ENVIRONMENTAL SCIENCE & POLICY 13 (2010) 89–96

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/envsci

Feeding the world's increasing population while limiting climate change impacts: linking N_2O and CH_4 emissions from agriculture to population growth

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ARTICLE INFO

Published on line 2 December 2009

Keywords:
N_2O
CH_4
Agricultural production
GHG emission
Mitigation
Food production
Population growth

ABSTRACT

The global demand for agricultural products, including food, is rapidly increasing due to population growth and shifts in consumption patterns. The required increase in agricultural production is predominantly to be achieved in countries with relatively low agricultural production levels at present. These are mainly developing countries and countries in transition, the so-called non-Annex I countries of the UNFCCC. However, intensification of agricultural production systems is currently closely linked to high emissions of greenhouse gases notably nitrous oxide (N_2O) and methane (CH_4). In this paper the relations between population growth, agricultural development and emissions of N_2O and CH_4 were assessed for 10 non-Annex I countries, viz. China, India, Vietnam, Brazil, Argentina, Mexico, Mongolia, Nigeria, Tanzania and South Africa. We combined FAO data on agricultural production levels, CENSUS data on population statistics and EDGAR data on N_2O and CH_4 emissions. The projected trends in agricultural production indicate that emissions of N_2O and CH_4 are expected to increase rapidly in the coming years and will level off from 2040 onwards. The results confirm the positive relation between population increase and increased emissions from agricultural activities for most countries. However, for some countries (South Africa, China and Mexico) this relation was weak or absent. Although numerous factors (e.g. changes in international trade) may have scattered the relation and we were unable to explain this decoupling, it suggests that population growth can be possible without additional emissions. The variation between the different countries and farming systems is however large and mitigation measures at farm-level should be tailored to the wide diversity in environmental conditions, regional customs and farming systems.

1. Introduction

The Kyoto protocol was adopted in 1997 with the aim to set binding targets to reduce greenhouse gases (GHG) emissions for industrialized countries, i.e. the so-called Annex I countries (UNFCC, 1997). Under the protocol these countries agreed to reduce their combined GHG emissions by 5.2% compared to the year 1990. The protocol entered into force on 16 February 2005. Non-Annex I countries, i.e. developing countries and countries in transition do not have targeted

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1462-9011/$ – see front matter
doi:10.1016/j.envsci.2009.11.001

reduction levels, but both Annex I and non-Annex I countries are obliged to provide annual reports on GHG emissions.

In 2000, total estimated GHG emissions from non-Annex I countries equaled 14 Gton CO_2 equivalents compared to 17 Gton from Annex 1 countries (EPA, 2006). However, the GHG emissions from non-Annex 1 countries increase rapidly and presumably will exceed the GHG emissions from Annex I countries by 2016 (EPA, 2006). Notably, in 2004 developing and least developed countries accounted for 73% of the growth in global GHG emissions (Raupach et al., 2007), indicating that future agreements to reduce emissions should include reduction options in non-Annex 1 countries.

For non-Annex 1 countries the share of agriculture to total GHG emissions is significantly higher compared to Annex 1 countries, 74 and 26%, respectively (Smith et al., 2007a). In contrast to other sectors the contribution of agriculture to global GHG emissions is dominated by N_2O (44%) and CH_4 (52%) and not by CO_2 (4%) (Baumert et al., 2005). Currently, the majority of the increase in GHG emissions in non-Annex I countries is linked to fossil fuel consumption (UNFCC, 2005) but future emission from agriculture cannot be ignored as economic development of most non-Annex I countries is rooted in agriculture and changes in agricultural production (e.g. the use of inorganic fertilizer), transport and processing systems will have a direct impact on the GHG emissions from these countries.

In the coming decades agricultural production has to triple at least because of population growth and shifts in consumption patterns (Groot et al., 1998; Tilman et al., 2002; Keyzer et al., 2005). The United Nations Population Fund (UNFPA) recently estimated a global population of 9.2 billion by 2050, of which the majority supposedly lives in non-Annex 1 countries (UNFPA, 2008). Although Smil (2001) and Von Braun (2005) indicate that food production over the last decades kept in pace with the increasing demand and the key issues today are distribution and access (Pingali, 2006), there are increasing concerns about threats to the global food supply from growing competition from feed production for livestock, bio-fuels and climate change (Roetter and van Keulen, 2007; Verhagen et al., 2007). Therefore, increasing yields and reducing pre- and postharvest losses are needed to meet the increasing demand (Roetter and van Keulen, 2007; Meerburg et al., 2009).

The growth in production is expected to be achieved mainly in non-Annex I countries because the increasing demand stems primarily from these countries and because there is potential still to increase agricultural production (Lal, 2007; Tilman et al., 2002).

Most studies on GHG emissions and agriculture focus on land use change and soil management in relation to CO_2 emissions (Smith et al., 2007b), whereas studies and data on non-CO_2 gasses, that dominate emissions from agriculture, are fragmented and scattered. Nonetheless, there may be more permanent options to reduce N_2O and CH_4 emissions compared to CO_2 reduction from agriculture as N_2O and CH_4 are strongly linked to inputs and management, while CO_2 emission occurs from above and below ground carbon stocks that are difficult to manage and have a non-permanent character (Mosier et al., 2005; Cerri et al., 2007). Moreover the Global Warming Potentials (GWPs) of N_2O and CH_4 are 310 and 21, respectively, meaning that N_2O and CH_4 are approximately 310 and 21 times more heat absorptive than carbon dioxide per unit of weight, respectively. Hence, the required agricultural growth is expected to be accompanied with a rapid growth of especially N_2O and CH_4 emissions from agriculture (Bongaarts, 1992), unless these emissions are decoupled from population and agricultural growth.

To increase the understanding of the relation between agricultural development and N_2O and CH_4 emissions from non-Annex 1 countries and to assess whether population growth, agricultural development and emissions of N_2O and CH_4 can be decoupled, we linked N_2O and CH_4 emission data from agriculture to trends in agricultural production and population for 10 selected non-Annex I countries. The developments in the near future up to the year 2050 were envisaged. This information provides a basis for site specific mitigation strategies for N_2O and CH_4 emissions from agriculture in non-Annex 1 countries.

2. Materials and methods

We selected 10 non-Annex I countries based on a geographic distribution, to capture the major agricultural systems, and data availability (Table 1). Data on trends in production levels were taken from FAOSTAT (www.fao.org). We focused on total cereal and livestock production (which from hereon are referred to as primary and secondary production, respectively) between 1990 and 2000. Primary production was expressed as the total cereal production in tonnes per year, i.e. the summed production of barley, buckwheat, cereals maize, millet, oats, paddy rice, rye, sorghum, triticale and wheat. Secondary production was assessed as the total stock of cattle and pigs, where a livestock unit (LU) value of 0.2 was used for pigs and of 1.0 for cattle (Seré et al., 1995). The sum of cattle and pigs was assumed to be an appropriate indicator of the total livestock herd. Forecasts on agricultural production levels were made using net agricultural production indices, which is an integrated measure of both primary and secondary production and is expressed in international dollars (I$). An international dollar is a hypothetical unit of currency that has the same purchasing power as a US$ in the USA at a given point in time and is commonly used as benchmarks for comparisons (UN, 2007).

Data on N_2O and CH_4 emissions were taken from the EDGAR32 database (Olivier et al., 1994; Olivier and Berdowski, 2001). The EDGAR32 database stores, amongst others, national emission inventories of direct and indirect greenhouse gases from anthropogenic sources. The EDGAR32 database follows the IPCC methodology for national reporting, but has a more consistent structure, i.e. uses less different values for emission factors than individual countries do. The EDGAR32 database covers national data on N_2O and CH_4 emissions from agricultural sources for the years 1990, 1995 and 2000.

Data on population size were taken from CENSUS-IDB population statistics, which contains country based annual demographic data from 1950 to 2050 using vital statistics provided by National Statistics Offices, and data on international migration, refugee movements, public health, socio-political circumstances, and historical events such as natural disasters and conflicts (Arriaga, 1994; www.census.gov).

Trends in agricultural production, population density and emissions of CH_4 and N_2O from agriculture were analyzed by

Table 1 – Some characteristics of the selected non-Annex 1 countries.

Continent	Country	Example of agricultural system[a]	Population growth between 2000 and 2005 (% per year)	Position in discussions on climate change
Africa	South Africa	Large scale monocultures	1.1	Relatively firm economy and highly developed agricultural sector
	Nigeria	Small holder systems	2.3	Relative low contribution of agriculture to GDP because of large revenues from oil, but still large part of the population depends on agriculture
	Tanzania	Medium size mixed farming systems	2.4	Economy depends heavily on agriculture, with most jobs linked to this sector
Asia	China	Intensive mixed farming systems	0.6	Rapidly developing economy and agricultural sector
	Vietnam	Intensive rice system	1.1	Active player in discussions on climate change
	Mongolia	Extensive livestock systems	1.5	Extensive farming systems
	India	Intensive rice system	1.8	Rapidly growing economy, agricultural sector and population
South America	Brazil	Large scale monocultures	1.4	Large producer of feed, bio-energy and livestock products
	Mexico	Small scale mixed farming systems	1.3	Mixed farming systems, Central America
	Argentina	Large scale livestock systems	1.0	Large scale farming system

[a] The example of agricultural system column presents one of various different farming systems that can be found in a country and serves for general orientating purposes only.

linking the various data sources in the overlapping time window 1990 and 2000. Subsequently, emissions of CH_4 and N_2O were related to demographic trends by linear regressions using national emission data and reported population sizes of 1990, 1995 and 2000. Whenever the correlation between demographic trends and emissions of CH_4 and N_2O were adequate, i.e. $R^2 > 0.75$, regressions were extrapolated to 2050 using demographic data. It was not possible to extrapolate relations between agricultural production levels and CH_4 and N_2O emissions, because there were no reliable forecasts on agricultural production levels on a country basis.

3. Results

Between 1990 and 2000, primary production increased in all selected countries, with the exception of Mongolia and Tanzania. The growth in primary production, during this period, was especially significant in Vietnam (growth = 74%), Brazil (growth = 41%), Argentina (growth = 26%) and South Africa (growth = 26%). In Mongolia primary production decreased with 80% and in Tanzania with 4%. In general, relative growth in primary production exceeded the growth in secondary production except for China where the secondary production increased with 27% and the primary production with only 1%. Highest growth rates in secondary production were observed in Vietnam (increase = 47%) and Mongolia (increase = 40%) (Fig. 1).

Subsequently, N_2O emissions from agricultural activities increased in all selected countries except for South Africa. The highest relative increase was found for Vietnam, where N_2O emissions increased with 101% in 10 years. Methane emissions increased in some, but not all countries. In Mongolia and Vietnam, CH_4 emissions increased with 33 and 23% in 10 years, respectively, whereas in the same time period in Argentina and South Africa CH_4 emissions decreased with 9 and 7%, respectively (Fig. 2). The different trajectories shown in Fig. 2 demonstrate that for most countries the relative increase in N_2O emissions exceeded the relative increase in CH_4 emissions between 1990 and 2000.

Fig. 3 confirms the expected positive relation between population size and net agricultural production for the selected countries. In general, population size was a proxy indicator of agricultural growth, but differences between countries were large. China showed the highest growth in agricultural production per inhabitant between 1990 and 2000,

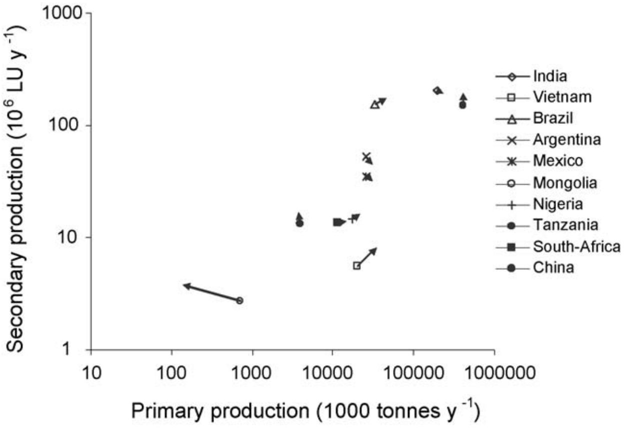

Fig. 1 – Agricultural development between 1990 and 2000 for primary production (crops) and secondary production (livestock) for 10 selected non-Annex 1 countries. *Note.* log–log scale.

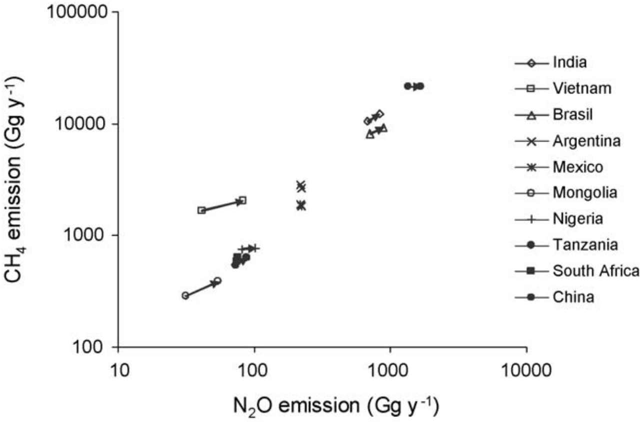

Fig. 2 – Trends in emissions of CH_4 and N_2O from agricultural activities between 1990 and 2000 for 10 selected non-Annex 1 countries. *Note.* log–log scale.

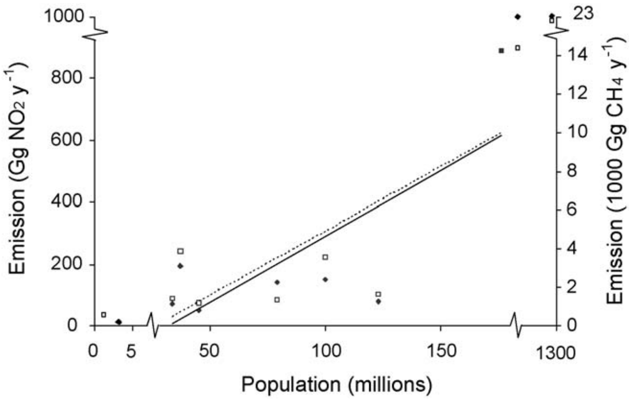

Fig. 4 – CH_4 (diamonds) and N_2O (squares) emissions from agriculture versus population size in all selected countries for the year 2000. Lines show linear regressions for N_2O (dotted, $R^2 = 0.78$) and CH_4 (solid, $R^2 = 0.85$).

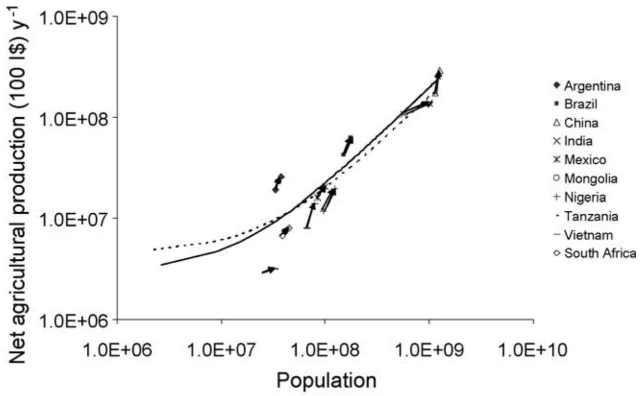

Fig. 3 – Population size and net agricultural production between 1990 and 2000 for all selected countries. Arrows show trends per country; lines show linear regression for 1990 (dashed, $R^2 = 0.91$) and 2000 (solid, $R^2 = 0.97$).

while India showed the lowest growth in agricultural production per inhabitant for the same time period. Between 1990 and 2000 the relation between population and net agricultural production steepened, indicating a general increase of production intensity.

In general, there was a positive relation between population and emissions of N_2O and CH_4 for all selected countries (Fig. 4). These relations were analyzed per country and regression statistics are provided in Table 2. The regression data of Table 2 were used to estimate N_2O and CH_4 emissions from agriculture towards 2050 for those countries where the correlation between emissions and population was relatively strong ($R^2 > 0.75$). The information in Table 2 is based on a 'business as usual' scenario, i.e. relations between population growth and emission of greenhouse gases were derived assuming no changes in setting, structure and management of current agricultural production. Based on this assessment, by 2050 Brazil and India will have the highest CH_4 and N_2O emissions of the selected countries, respectively. However, by unit of total land surface highest emissions are expected for Vietnam for both CH_4 and N_2O emissions. Highest growth rates in emissions are expected for Nigeria for both gases (63%) (Fig. 5).

4. Discussion

Population growth is considered to be one of the major driving forces for increasing CO_2 emissions: a 1% increase in

Table 2 – Significant ($p < 0.05$) parameters in linear regression equations between population and emissions of CH_4 and N_2O from agriculture (Gg y^{-1}), n/a = not applicable because of insignificant parameters.

Country	CH_4		N_2O	
	Equation	R^2	Equation	R^2
South Africa	n/a	0.07	n/a	0.07
Nigeria	$1 \times 10^{-5} \times$ population	0.93	$8 \times 10^{-7} \times$ population	1.00
Tanzania	$3 \times 10^{-5} \times$ population	0.78	n/a	0.58
China	n/a	0.43	n/a	0.49
Vietnam	$3 \times 10^{-5} \times$ population	0.93	$4 \times 10^{-6} \times$ population − 198	1.00
Mongolia	$1 \times 10^{-4} \times$ population	0.96	n/a	0.56
India	n/a	0.56	$8 \times 10^{-7} \times$ population	0.97
Brazil	$7 \times 10^{-5} \times$ population	0.69	$5 \times 10^{-6} \times$ population	0.81
Mexico	n/a	0.30	n/a	0.01
Argentina	n/a	0.50	$6 \times 10^{-6} \times$ population	0.86

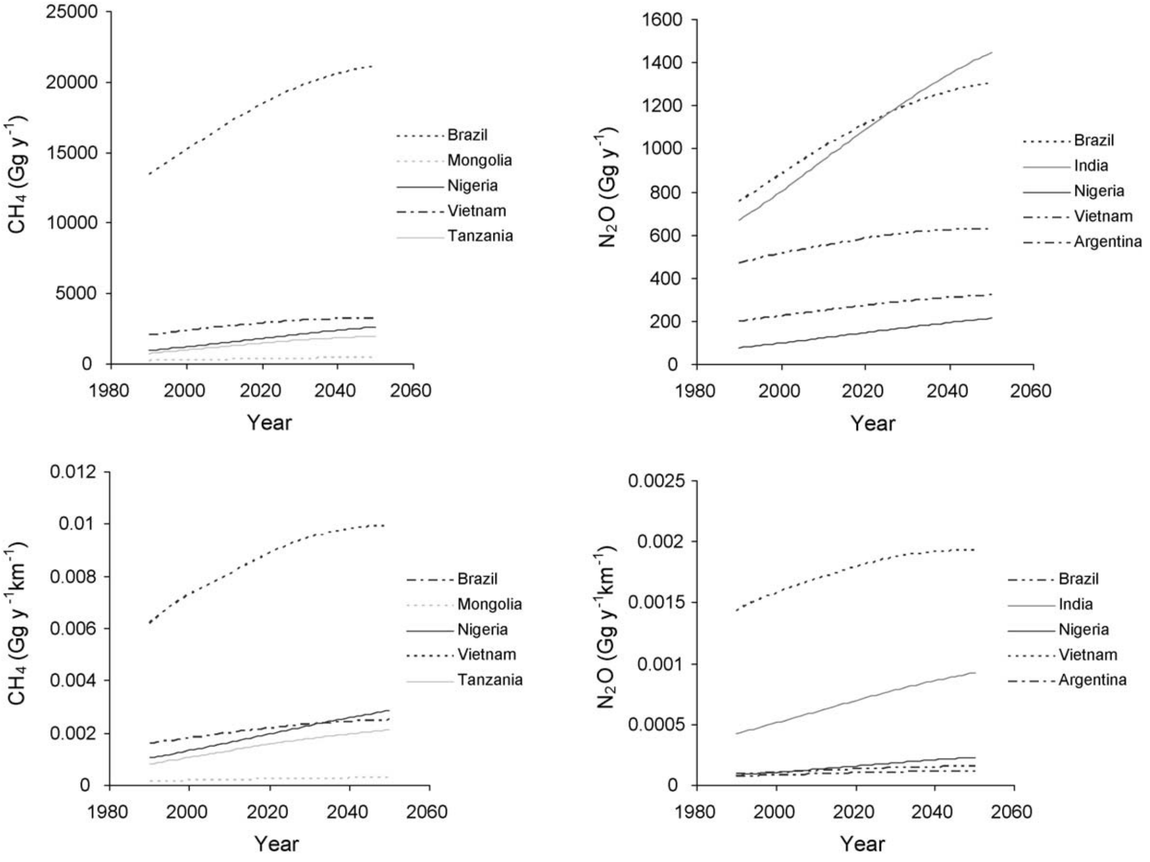

Fig. 5 – *Above*: Estimated course of CH_4 (left) and N_2O (right) emissions from agriculture from 1990 to 2050. *Below*: Idem per unit of total land surface.

population is associated with an average 1.42% increase in CO_2 emissions (Shi, 2003). For CH_4 and N_2O emissions, which mainly originate from agriculture, such 'rules of thumb' are not available, because of the wide variety of farming practices and environmental settings. The FAO (2000) forecasts that population growth rates will gradually decrease, but meanwhile the global grain demand is projected to double from 2000 to 2050 (Cassman, 1999) due to population growth, shifting diets, changing life styles and increasing demand for bio-energy. Especially shifts in diets may lead to a regional increase in the demand for animal proteins, which is already happening in, amongst others, China and Vietnam (Tilman et al., 2002) and can be deduced from Fig. 1 where China and Vietnam show a rapid increase in secondary production. Likewise, the EPA (2006) has predicted 153% increases in emissions from enteric fermentation (mainly CH_4) and 86% increase in manure management (mainly N_2O) between 1990 and 2020 in East-Asia.

The vast majority of the global agricultural production increase is to be realized on existing farm lands (Tilman et al., 2002). Consequently, agriculture has to intensify, which is already happening (Fig. 3) and will affect agricultural greenhouse gas emissions. Although more intensive agriculture may ultimately result in less greenhouse gas emissions per unit of product or protein (FAO, 2008), the gross production of more products will result in increased emissions, unless it is possible to decouple population growth from agricultural growth and greenhouse gas emissions. Fig. 3 demonstrates positive relations between population size and net agricultural production, although the relations may deviate for individual countries due to imports and exports of products. The relation, however, between population size and emissions of N_2O and CH_4 is less solid (Fig. 4) and is sometimes absent as is shown in Table 2. Especially, South Africa, China and Mexico have weak or absent relations between population size and emissions of CH_4 and N_2O. These countries demonstrate that – in principle – it is possible to decouple population growth from emissions of CH_4 and N_2O. Nevertheless, it was difficult to find explaining factors for this decoupling. For China the active population policy, which is expected to result in a drastic decrease in population growth from 2015 onwards, may interfere with our results. For Mexico, and to a lesser extent Mongolia, the use of fertilizers and the number of livestock decreased (not shown) which explains the limited agricultural growth. However, this cannot explain the observed decoupling between population size and emissions of N_2O and CH_4. Other non-agricultural factors such as international trade may have contributed to the decoupling at national level as well, which should be referred to as dislocation in stead of decoupling, because trade induced dislocation does not result in a total decrease in emissions at a global scale.

Using the data we expect average CH_4 and N_2O emissions to increase by 151 and 148% respectively by 2050 for the countries with a positive relation between population and N_2O and CH_4

emissions (Table 2) if no further measures are taken to implement mitigation measures. Options for mitigation of CH_4 and N_2O emissions from agriculture include adapted fertilizer applications (Smith et al., 2007a), reducing animal waste emissions, e.g. by anaerobic digesters (Lucas et al., 2007), modified livestock housing, breeding and feeding technologies (Schils et al., 2005; Smith et al., 2007a; Iqbal et al., 2008) and improved production systems (Smith et al., 2007a; Maraseni et al., 2009), but the effectiveness of measures largely depends on the applicability within different farming systems (EPA, 2006) and the rate of adoption of mitigation measures (Cole et al., 1997). Mitigation measures may reduce emissions from agriculture by 30–85% (Mosier et al., 1998; Cole et al., 1997) depending on the effectiveness of the measure for a specific farming system. However, none of these measures has been consciously implemented and tested at farm scale (Oenema et al., 2001).

At the time of writing the UNFCCC conference on climate change in Copenhagen (COP15) was still upcoming, with presumably more conferences to follow. During these kinds of conferences trends and efforts are discussed and negotiated and up to date information about the contributions and forecasts of different sources on GHG emissions is inevitable. There are also more sophisticated projections available compared to our approach like those published by Schmittner et al. (2008), Knutti et al. (2003), Loutre and Berger (2000) and Leggett et al. (1992). These projections are the result of complex simulation modeling and often focus on CO_2 emission and energy consumption and are used to support the IPCC. In this paper we wanted to stress that due to population growth and shifts in consumption patterns agricultural GHG (especially non-CO_2) emissions will increase and that adaptations of agricultural production systems are required to halt this increase. Therefore, a simple method was used to identify the mechanisms that drive this process. Although this may oversimplify the situation, its transparency may increase the awareness that without adequate measures, the required increase in agricultural production is likely to be achieved at the expense of greenhouse gas emissions.

Nevertheless, the use of data from different sources may pose a jeopardy to the results. Firstly, although the data sources are independently managed, they may have some common grounds. For instance, the EDGAR32 database also used FAO data on agricultural trends for estimating GHG emissions besides independent data sources like atmospheric studies and IPCC data (Olivier and Berdowski, 2001), which may put the independency of different data sources at stake. Secondly, linking population size to agricultural production levels poses a jeopardy to our study, since agricultural production is increasingly a global market, where sites of production and consumption are often dislocated. Thirdly, we had only three data points to relate emissions to population growth (Table 2 and Fig. 4). Although we tested the parameters for significance, it is still a minor basis for extrapolation until 2050. Due to the absence of reliable additional date that might be used to strengthen this extrapolation, the conclusions of this study should be interpret as a potential (and probably likely) scenario, but not as a quantification of future emissions. Fourthly, we assumed a static world, i.e. there were no drastic changes in consumption patters, resulting in changing demands for agricultural production. However, actually this last issue probably provides the strongest measure to remediate greenhouse gas emission from agriculture. I.e. Stehfest et al. (2009) estimated that a low meat diet as recommended for health reasons would reduce the mitigation costs to achieve a 450 ppm CO_2 eq. target by about 50% compared to business as usual.

The selected non-Annex I countries represent a broad range of agricultural settings (Table 1). Agricultural settings may differ in spatial scales, geography, climate, production resources, institutional organization and policies affecting agricultural conditions. Our study demonstrates diverse responses in CH_4 and N_2O emissions from agricultural production for the selected non-Annex 1 countries. To combat increasing N_2O and CH_4 emissions from agriculture mitigation measures should take account of the agricultural diversity. This diversity ranges from large scale monocultures in e.g. South Africa to small scale mixed farming systems in e.g. Nigeria (Table 1). To reduce emissions of CH_4 and N_2O from agriculture in non-Annex 1 countries tailor made mitigation measures for each farming system are needed. Regional solutions should be sought in order to solve the global problem. Future studies should focus on identification of most effective mitigation measures per farming system in order not to feed the world at the expense of the climate.

Acknowledgements

This study was carried out as part of the climate change and police research programme (BO-01-004) of the Dutch Ministry of Agriculture, Nature and Food Quality.

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