1 Tg/yr.

Reduction options

Biogenic sources make up approximately 410 Tg CH_4/yr. Of this amount approximately 155 Tg/yr is natural and approximately 255 Tg/yr is anthropogenic. Management of wetland soils, rice, waste, biomass burning and ruminants may contribute significantly to methane reductions. The drainage of wetlands for agriculture since the turn of the century may have contributed to the reduction of natural methane emissions. No global estimates of this process have been made yet. A further decrease of emissions may be expected as wetlands continue to be converted for agricultural purposes. In rice production, methane reductions are possible by intermittent draining during the growing season in areas with abundant water. A reduction in the organic fertilizer application, like rice straw may be an important measure. In waste management, methane reductions are possible through either composting or fermenting of organic waste. In composting, practically no methane is produced. In controlled fermenting, nearly all biogas can be collected and used for energy purposes. A higher efficiency in agriculture may reduce methane emissions: it reduces the methane emissions per unit of produce and therefore the need for land conversion in developing countries and thus the biomass burning from deforestation. In ruminants, methane reductions per unit of produce are possible by changes in the diets. An decrease in fodder in combination with an increase of grains and high protein feeds increases the weight gain in beef production and the milk production per dairy cow and thus reduces the percentage of the feed intake that is converted to methane. In animal waste, the option again is either composting or fermenting with biogas collection.

Nitrous oxide

Nitrous oxide is an important greenhouse gas with a long lifetime of about 150 years. Nitrous oxide has even 270 times the greenhouse potential of CO_2 (on a weight basis and when calculated over a 100 years time horizon, IPCC, 1992). Its present concentration is 310 ppbv, this is about 8% higher than the pre-industrial concentration of 285 ppbv. Nitrous oxide is relatively inert in the troposphere. It is broken down in the stratosphere by photolysis and oxidation. It is an important source of stratospheric nitrogen oxides which start a chain of reactions leading to stratospheric ozone destruction. In Table 2 a current overview is given of sources and sinks of nitrous oxide (IPCC, 1992).

A number of sources have been identified. These include oceans, natural soils, agricultural soils, biomass burning, fossil fuel combustion and industrial processes. The knowledge of the magnitude of the sources and sinks is still poor. Sources other than those in Table 2, are suspected to be important. These

Table 2. Estimated sources and sinks of nitrous oxide (Tg N/yr).

Sources			
Natural			
– Oceans	1.4	-	2.6
– Tropical soils			
– Wet forests	2.2	–	3.7
– Dry savannas	0.5	–	2.0
– Temperate soils			
– Forests	0.05	–	2.0
– Grasslands	?		
Anthropogenic			
– Cultivated soils	0.03	–	3.0
– Biomass burning	0.2	–	1.0
– Stationary combustion	0.1	–	0.3
– Mobile combustion	0.2	–	0.6
– Adipic acid production	0.4	–	0.6
– Nitric acid production	0.1	–	0.3
Sinks			
Removal by soils	?		
Photolysis in the stratosphere	7	–	13
Atmospheric increase	3	–	4.5

Source: IPCC, 1992.

include contaminated inland and coastal waters, waste water treatment, animal manure systems, atmospheric deposition of NO_x and NH_x, atmospheric formation. Moreover, there may still be not yet identified (industrial) sources. An overview is given here of soil related sources and sinks.

Aquatic sources

The estimate of 1.4–2.6 Tg N_2O-N/yr in Table 2 is from Elkins (1989). This oceanic source does not include coastal and inland waters, nor aquifers. Nitrogen loading of inland and coastal waters by human waste disposal and runoff from fertilized fields induces nitrous oxide emissions. Measurements of nitrous oxide emissions from inland and coastal waters are higher than those reported from oceans. This implies that inland and coastal waters may be important global sources, although world estimates have yet to be made (Bouwman, 1993). Ronen *et al.* (1988) estimated that aquifers contaminated with nitrogen may contribute 0.5–1.1 Tg N_2O-N/yr.

Natural soils

There is an enormous variability of soil and climate conditions affecting biogenic production of N_2O in soils. Recent estimates of regional N_2O fluxes are based on a stratification of ecosystems describing part of this variability (Bouwman, 1993). There is however still room for improvement as the soil processes responsible for N_2O formation are not incorporated in the estimation models. N_2O is formed both in nitrification and denitrification processes (Batjes and Bridges, 1992). Emissions of N_2O from soils are natural (so-called back-ground emission) and fertilizer induced (anthropogenic). IPCC estimated a global annual fertilizer induced emission of 0.03–3.0 Tg N_2O-N/yr, see Table 2. Bouwman estimated global annual N_2O emission from pre-agriculture natural soils is 6.7 (range 3–10) Tg N_2O-N/yr. A recent estimate of nitrous oxide emissions from non-cultivated lands is 5.6–6.0 Tg N_2O-N/yr (Bouwman, 1993).

Agricultural soils

Mosier (in this issue) summarizes the available information about nitrous oxide emissions from agricultural soils. He gives a method for estimating emissions on a national basis and some technical options to reduce emissions, like optimizing fertilizer application and the use of nitrification inhibitors. His estimate of global nitrous oxide emissions directly from agricultural fields as a result of nitrogen applications is 2–3 Tg N/yr.

Arable land

The N_2O emissions from arable lands can be calculated by adding the fertilizer induced emissions to the background (natural) emissions. Bouwman (1993) used the following simple equation: "Background" flux + 0.0125 * N-fertilizer. The background flux depends on natural environmental conditions and may range from 0.01 to 2.9 kg N/ha per year, with an average of 0.7 kg N/ha per year. The average fertilizer induced emission thus calculated was 0.7 kg N/ha per year. This gives a global emission from arable land of 2 Tg N_2O-N/yr or an average of 1.4 kg N_2O-N/ha per year (Bouwman, 1993).

Grasslands

The background emissions from 2900 Mha grasslands on earth are estimated at 1.2 Tg N_2O-N/yr, or 0.5 kg N/ha per year on average (Bouwman, 1993). The extra emission from animal droppings and urine and the extra

manure application on grasslands is unknown, because the quantity is difficult to estimate. The overall emission from manure is estimated below.

Manure
Animal manure is applied to the fields in many agricultural regions. However, it is difficult to assess the distribution over arable land and grassland, and how much is used for fuel. Therefore Bouwman (1993) made an overall estimate. He estimated N in animal feed and in excreta, ammonia losses and manure production per animal. N_2O losses from manure were tentatively estimated at 0.5%. He also estimated the total N produced by animals at 105 Tg N/yr, yielding an emission of 0.5 Tg N_2O-N/yr (Bouwman, 1993). This may be an underestimate, as emissions from manure treated soils may be considerable.

Waste water
In many countries waste water is collected and treated to reduce surface water pollution. A global estimate of nitrous oxide from waste water treatment is made by Khalil and Rasmussen (1992). They estimated 0.2–1.9 Tg N/yr. Recently some measurement results have been published on this source. De Bruyn *et al.* (in this issue) present some results for the Belgium situation.

Biomass burning
Biomass burning is a source of nitrous oxide. Emissions are depending on the nitrogen content of the fuel. Crutzen and Andreae (1990) estimated N_2O emissions from savanna burning and deforestation at 0.1–0.3 Tg/yr. This estimate is based on an emission factor (in mass of N_2O-N) of 0.7% (range 0.5 to 0.9%) of the N content of the fuel.

Enhanced soil emissions after savanna and grassland burning
After burning of savanna or grassland nitrous oxide emissions may be enhanced from the remaining material for a prolonged period after the first rains following the dry period. Measurements of this phenomenon are scarce (Anderson *et al.*, 1988; Anderson and Poth, 1989). Bouwman (1993) made an estimate based on the following assumptions. A total global amount of nitrogen of 12 Tg N/yr remains on the ground after burning. Of this amount 20% volatilizes as ammonia, and from the remaining part 1% is released as nitrous oxide after mineralization and nitrification. The N_2O emission would then be 0.1 Tg/yr.

Conversion of tropical forest to agriculture
Keller *et al.* (1986) found that conversion of tropical forest to pasture or arable land could increase the global nitrous oxide emissions. Luizao *et al.* (1989) found that the annual flux of nitrous oxide from a recently converted forest plot (4 years from conversion) was three times higher than a comparable undisturbed plot with identical soils. Keller and Reiners (1991; 1992) examined the effect of pasture age and forest conversion. They also found increased fluxes after forest conversion and a decrease with age of pasture. Bouwman (1993) made an estimate of the global implications of these observations. The following assumptions were made. The N_2O pulse from accelerated decomposition and N-mineralisation after conversion lasts for 10 years. A five-fold increase can be expected of the average fluxes from tropical rainforests of 1.4 kg N_2O-N/ha/yr in the first year and a gradual decrease over ten years. Bouwman (1993) found an annual enhanced flux (= new minus original flux) of about 0.26 Tg N/yr at present.

It is now widely believed that the atmospheric increase of nitrous oxide is predominantly caused by soil related emissions. Appropriate management of fertilized soils is thus likely of offer possibilities for reductions of these emissions.

Implications of mitigation policies

Methane

If the global emissions of methane were reduced by 10–20% in the coming decades, atmospheric concentrations could probably be stabilized (Rotmans *et al.*, 1992). The options described above appear to make this technically feasible. Also, many possible reduction measures make sense in economic terms. So, even a reduction of concentrations may become possible. Different continents may set different priorities. In coal mining, Eastern Europe and Asia may make the greatest methane emission reduction. Asia can make a reduction in emissions from wet rice by intermittent draining during the growing season and reduction of organic fertilizers. Waste gas recovery is seen as the most profitable in North America and Europe because of centralized waste collection and disposal systems. This may include centralized fermenting of animal waste and biogas recovery. Reductions in emissions from ruminants are difficult to achieve. Some improve-

ments in the cattle diet are feasible in Eastern Europe, Asia, Latin America and Africa. Reduced production and consumption of beef and dairy products can make an important contribution in OECD countries. Biomass burning may be controlled by restricting deforestation.

Nitrous oxide

The global emissions of nitrous oxide would need to be reduced with 70–90% relative to 1990 in the coming decades in order to achieve stabilization of atmospheric concentrations at their present level. This reduction will be hard to achieve as many sources are related to intensification of agricultural production. Especially if conversion of natural ecosystems, such as tropical forests, into agricultural systems would have to be minimized, intensification of agricultural production appears to be the most important way to keep up with increasing demands for food and other agricultural products. It is hard to see any solution that would not be based to a large extent on the application of fertilizer. Thus, types and application methods of (nitrogenous) fertilizer would have to be optimized in relation to local soil and climate conditions and crop type in order to minimize releases of nitrous oxides. Nitrification inhibitors like coated calcium carbide have proven useful in the reduction of nitrous oxide production from ammonium based fertilizers. Acetylene is a nitrification inhibitor and it reduces methane emissions from flooded rice soils (Mosier in this issue). In areas characterized by overproduction reductions of fertilizer application may be feasible. Also a shift in diet towards less meat may reduce animal numbers in industrial countries, with an associated reduction in manure and nitrous oxide emissions. The only emissions that can easily be reduced in the short term seem to be industrial emissions associated with adipic acid production needed in nylon 6.6 production.

Preliminary results from selected countries

Methane

This section is based on a transparency study of preliminary national emission inventories (OECD, 1993). Most OECD countries and some others have so far contributed to the IPCC initiative to compile national emission estimates of greenhouse gases. The preliminary results of country submissions to IPCC for methane and for the base years 1988/90 are given in Tables 3, 4 and 5 (Van Amstel, 1993). The results are preliminary as methods and emission factors are not yet finalized in IPCC/OECD. The total for the countries represented is 101 Tg/yr, while the estimated world total for net anthropogenic methane emissions is 335 Tg/yr (excluding sewage treatment on which countries did not report). So, 30% of the global total methane emissions are represented. The countries represented cover 25% of the Earth's land surface, 20% of the worlds population and about 50% of global GNP.

The mean per capita emission of methane for these countries is 96 kg/yr, while the world average is estimated at 63 kg/yr. The per capita emission ranged from 37 kg/yr in Belgium to 501 kg/yr in New Zealand. The mean per unit area emission of methane in the represented countries is 1948 kg/km2, while the world average is 2552 kg/km2. One expects that the world average would be lower then the average for the represented countries, because these are the higher emittors. However the large surface area of some of the represented countries has an influence on the average. It may also be an indication that the top-down world budget differs from the represented country totals. A densely populated country like the Netherlands has the highest per unit area emission of 24500 kg/km2, Canada has the lowest per unit area emission of 319 kg/km2. The mean per unit GNP emission is 6331 kg/million $US.Japan has the lowest with 185 kg/million $US and New Zealand has the highest figure with 43107 kg/million $US (Van Amstel, 1993). When comparing the national IPCC submissions with top-down calculations (e.g. Subak *et al.*, 1992, World Resources Institute, 1992) large discrepancies are found. This means that methods and assumptions in top-down reports still differ from what countries find.

Nitrous oxide

Countries reported on their nitrous oxide emissions from various sources for the base years 1988/1990. A summary of their preliminary results is given in Table 6. These results will change as methods and emission factors are not yet finalized within IPCC/OECD.

The total for the countries represented is 0.65 Tg N_2O/yr. This is at the lower end of the estimated world total from anthropogenic sources of 1 to 6 Tg/yr. As uncertainty ranges are high for these estimates, and many countries have yet to report on nitrous oxide emissions it is too early to calculate accurate per capita and per unit area emissions from these data.

Table 3. National net anthropogenic methane emissions (Tg/yr) from OECD countries and a few others

Country	Year	Methane	Source
Australia	1988	5.426	Australia, 1991
Belgium	1990	0.362	Van Rensbergen and Debruyn, 1991
Canada	1990	2.942	Jaques, 1992
Denmark	1989	0.645	Fenger *et al.*, 1990
Finland	1988	0.250	Boström *et al.*, 1992
Germany	1989	3.100	Weber, 1991
Italy	1989	2.500	ENEA, 1991
Japan*	1988	0.540	Japan, 1990
Netherlands	88-90	0.831	Van den Born *et al.*, 1991
New Zealand	1988	1.700	Von Dadelszen, 1991
Norway	1989	0.322	Rypdal, 1992
Poland	1988	1.543	Cofala and Klimond, 1991
Sweden	1990	0.460	Sweden, 1991
Switzerland	1988	0.240	Switzerland, 1991
Thailand	1988	0.616	Sungsuwan and Buranasajja, 1990
United Kingdom	1988	3.433	Munday, 1990
United States	1988	33.000	United States, 1991
Former USSR*	1988	43.000	Andronova and Karol, 1992

*result of independent research, not official.

Transparency and a common framework for reporting

From this detailed comparison of country reports it could be concluded that emission factors used in comparable sectors still differed because different measurement results were extrapolated. A default set of emission factors should be developed. These should be used by countries, unless local emission factors, based on published experiments, are available. Countries used different reporting formats and a different amount of explanatory detail. This made comparison difficult and for some countries even impossible. For facilitating the comparison between countries and thus the debate about appropriate response policies, a standard reporting format is needed. This implies a common set of source sector definitions. Enough information should be given about activity data, emission factors, methods used, and assumptions made, in order to allow a third party to reconstruct the emission figures. This last requisite is called transparency. Verification checks should be a routine part of the centralized reporting function of the Climate Convention. Verification includes source category definition checks, checks on activity data used, cross-country comparison of emission factors and related assumptions and comparison of emission estimates with independant estimates.

Studies from developing countries are still lacking, with some exceptions. With respect to sources, information about emissions from land use change, biomass burning, wet rice and fertilizer use were still lacking. Many developing countries however will be funded (by UNEP, UNDP, regional development banks, bilateral arrangements) to develop emission inventories. To speed up the process, some regional workshops were organized in Africa and Latin America to introduce and discuss the IPCC/OECD methodology with country representatives.

Conclusions

The conclusions from the workshop were

1. More field measurements are needed to enlarge the data base of emission factors in practically all source categories for different circumstances with respect to soil type, management practices and climate. Country specific emission factors are still lacking in many countries.

Table 4. Methane emissions from selected countries

Country	Year	Emission Tg/yr	Population (million)	Per cap. em. (kg)	Land area (km^2)	Emission (kg/km^2)	GNP $US (million)	Emission (kg/mio $US)	Share:world emission (%)
Australia	87-88	5.426	16.87	322	7617930	712	242131	22409	1.6
Belgium	1990	0.362	9.85	37	30250	11967	162026	2234	0.1
Canada	1990	2.942	26.52	111	9220970	319	500337	5880	0.9
Denmark	1989	0.645	5.14	125	42370	15223	105263	6128	0.2
Finland	1988	0.250	4.98	50	304610	821	109705	2279	0.1
Germany	1989	3.100	77.57	40	349470	8871	1432459	2164	0.9
Italy	1989	2.500	57.06	44	294060	8502	871955	2867	0.7
Japan	1988	0.540	123.46	4	376520	1434	2920310	185	0.2
Netherlands	88-90	0.831	14.95	56	33920	24499	237415	3500	0.2
New Zealand	1988	1.700	3.39	501	267990	6344	39437	43107	0.5
Norway	1990	0.322	4.21	76	306830	1049	72028	4470	0.1
Poland	1988	1.543	38.42	40	304450	5068	66974	23039	0.5
Sweden	1990	0.460	8.44	55	411620	1118	184230	2497	0.1
Switzerland	1988	0.240	6.61	36	39770	6035	197984	1212	0.1
Thailand	1988	0.616	55.70	11	510890	1206	64437	9560	0.2
United Kingdom	1988	3.433	57.24	60	241600	14209	834166	4115	1.0
United States	1988	33.000	249.22	132	9166600	3600	5237707	6300	9.9
Russia	1988	43.000	288.60	149	22272000	1931	2659500	16168	12.8
Total represented countries		100.910	1048.23	96	51791850	1948	15938064	6331	30.1
World Total	1990	335.000	5292.20	63	131288410	2552			100.0

Source: National inventories and calculations from this study

Table 5 Methane emissions per sector from selected countries

Methane kton/yr	Australia 1988	Belgium 1990	Canada 1990	Denm 1989	Neth. 1988/90	Norway 1989	Poland 1988	Sri Lanka 1988/89	UK 1988	USA 1988	F. USSR 1988	Total repr.	World 1990	Share: (%)
Energy Combustion	263	5	7	42	12		34					364		
Production gas and oil		39	288	9	153	23	128		564	1991	19000	22194	50000	44
Production of coal	577	15	143	16		6	968		922	7456	12000	22172	50000	44
Transport	94	16	23	7	8		8	1	21	216		394		
Enteric fermentation	2793	169	648	136	378	70		193	1140	6238	12000	23764	80000	30
Animal waste	522	115	330	125	15	70		9		3930		5116	25000	20
Flooded rice fields	20							407		781		1208	60000	2
Landfills	666	2	1406	310	260	153	405	122	716	1150		5189	30000	17
Land use change								16				16		
Biomass burning	492		80					12				584	40000	1
Industrial processes		2			4							6		
Total methane emission	5426	362	2924	645	831	322	1543	759	3433	21761	43000	81006	335000	24
Population (millions)	17	10	27	5	15	4	38	17	57	249	289	728	5292	14
Emission (kg CH4 per capita)	322	37	110	126	56	77	40	44	60	87	149	111	63	176

Source: National inventories and OECD (1993)

Table 6. Summary of national nitrous oxide emissions (kton N_2O/yr) as reported to IPCC.

	AUS 1988	BEL 1990	CAN 1990	DEN 1989	NL 88/90	SRI L 88/89	USA 1988
Energy stationary		10.7	17.0	1.5	1.5		
Energy mobile	5.1	1.3	38.3	6.8	2.7		74.0
Fertilizer use	21.0	13.9	28.5	11.6*	14.9*	0.2	103.5
Industrial processes			33.0				250**
Agricultural waste	0.9						
Forestry	11.0					0.4	
TOTAL	38.0	25.9	116.8	19.9	18.1	0.6	427.5

*fertilizer use including organic.
**i.e. adipic acid production.

2. Because of the dependency of agricultural emissions of methane and nitrous oxide on local soil, climate and management conditions, extrapolation of measurement results will remain a difficult task for the coming years.
3. A standard reporting format for the country inventories of greenhouse gases will facilitate cross-country comparison of results and discussion on extrapolation methods, emission factors and related assumptions. From the policy point of view, it would facilitate the international debate about appropriate response strategies.
4. Options for the control of methane emissions are known for most agricultural sources. Implementing these measures can contribute significantly to the goal of stabilizing atmospheric concentrations.
5. Because the emissions of nitrous oxide are to a large extent related to production of food and other agricultural products for a growing world population, large emissions reductions are probably not possible and thus concentrations of nitrous oxide will not be stabilized within the foreseeable future. Nevertheless by minimizing losses of nitrous oxide from agricultural soils through the development and application of appropriate methods and types of nitrogenous fertilizer, the agricultural sector can contribute to slowing down the rate of growth of atmospheric nitrous oxide concentrations.

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