Cool Farming:
Climate impacts of agriculture and mitigation potential

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Overall finding and conclusions:

Agriculture contributes significantly to greenhouse gas emissions (GHG). Agricultural soil and livestock directly emit large amounts of potent greenhouse gases. Agriculture's indirect emissions include fossil fuel use in farm operations, the production of agrochemicals and the conversion of land to agriculture. The total global contribution of agriculture, considering all direct and indirect emissions, is between 8.5 – 16.5 Pg CO_2-eq[1,2], which represents between 17 and 32% of all global human-induced GHG emissions, including land use changes (Figure 1).

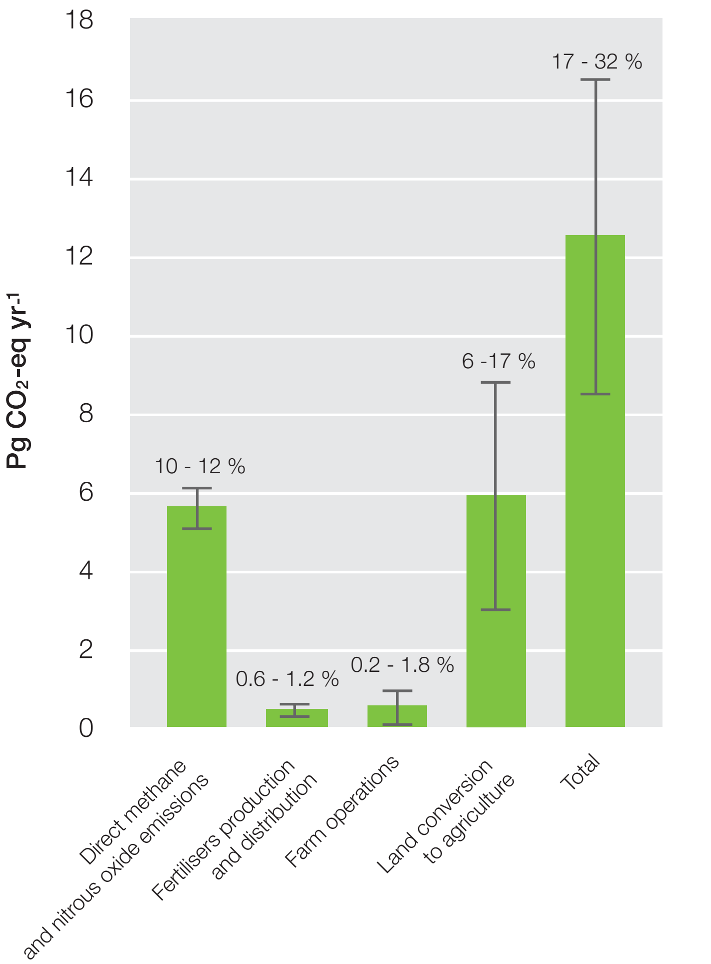
Some historic anomalies in the atmospheric GHG concentrations can be attributed to early changes in farming practices such as the development of wet rice cultivation several thousands of years ago. In the last century, there have been even more substantial changes in agriculture, with the uptake of synthetic fertilisers, development of new crop varieties ("Green Revolution") and the adoption of large-scale farming systems. The sustainability of modern "industrial" agriculture has been questioned.

The solution to the environmental problems caused by today's agricultural methods lies in a shift to farming practices which could provide large-scale carbon sinks, and offer options for mitigation of climate change: improved cropland management (such as avoiding bare fallow, and appropriate fertiliser use), grazing-land management, and restoration of organic soils as carbon sinks. Since meat production is inefficient in its delivery of products to the human food chain, and also produces large emissions of GHG, a reduction of meat consumption could greatly reduce agricultural GHG emissions. Taken together, these could change the position of agriculture from one of the largest greenhouse gas emitters to a much smaller GHG source or even a net carbon sink.

Footnote 1) 1 Pg (Peta gram) = 1 Gt (Giga tonne) = 1000 million tonnes. To convert Pg CO_2-eq to million tonnes multiply by 1000; e.g. 15.5 Pg CO_2-eq equals 15.5 Gt CO_2-eq or 15500 million tonnes CO_2-eq.

Footnote 2) Emissions of greenhouse gases nitrous oxide (N_2O) and methane (CH_4) are often expressed as the equivalent units in CO_2 in terms of their global warming potential in 100 years: N_2O has 296 times the warming potential of CO_2 and CH_4 23 times.

Figure 1. Global contribution of agriculture to greenhouse gas emissions.



Total global contribution of agriculture to greenhouse gas emissions, including emissions derived from land use changes. The overall contribution includes direct (methane and nitrous oxide gases from agriculture practices) and indirect (carbon dioxide from fossil fuel use and land conversion to agriculture). Percentages are relative to global greenhouse gas emissions.

Overview: The main sources of greenhouse gas emissions in agriculture

Agriculture directly contributes between 5.1 and 6.1 Pg CO_2-eq (10 – 12%) to global greenhouse gas emissions. These emissions are mainly in the form of methane (3.3 Pg CO_2-eq yr^{-1}) and nitrous oxide (2.8 Pg CO_2-eq yr^{-1}) whereas the net flux of carbon dioxide is very small (0.04 Pg CO_2-eq yr^{-1}).

Nitrous oxide (N_2O) emissions from soils and methane (CH_4) from enteric fermentation of cattle constitute the largest sources, 38% and 32% of total non-CO_2 emissions from agriculture in 2005, respectively. Nitrous oxide emissions are mainly associated with nitrogen fertilisers and manure applied to soils. Fertilisers are often applied in excess and not fully used by the crop plants, so that some of the surplus is lost as N_2O to the atmosphere. Biomass burning (12%), rice production (11%), and manure management (7%) account for the rest (Table 1).

Clearing of native vegetation for agriculture (i.e. land use change rather than agriculture per se) does release large quantities of ecosystem carbon as carbon dioxide (5.9 ± 2.9 Pg CO_2-eq yr^{-1}).

The magnitude and relative importance of the different sources and emissions vary widely between regions. Globally, agricultural methane (CH_4) and nitrous oxide (N_2O) emissions have increased by 17% from 1990 to 2005, and are projected to increase by another 35 – 60% by 2030 driven by growing nitrogen fertiliser use and increased livestock production.

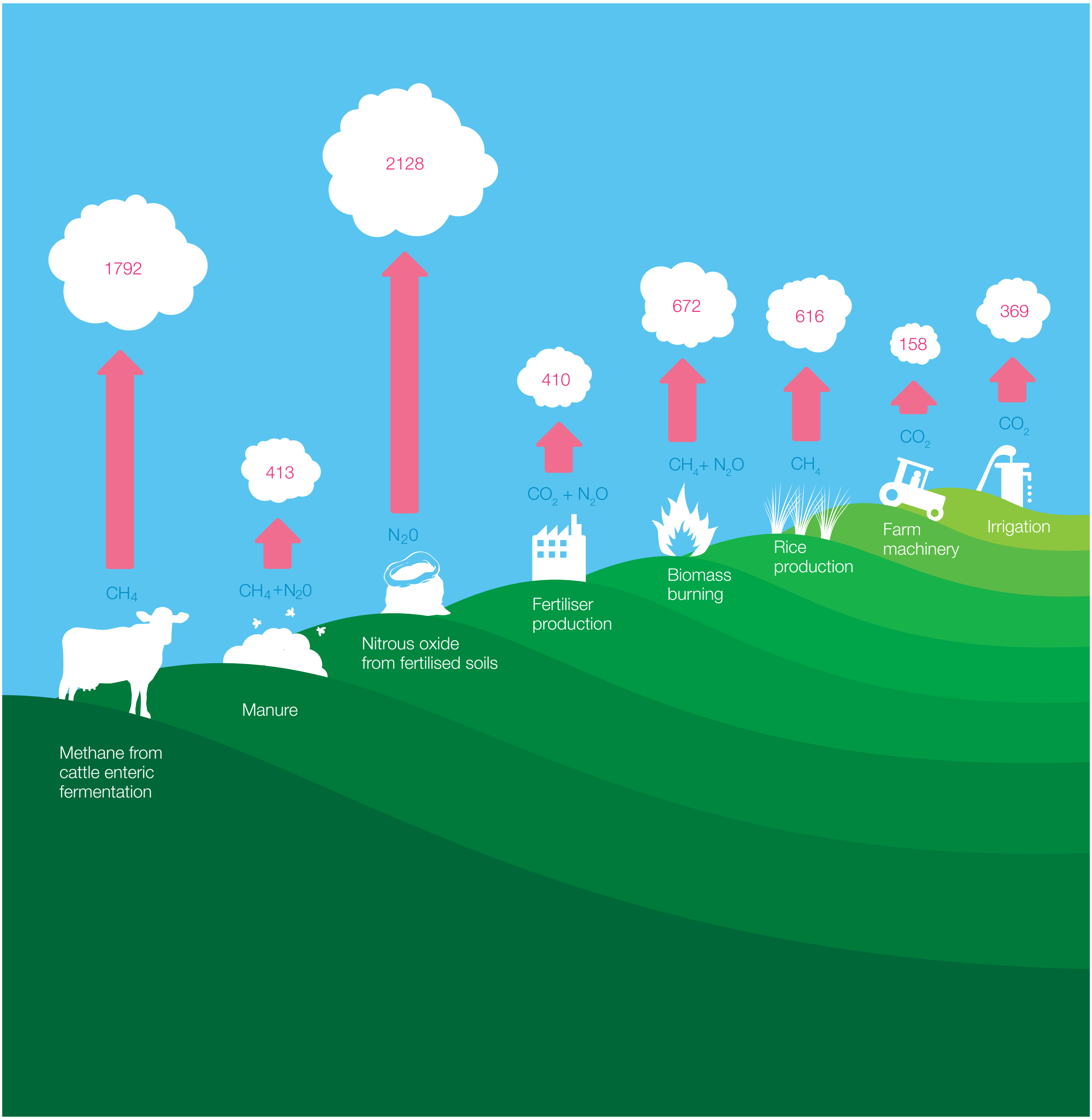
Table 1. Sources of direct and indirect agriculture greenhouse gases

Sources of agriculture GHG	**Million tonnes CO_2-eq**
Nitrous oxide from soils	2128
Methane from cattle enteric fermentation	1792
Biomass burning	672
Rice production	616
Manure	413
Fertiliser production	410
Irrigation	369
Farm machinery (seeding, tilling, spraying, harvest)	158
Pesticide production	72
Land conversion to agriculture	5900

The values in the table are averages of the ranges given throughout the text.

Figure 2. sources of agricultural greenhouse gases, excluding land use change

Mt CO_2-eq



Agrochemicals and climate change

In addition to the direct agriculture emissions mentioned above, the production of agrochemicals is another important source of greenhouse gas emissions. Especially the life cycle of fertiliser contributes significantly to the overall impact of industrialized agriculture. The production of fertilisers is energy intensive, and adds a noticeable amount, between 300 and 600 million tonnes (0.3 - 0.6 Pg) CO_2-eq yr^{-1}, representing between 0.6 - 1.2% of the world's total GHGs. The greatest source of GHG emissions from fertiliser production is the energy required, which emits carbon dioxide, although nitrate production generates even more CO_2-eq in the form of nitrous oxide. With the intensification of agriculture, the use of fertilisers has increased from 0.011 Pg N in 1960/61, to 0.091 Pg N in 2004/2005. Application rates vary greatly between regions with China contributing 40% and Africa 2% to global mineral fertiliser consumption.

Compared to fertiliser production, other farm operations such as tillage, seeding, application of agrochemicals, harvesting are more variable across the globe with emissions between 0.06 and 0.26 Pg CO_2-eq yr^{-1}. Irrigation has average global GHG emissions of between 0.05 and 0.68 Pg CO_2-eq yr^{-1}. The production of pesticides is a comparatively low GHG emitter with 0.003 to 0.14 Pg CO_2-eq annually.

Land use

The amount of carbon stored in croplands is the lowest of all land types (with the exception of deserts and semideserts). Therefore, all land use change to cultivated land will result in a net emission of carbon. However, the actual contribution of land use change has a high uncertainty, but is estimated to be 5.9 ± 2.9 Pg CO_2-eq. Land use change is mainly driven by economics and legislation, but also by the availability of land. The main expansion of global croplands is thought to be over, though expansion into tropical forests continues to be a major problem. Global woodland areas are projected to decrease at an annual rate of ~43,000 km^2, but developed countries are projected to increase their woodland area by 7,400 km^2 per year.

Animal farming

Animal farming has a wide range of different impacts, ranging from the direct emissions of livestock, manure management, use of agrochemicals and land use change to fossil fuel use. Enteric fermentation contributes about 60%, the largest amount, to global methane emissions. The demand for meat determines the number of animals that need to be kept. Furthermore, the livestock sector is the largest user of land, with a shift in practice away from grazing to the growth of livestock feed crops. The use of high energy feed crops has recently encouraged the deforestation of the Amazon rainforest in Brazil, a major producer of soya used in animal feed. The demand for meat is increasing steadily, driven by economic growth, and is likely to encourage the expansion of intensive animal farms. The greatest increase in meat consumption is observed in developing countries (77% increase between 1960 and 1990), which previously had a very low meat consumption (8% of calories from animal sources) compared to developed countries (27% of calories from animal sources) in 1960. Sheep and beef meat have the highest climate impact of all types of meat, with a global warming potential of 17 and 13 kg CO_2-eq per kg of meat, while pig and poultry have less than half of that.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Mitigation

Agriculture has a significant climate change mitigation potential, which could change the position of agriculture from the second largest emitter to a much smaller emitter or even a net sink. There are a wide range of mitigation options in agriculture with an overall potential of up to 6 Pg CO_2-eq yr^{-1}, but with economic potentials of around 4 Pg CO_2-eq yr^{-1} at carbon prices up to 100 US$ t CO_2-eq^{-1}. This overall potential could mitigate close to 100% of agriculture's direct emissions. By far the greatest mitigation contribution originates from soil carbon sequestration (5.34 Pg CO_2-eq yr^{-1}), but also methane (0.54 Pg CO_2-eq yr^{-1}) and nitrous oxide (0.12 Pg CO_2-eq yr^{-1}) emissions can be considerably reduced.

The low carbon concentration in croplands means that there is a great potential to increase carbon content through beneficial management practices. Where land uses have changed to become predominantly agricultural, restoration of the carbon content in cultivated organic soils has a high per-area potential and represents the area of greatest mitigation potential in agriculture.

The most prominent options for mitigation in agriculture emissions are:

1. Cropland management (mitigation potential up to ~1.45 Pg CO_2-eq yr^{-1}) such as:

- Avoiding leaving land bare: Bare soil is prone to erosion and nutrient leaching and contains less carbon than the same field with vegetation. Important solutions are "catch" and "cover" crops, which cover the soil in between the actual crop or in fallow periods, respectively.
- Using an appropriate amount of nitrogen fertiliser by avoiding applications in excess of immediate plant requirements, by applying it at the right time, and by placing it more precisely in the soil. Reducing the reliance on fertilisers by adopting cropping systems such as use of rotations with legume crops has a high mitigation potential.
- No burning of crop residues in the field.
- Reducing tillage: No-till agriculture can increase carbon in the soil, but in industrial farming settings this maybe offset by increasing reliance on herbicides and machinery. However, for organic systems some preliminary study results showed that reduced tillage without the use of herbicides has positive benefits for carbon sequestration in the soil.

2. Grazing land management (mitigation potential up to ~1.35 Pg CO_2-eq yr^{-1}) such as reducing grazing intensity or reducing the frequency and intensity of fires (by active fire management). These measures typically lead to increased tree and shrub cover, resulting in a CO_2 sink in both soil and biomass.

3. Restoration of organic soils that are drained for crop production and restoration of degraded lands to increase carbon sinks (combined mitigation potential ~2.0 Pg CO_2-eq yr^{-1}): avoid drainage of wetlands, carry out erosion control, add organic and nutrient amendments.

4. Improved water and rice management (~0.3 Pg CO_2-eq yr^{-1}); in the off-rice season, methane emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding waterlogging.

5. Lower but still significant mitigation is possible with set-asides, land use change (e.g., conversion of cropland to grassland) and agro-forestry (~0.05 Pg CO_2-eq yr^{-1}); as well as improved livestock and manure management (~0.25 Pg CO_2-eq yr^{-1}).

6. Increasing efficiency in the manufacturing of fertilisers can contribute significantly with a reduction of up to about ~0.2 Pg CO_2-eq yr^{-1}. Improvements would be related to greater energy efficiency in ammonia production plants (29%), introduction of new nitrous oxide reduction technology (32%) and other general energy-saving measures in manufacturing (39%).

7. Consumers can play an important role in the reduction of agricultural GHG emissions. A reduction in the demand for meat could reduce related GHG emissions considerably. Adopting a vegetarian diet, or at least reducing the quantity of meat products in the diet, would have beneficial GHG impacts. A person with an average US diet for example, could save 385 kcal (equating to 95 – 126 g CO_2) of fossil fuel per day by replacing 5% of meat in the diet with vegetarian products.

The soy industry destroys large areas of the pristine Amazon rainforest to clear land for soy plantations


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1. Introduction

Agricultural practices have changed dramatically since the time of hunters and gatherers, which initially were related to land use change and changes in management practices like irrigation and tillage. Several historical greenhouse gas (GHG) anomalies are thought to be associated with these shifts like, for example, an increase in the methane concentration with the start of paddy rice farming in Asia about 5000 years ago (Desjardins *et al.*, 2007). These anomalies are presented in detail by Ruddiman (2003), and Salinger (2007). With an ever increasing population to feed, larger scale changes were needed to meet the demand for food. During the 20th century, agronomic research focused on creating high yielding varieties, and agriculture intensified by mechanisation and the use of agrochemicals such as mineral fertilisers, herbicides and pesticides. The "Green Revolution" enabled, for example, cereal production in Asia to double between 1970 and 1975 with a concurrent land use change to agriculture of only 4%. However, it generally encouraged the further expansion into previously uncultivated areas due to higher profits (IFPRI, 2002). Intensive agriculture relies on high external inputs, particularly of fertilisers, pesticides, herbicides, irrigation and fossil fuels, applying management strategies that are simple to maintain at a large scale (Jackson *et al.*, 2007). The environmental and social costs (pollution, loss of biodiversity and traditional knowledge) are high and may potentially undermine future capacity to maintain required levels of food production (Jackson *et al.*, 2007) (Foley *et al.*, 2005).

It is currently estimated that there is still more land under extensive agriculture (17%) compared to intensive agriculture (10%), with an even greater share occupied by domestic livestock (40%). However, with an increasing demand for food, this may change in favour of more and more intensively farmed land (Jackson *et al.*, 2007). Indeed, some have argued that since land suitable for conversion to agriculture is dwindling (Desjardins *et al*., 2007), intensification on the agricultural land currently available will be the only way to feed the projected 9 billion people on the planet (FAO, 2002) by the end of this century (Riedacker and Dessus, 1997). In addition the increasing competition for access to the dwindling stocks of fossil fuels will increase the competitiveness of crops grown for bioenergy and will cause a financial incentive to increase the amount of land used for intensive arable purposes, and ultimately lead to higher prices for agricultural and forestry products (Sims *et al*, 2006) and competition for land between energy and food production.

Agriculture is a major contributor of GHGs to the atmosphere, but the emissions vary depending on the land use and the way that the land is managed. However, a quantified separation of intensive and extensive agriculture is difficult for a number of reasons, a) there are many complex interactions between different practices and effects, b) statistics on intensity of land use are rarely available (statistics are collected in a different form), and c) often, intensive and non-intensive farming practices are present on the same farm, making categorisation of farms as intensive / non-intensive very difficult. For this reason, we focus on the individual practices known to influence GHG emissions to the atmosphere, and were possible we present information at the aggregated systems level to examine the impacts of intensive vs. non-intensive agriculture.

2. Greenhouse gas emissions from agriculture

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Recently, the contribution of Working Group III to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report assessed greenhouse gas emission trends from agriculture (IPCC WGIII Ch.8, 2007). The following two sections are largely derived from that report.

2.1 Global GHG emissions from agriculture, excluding land use change

Agricultural lands (lands used for agricultural production, consisting of cropland, managed grassland and permanent crops including agro-forestry and bio-energy crops) occupy about 40-50% of the Earth's land surface. Agriculture accounted for an estimated emission of 5.1 to 6.1 Pg CO_2-eq yr^{-1} in 2005 (10-12% of total global anthropogenic emissions of GHGs). Methane (CH_4) contributes 3.3 Pg CO_2-eq yr^{-1} and nitrous oxide (N_2O) 2.8 Pg CO_2-eq yr^{-1}. Of global anthropogenic emissions in 2005, agriculture accounts for about 60% of N_2O and about 50% of CH_4 (IPCC WGIII Ch.8, 2007). Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with CO_2 emissions around 0.04 Pg CO_2 yr^{-1}, though clearing of native vegetation for agriculture (i.e. land use change rather than agriculture per se) does release large quantities of ecosystem carbon as carbon dioxide (5.9 ± 2.9 Pg CO_2-eq yr^{-1} (IPCC, 2001)).

Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005, an average annual emission increase of about 0.06 Pg CO_2-eq yr^{-1}. During that period, the five regions composed of developing countries and countries with economies in transition showed a 32% increase, and were, by 2005, responsible for about three-quarters of total agricultural emissions. The other five regions, mostly industrialised countries, collectively showed a decrease of 12% in the emissions of these gases (IPCC WGIII Ch.8, 2007).

Nitrous Oxide emissions from soils and CH_4 from enteric fermentation constitute the largest sources, 38% and 32% of total non-CO_2 emissions from agriculture in 2005, respectively (US-EPA, 2006a). Biomass burning (12%), rice production (11%), and manure management (7%) account for the rest.

Both the magnitude of the emissions and the relative importance of the different sources vary widely among world regions. In Africa, North America, Europe and most of Asia (seven of the ten world regions as defined by US-EPA 2006a), N_2O from soils was the main source of GHGs in the agricultural sector in 2005, mainly associated with N fertilisers and manure applied to soils. In Latin America and the Caribbean, the countries of Eastern Europe, the Caucasus and Central Asia, and OECD Pacific (the other three regions in US-EPA 2006a) CH_4 from enteric fermentation was the dominant source (US-EPA, 2006a; IPCC WGIII Ch.8, 2007). This is due to the large livestock population in these three regions which, in 2004, had a combined stock of cattle and sheep equivalent to 36% and 24% of world totals, respectively (FAO, 2002).

Emissions from rice production and burning of biomass were heavily concentrated in the group of developing countries, with 97% and 92% of world totals, respectively. While CH_4 emissions from rice occurred mostly in South and East Asia, where it is a dominant food source (82% of total emissions), those from biomass burning originated in Sub-Saharan Africa and Latin America and the Caribbean (74% of total). Manure management was the only source for which emissions where higher in the group of developed regions (52%) than in developing regions (48%; US-EPA, 2006a).

The balance between the large fluxes of CO_2 emissions and removals in agricultural land is uncertain. A study by US-EPA (2006b) showed that some countries and regions have net emissions, while others have net removals of CO_2. Except for the countries of Eastern Europe, the Caucasus and Central Asia, which had an annual emission of 0.026 Pg CO_2 yr^{-1} in 2000, all other countries showed very low emissions or removals.

Globally, agricultural CH_4 and N_2O emissions increased by 17% from 1990 to 2005, an average annual emission increase of 0.058 Pg CO_2-eq yr^{-1} (US-EPA, 2006a). Both gases had about the same share of this increase. Three sources together explained 88% of the increase: biomass burning (N_2O and CH_4), enteric fermentation (CH_4) and soil N_2O emissions (US-EPA, 2006a).

2.2 Projected changes in GHG emissions from agriculture over the next 25 years

Agricultural N_2O emissions are projected to increase by 35-60% up to 2030 due to increased nitrogen fertiliser use and increased animal manure production (FAO, 2002). Similarly, Mosier and Kroeze (2000) and US-EPA (2006a) estimated that N_2O emissions will increase by about 50% by 2020 (relative to 1990). If demands for food increase, and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further. But improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or protein) produced, and perhaps also a reduction in emissions per capita food consumption.

If CH_4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production (from enteric fermentation and manure management) is expected to increase by 60% in the period 1990 to 2030 (FAO, 2002). However, changes in feeding practices and manure management could ameliorate this increase. US-EPA (2006a) forecast that combined methane emissions from enteric fermentation and manure management will increase by 21% between 2005 and 2020.

The area of rice grown globally is forecast to increase by 4.5% to 2030 (FAO, 2002), so methane emissions from rice production would not be expected to increase substantially. There may even be reductions if less rice is grown under continuous flooding (causing anaerobic soil conditions) as a result of scarcity of water, or if new rice cultivars that emit less methane are developed and adopted (Wang *et al.*, 1997). However, US-EPA (2006a) projects a 16% increase in CH_4 emissions from rice crops between 2005 and 2020, mostly due to a sustained increase in the area of irrigated rice.

No baseline agricultural non-CO_2 GHG emission estimates for the year 2030 have been published, but according to US-EPA (2006a), aggregate emissions are projected to increase by ~13% during the decades 2000-2010 and 2010-2020. Assuming similar rates of increase (10-15%) for 2020-2030, agricultural emissions might be expected to rise to 8 – 8.4, with a mean of 8.3 Pg CO_2-eq by 2030. With projected global median emissions of about 55 Pg CO_2-eq in the same time period, agriculture would contribute about 15% (IPCC WGIII Ch.8, 2007) equating to a 3% increase of its contribution. However, this slight increase has a high uncertainty considering the wide potential ranges of future emissions. The future evolution of CO_2 emissions from agriculture is uncertain.

The Middle East and North Africa, and Sub-Saharan Africa have the highest projected growth in emissions, with a combined 95% increase in the period 1990 to 2020 (US-EPA, 2006a). Sub-Saharan Africa is the one world region where per-capita food production is either in decline, or roughly constant at a level that is less than adequate (Scholes and Biggs, 2004). This trend is linked to low and declining soil fertility (Sanchez, 2002), and inadequate fertiliser inputs. Although slow, the rising wealth of urban populations is likely to increase demand for livestock products. This would result in intensification of agriculture and expansion to still largely unexploited areas, particularly in South and Central Africa (including Angola, Zambia, DRC, Mozambique and Tanzania), with a consequent increase in GHG emissions.

East Asia is projected to show large increases in GHG emissions from animal sources. According to FAO (FAOSTAT, 2006), total production of meat and milk in Asian developing countries increased more than 12 times and four times, respectively, from 1961 to 2004. Since the per-capita consumption of meat and milk is still much lower in these countries than in developed countries, increasing trends are expected to continue for a relatively long time. Accordingly, US-EPA (2006a) forecast increases of 153% and 86% in emissions from enteric fermentation and manure management, respectively, from 1990 to 2020. In South Asia, emissions are increasing mostly because of expanding use of N fertilisers and manure to meet demands for food, resulting from rapid population growth.

In Latin America and the Caribbean, agricultural products are the main source of exports. Significant changes in land use and management have occurred, with forest conversion to cropland and grassland the most significant, resulting in increased GHG emissions from soils (CO_2 and N_2O). The cattle population has increased linearly from 176 to 379 million head between 1961 and 2004, partly offset by a decrease in the sheep population from 125 to 80 million head. All other livestock categories have increased in the order of 30 to 600% since 1961. Cropland areas, including rice and soybean, and the use of N fertilisers have also shown dramatic increases (FAOSTAT, 2006). Another major trend in the region is the increased adoption of no-till agriculture, particularly in the Mercosur area (Brazil, Argentina, Paraguay, and Uruguay). This technology is used on ~300,000 km^2 every year in the region, although it is unknown how much of this area is under permanent no-till (IPCC WGIII Ch.8, 2007).

In the countries of Central and Eastern Europe, the Caucasus and Central Asia, agricultural production is, at present, about 60-80% of that in 1990, but is expected to grow by 15-40% above 2001 levels by 2010, driven by the increasing wealth of these countries. A 10-14% increase in arable land area is forecast for the whole of Russia due to agricultural expansion. The widespread application of intensive management technologies could result in a 2 to 2.5-fold rise in grain and fodder yields, with a consequent reduction of arable land, but will increase N fertiliser use. Decreases in fertiliser N use since 1990 have led to a significant reduction in N_2O emissions. But, under favourable economic conditions, the amount of N fertiliser applied will again increase, although unlikely to reach pre-1990 levels in the near future, due to the increasing cost of manufacture driving efficiency in use. US-EPA (2006a) projected a 32% increase in N_2O emissions from soils in these two regions between 2005 and 2020, equivalent to an average rate of increase of 0.004 Pg CO_2-eq yr^{-1}.

OECD North America and OECD Pacific are the only developed regions forecasting a consistent increase in GHG emissions in the agricultural sector (18% and 21%, respectively between 1990 and 2020). In both cases, the trend is largely driven by non-CO_2 emissions from manure management and N_2O emissions from soils. In Oceania, nitrogen fertiliser use has increased exponentially over the past 45 years with a 5 and 2.5 fold increase since 1990 in New Zealand and Australia, respectively. In North America, in contrast, nitrogen fertiliser use has remained stable; the main driver for increasing emissions is management of manure from cattle, poultry and swine production, and manure application to soils. In both regions, conservation policies have resulted in reduced CO_2 emissions from land conversion. Land clearing in Australia has declined by 60% since 1990 with vegetation management policies restricting further clearing, while in North America, some marginal croplands have been returned to woodland or grassland.

Western Europe is the only region where, according to US-EPA (2006a), GHG emissions from agriculture are projected to decrease up to 2020. This is associated with the adoption of a number of climate-specific and other environmental policies in the European Union, as well as economic constraints on agriculture (IPCC, WGIII, Ch. 8, 2007).

2.3 Indirect emissions arising from agricultural practices

In the previous two sections only the direct agricultural emissions are considered, however, for a complete analysis the indirect carbon emissions, which arise from use of farm machinery, production of fertilisers, production and use of pesticides and irrigation should be added to estimate the total GHG emissions from agriculture.

Table 2 shows a summary of global GHG emissions of different farm operations (Lal, 2004c). The large ranges in values reflect different management practices, but still there is a high uncertainty associated with these values. This is a result of the extrapolation to the total cropland and arable land, which may in general not all require irrigation and therefore is generally overestimated. On the other hand, permanent pastures have not been considered at all, which are in some parts managed to some extent. Generally, management practices and therefore energy consumption will vary widely in different global regions, which is reflected by the wide range (one order of magnitude!) of emissions that may be emitted at a global level (Table 2). In contrast, the emission range of fertiliser production and use is much narrower. Emissions from fertiliser are based on the global consumption and the minimum value (0.284 Pg) is actually very similar to the global emissions (0.283 Pg) as given by Kongshaug (1998). The sum of all farm practices (including fertiliser) contributes a significant amount to global carbon emissions, between 0.4 and 1.7 Pg of CO_2-eq. Here, the production of fertiliser is the largest single emitter (0.3 – 0.6 Pg CO_2-eq), followed by the use of farm machinery for a variety of management practices (0.06 – 0.26 Pg CO_2-eq), irrigation (0.05 – 0.68 Pg CO_2-eq) and pesticide production (up to 0.14 Pg CO_2-eq).

Total global agricultural GHG emissions will be the sum of agricultural emissions (5.1 – 6.1 Pg, 10 – 12 % of total global emissions), land use change (5.9 ± 2.9 Pg; 6 – 17 % of total global emissions), agrochemical production/distribution (0.3 – 0.7 Pg, 0.6 – 1.4 % of total global emissions) and farm operations (including irrigation) (0.1 – 0.9 Pg, 0.2 – 1.8 % of total global emissions). Consequently, the total global contribution of agriculture considering all direct (such as soil and livestock emissions) and indirect (such as fossil fuel use, fertiliser production and land use change) would be between 16.8 and 32.2 %, including land use change (see section 3.2).

Table 2: GHG emissions from fossil fuel and energy use in farm operations and production of chemicals for agriculture.

	kg CO_2-eq km^{-2}	Pg CO_2-eq
Tillage[a]	440 – 7360	0.007 – 0.113
Application of agrochemicals[b]	180 – 3700	0.003 – 0.057
Drilling or seeding[c]	810 – 1430	0.015 – 0.022
Combine harvesting[d]	2210 – 4210	0.034 – 0.065
Use of farm machinery	**Subtotal**	**0.059 – 0.257**
Pesticides (production)[e]	220 – 9220	0.003 – 0.14
Irrigation[f]	3440 – 44400	0.053 – 0.684
Fertiliser (production)[g]	–	0.284 – 0.575
Total		**0.399 – 1.656**

Data retrieved from (Lal, 2004c) in carbon per ha transformed into Pg CO_2-eq by using the area under permanent crops and arable land (15.41 M km^2) in 2003 (FAOSTAT, 2007).

a from Lal, 2004c Table 2, minimum value of rotary hoeing to maximum value of mouldboard ploughing.

b from Lal, 2004c Table 4. minimum and maximum from “Spray herbicide, Chemical Incorporation, Fertiliser spraying and spreading”.

c Table Lal, 2004c 4, minimum and maximum value from “Plant/sow/drill”

d Table Lal, 2004c 4, minimum and maximum value from “Soybean and corn harvesting”

e low and high herbicide rates (0.5 – 2 kg ha-1) as described by Clemens *et al.* (1995) in Table 4 multiplied by low and high carbon emissions as described by Lal (2004c) in Table 5

f from Lal, 2004c Table 3

g carbon emission range from Table 3 (this report) multiplied by consumption in Table 4 (this report)

3. Greenhouse gas emissions from specific agricultural practices

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3.1 Greenhouse gas emissions from the production, transport and use of agricultural fertilisers

Fertilisers are increasingly used in agriculture (Figure 3 and Figure 4). The life cycle of fertiliser contributes significantly to the overall impact of conventional agriculture. The production of fertilisers is energy intensive, and emits about 1.2% of the world's total GHGs (Wood and Cowie, 2004). Before 1930, nitrates used to be mined but this practice is now more expensive than the synthetic fertiliser production using fossil fuel energy with which it has been replaced. There is a great difference between the energy requirements, and hence GHG emissions, for the production of different types of fertilisers (Table 3). Generally, fertilisers containing N compounds consume up to 10 times more energy and consequently result in more GHG emissions. In comparison, fresh manure is a very low carbon emitting alternative when it is available to provide land with nutrients (Lal, 2004c) (Table 3). However, the actual energy consumed during the production can vary widely as very modern plants have the potential to efficiently use the heat produced during the reaction process and hence may even have a negative energy balance, for production of nitrate will also generate nitrous oxide as a by-product. Considering that nitrous oxide has a global warming potential of ~296 compared to carbon dioxide, this is the main GHG in the nitrate production (Brentrup *et al*., 2004) (Wood and Cowie, 2004). As a result, nitrous oxide contributes 26% (0.074 Pg CO_2-eq yr^{-1}) of the global total fertiliser production GHG emissions (0.283 Pg CO_2-eq yr^{-1}) (Kongshaug, 1998). The energy consumption of superphosphate and muriate of potash will mainly be associated with mining activities. Additional greenhouse gas emissions will arise from the transport of these fertilisers as mines are not evenly distributed around the world (www.fertilizer.org). Generally, transport and storage will add more to the total GHG emission of fertiliser use (Table 3 & Table 4).

The final use of the fertiliser on the farm will have again a variety of impacts. The machinery used to apply the fertiliser will require fuel, adding to the GHG emissions. Fertilisers are not used fully by the crop, which on average globally only recover about 50% of fertiliser N supplied (Eickhout *et al.,* 2006). Consequently, a great proportion accumulates in soils and is either lost directly as nitrous oxide, or leaches into water courses, enhancing downstream, indirect nitrous oxide emissions. The amount lost will greatly depend on many other factors such as climate, soil and management practices (Brentrup *et al*., 2004) (Eickhout *et al*., 2006).

3.1.1 Effect of agriculture intensification on fertiliser use and emissions.

The intensification of agriculture has greatly increased the use of fertilisers in the last century, which is reported to have increased by over 800% in about 45 years, from 0.011 Pg N in 1960/61, to 0.091 Pg N in 2004/2005 (www.fertilizer.org). However, application rates vary greatly between different countries (Figure 3) with rates mainly driven by economy and legislation. Generally, there is a great difference in the fertiliser consumption between developed and developing countries (Figure 4). The decreasing trend in developed countries is driven by environmental legislation, which may impose threshold levels with associated fines. Furthermore, consumer pressure through supermarkets encourages the uptake of Environmental Management Systems, which address a variety of issues resulting in the optimisation of fertiliser use (Furness, 2003). Within the developing countries China (40% globally; 95% of East Asia) and India (20% globally; 80% of South Asia) are the main drivers of the increase in fertiliser use (Figure 4). In China, the cost of fertilisers has been very low, achieved by subsidies for production and distribution before 1985 (Zeng, 2003). Consequently, application rates are much higher than in other parts of the world (Figure 3). This causes not only an increase in GHG emissions, but also pollution and eutrophication of watercourses. In this case, the high number of small-scale farmers makes it difficult to monitor fertiliser use and enforce more sustainable practices (Zeng, 2003). The Chinese case is contrasted by the situation in Africa, which only uses 2% of the total global fertiliser consumption (www.fertilizer.org). In fact, the amount used by small-scale African farmers is usually underneath the recommended level for the maintenance of soil fertility, resulting in nutrient depletion and loss of soil organic matter (i.e. lower carbon levels in the soil) (Batjes, 2004).

Table 3: Energy requirement and carbon dioxide emissions resulting from the production of different fertilisers.

Fertiliser	Energy requirement in MJ kg^{-1} N	Carbon dioxide emissions in kg (CO_2)/kg produced*
Nitrogen	65 – 101	3.294 – 6.588
Phosporus	15	0.366 – 1.098
Potassium	8	0.366 – 0.732
Lime		0.110 – 0.842
Manure		0.026 – 0.029
N as manure[a]		0.6 – 2.9

Data from (Lal, 2004c); *includes transportation, storage and transfer of agricultural chemicals.

[a]Manure has a nitrogen content of between 1 and 4.5% (Moreno-Caselles *et al.*, 2002), therefore the CO_2 emissions per kg of N have been given here.

Table 4: Total annual GHG emissions from the production of fertilisers (Kongshaug, 1998).

	N	P	K
World			
Consumption in Pg	0.083	0.014	0.017
Total emissions in kg CO_2-eq per kg of fertiliser produced			
Average	3.14	0.7	0.75
Best	1.6	-1.4	0.25
Europe			
Consumption in Pg	0.011	0.001	0.005
Total emissions in kg CO_2-eq per kg of fertiliser produced			
Average	5.3	0.04	0.15
Best	2.45	-0.1	0.06
Total emissions in kg CO_2-eq per kg of fertiliser produced (Includes transport and storage*)	3.30 – 6.6	0.36 – 1.1	0.36 – 0.73
Total emissions in Pg CO_2-eq	0.27-0.55	0.005-0.015	0.006-0.012

*(Lal, 2004c)

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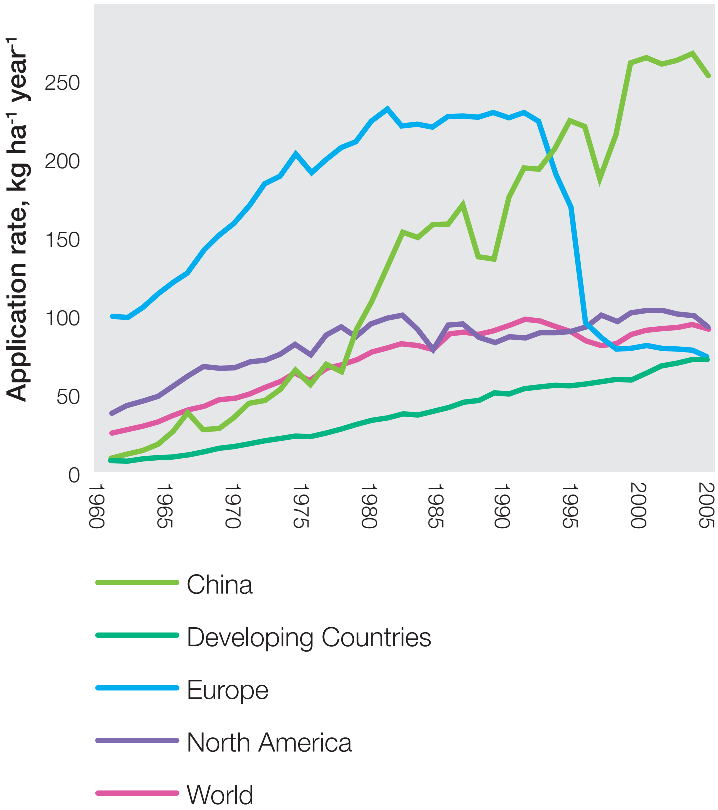
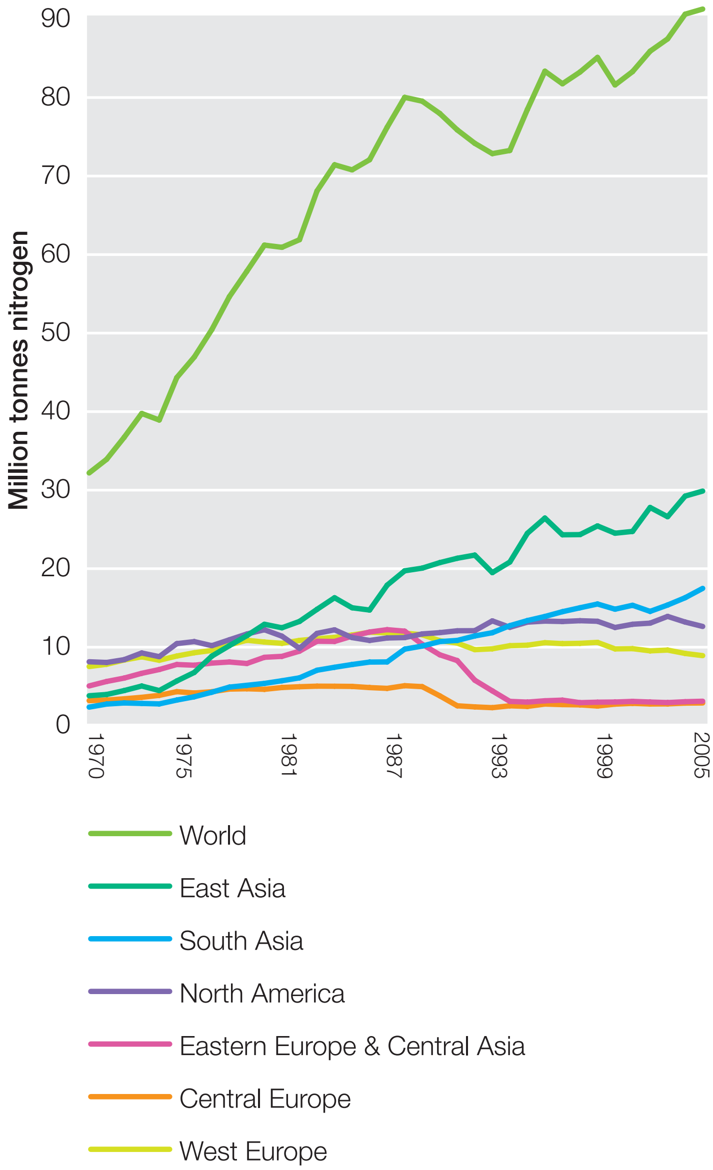
Figure 3. Rate of chemical fertiliser use in arable land in China in comparison with the rest of developing countries, Europe, North America and the world.



“Rate of chemical fertiliser use in arable land (including permanent crop land) in China in comparison with the rest of developing countries, Europe, North America and the world. The rates are based on N for nitrogen, P_2O_5 for phosphorous, and K_2O for potassium. Data source: FAO (2002).” Copied from (Yang, 2006).

Figure 4. World nitrogen fertiliser consumption in regions.



Nitrogen fertiliser consumption in selected regions and world total. Source IFA statistics.

3.2 Greenhouse gas emissions from deforestation and land conversion caused by the expansion of agriculture into uncultivated areas.

Generally, intensively managed land will have lower carbon stocks than natural vegetation (Table 5 & Figure 5). Croplands have the lowest “carbon stock concentration” of all earth biomes, except for deserts and semideserts. In contrast, wetlands have by far the greatest “carbon stock concentration” (more than eight times that of croplands) but they do not even contribute twice as much to the global carbon stock due to the small percentage of land covered by wetlands (Table 5). As a result, the conversion from one land use to croplands can have a considerable effect on carbon stocks (Figure 5).

Houghton (1999, 2003) estimated the net global emissions resulting from land cover change to be about 8.1 Pg CO_2 yr^{-1} in the 1990s (compared with 23.4 Pg CO_2 yr^{-1} from fossil-fuel emissions). Here, agriculture was the most important contributor to land conversion (croplands 68%, pastures 13%, cultivation shift 4%, harvest of wood 16% and establishment of plantations -1%) (Houghton, 1999) and contributes to around 20% of total GHG emissions. In contrast, the IPCC published values of 5.9 ± 2.9 in 2001 (IPCC, 2001). Estimates of land use changes are probably the most uncertain within the GHG inventory (Figure 6 & Figure 7), as actual emissions will depend on several factors (Ramankutty *et al.*, 2007). Despite the uncertainty, it is clear that land use change is a major contributor to global GHG emissions. In some areas, such as e.g. Brazil, it will even be a more important source of GHG than fossil fuels (Cerri *et al.*, 2007). Brazil alone contributed 5% of total global GHG emissions by deforestation in 1990 (Fearnside, 2005). However, the total emissions resulting from this deforestation will be even greater, since future changes in land use could result in further emissions (Fearnside, 2005).

For a complete estimation of the impact of land use change on global climate there are also several non-GHG effects to consider, which alter the physical properties of the land surface. These effects are discussed, for example, in Pielke Sr *et al.,* (2007), Foley *et al.,* (2005).

Table 5: Global carbon stocks in vegetation and top one metre of soils.

Biome	Area	Carbon Stocks (Pg CO_2-eq)			Carbon stock concentration (Pg CO_2-eq M km^{-2})
	M km^2	Vegetation	Soils	Total	
Tropical forests	17.60	776	791	1566	89
Temperate forests	10.40	216	366	582	56
Boreal forests	13.70	322	1724	2046	149
Tropical savannas	22.50	242	966	1208	54
Temperate grasslands	12.50	33	1080	1113	89
Deserts and semideserts	45.50	29	699	728	16
Tundra	9.50	22	443	465	49
Wetlands	3.50	55	824	878	251
Croplands	16.00	11	468	479	30
Total	151.20	1706	7360	9066	60

Source: IPCC 2001, Land use, land use change and forestry.

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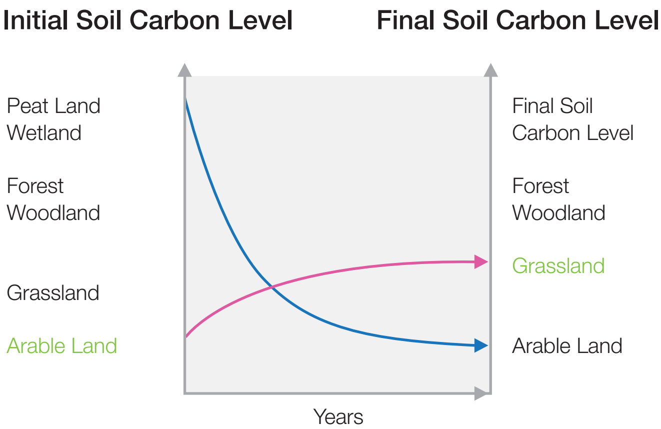
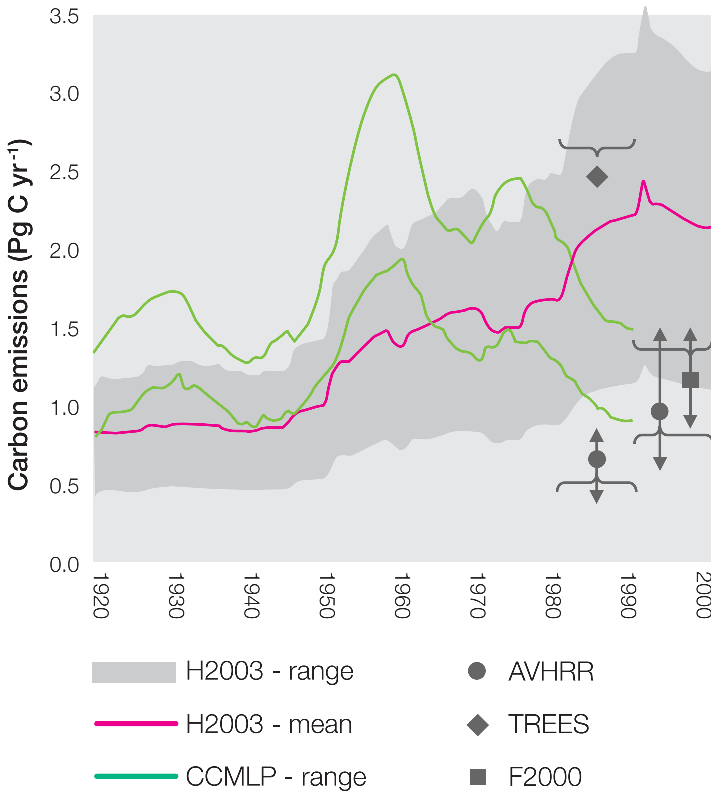
Figure 5. Changes in carbon stock from peat land to arable land and from arable land to grassland.



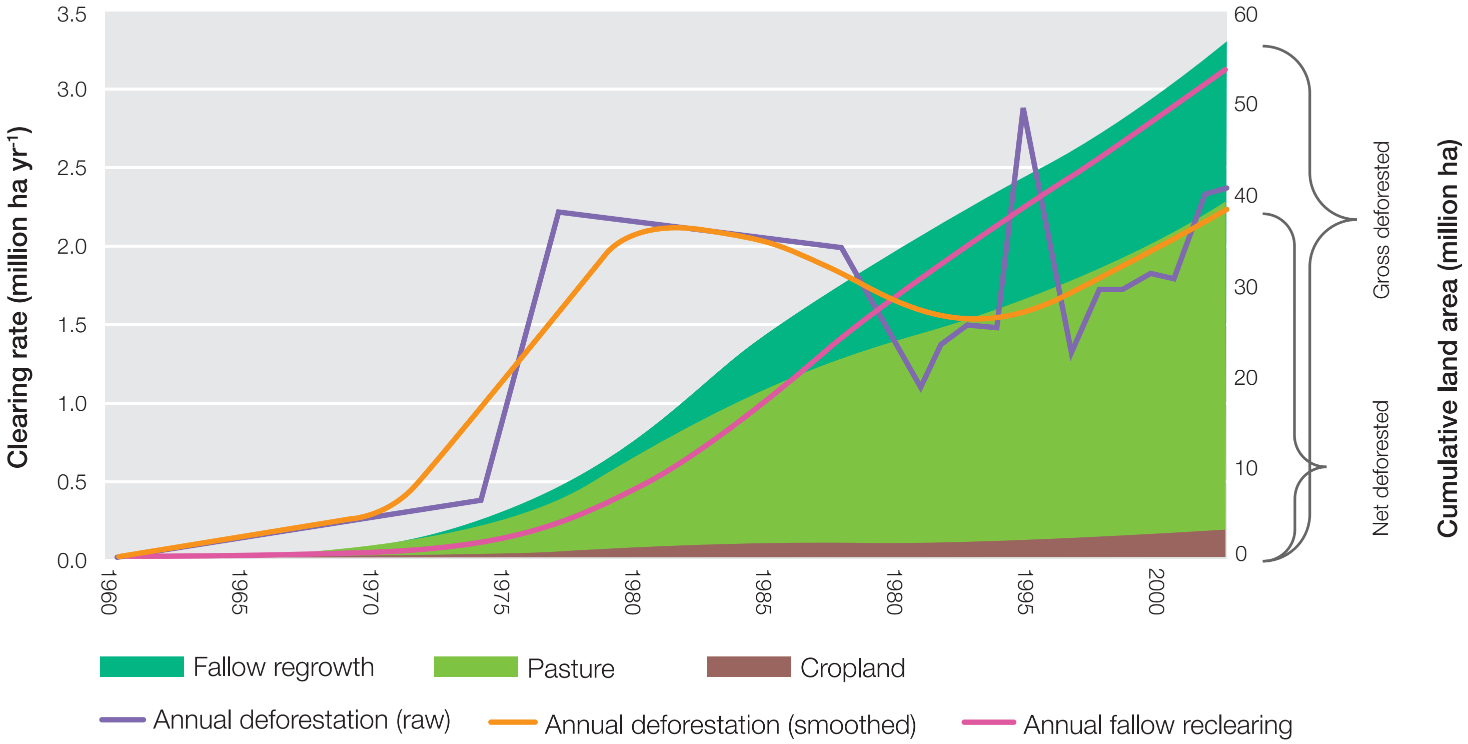
Changes in carbon stock from peat land to arable land (red/dark line) and from arable land to grassland (blue/light line). Each Eco-system and agro-forestry management crop system has a soil carbon equilibrium. Time constant of exponential change depends on climate change but averages around 33 years (see Table 5 for range of values). Source: IPCC 2001.

Figure 6. Intercomparison of five different estimates of carbon emissions from global land-cover change.



Intercomparison of five different estimates of carbon emissions from global land-cover change. The H2003 and CCMLP estimates were global, while the AVHRR, TREES and F2000 studies were pan-tropical. H2003 and CCMLP estimated annual values, while the other three studies estimated decadal averages. Multiply with a factor of 3.66 to get Pg CO_2-eq Taken from: (Ramankutty *et al.,* (2007)

Figure 7. Deforestation and fallow reclearing rates in the legal Amazon from 1961–2003.



Deforestation and fallow reclearing rates in the legal Amazon from 1961–2003 (primary y-axis); and land-cover transitions following deforestation estimated by a Markov transition model (cumulative values shown on secondary y-axis). Divide by a factor of 100 to get M km^2 Taken from (Ramankutty *et al*., 2007)

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3.2.1 Historic and future trends

Land cover change is the oldest global impact of human kind (Kates and Parris, 2003). However, the rate of change has increased dramatically, and since 1945 more land was converted to cropland than in the previous two centuries combined (Cerri *et al.,* 2007). In the last four decades, agricultural land increased by about 10% (4.43 M km^2), which was achieved at the expense of forest land and other land mainly in the developing world (Table 6). Croplands and pastures are among the largest ecosystems on the planet, rivalling forest cover in extent and together occupy ≈ 35% of the ice-free land surface (Ramankutty *et al.,* 2007). This amount of land is still more than half as much than would be required if crop yields would have remained at the levels from 1961 (Mooney *et al.,* 2005). The period of major expansion into uncultivated lands is thought to be over, as most arable land with a good quality is already being used apart from some areas in humid, tropical regions (Desjardins *et al.,* 2007). Generally two global trends can be observed: "decreasing tropical and increasing temperate boreal forests" (Kates and Parris, 2003). Both these trends are driven mainly by economics. Agriculture in temperate regions has become less viable on more marginal lands that are often converted back to woodland. Siberia is an exception where deforestation rates are still very high (Kates and Parris, 2003). On the other hand, in tropical rainforest regions, global trade encourages the destruction of the forest to make way for croplands and grasslands. Consequently, the area of forest has been reduced by almost 10% since 1980 (Desjardins *et al.*, 2007, Zhang *et al.*, 2006) forecasting that by 2030 the annual global increase in agricultural, arable and permanent cropland will be 45,250, 12,690 and 89,130 km^2, respectively. In contrast, permanent pasture and woodland areas will in the same time decrease by an annual rate of 40,490 and 42,860 km^2, respectively. Here, again there is a marked difference between different regions generally with developed countries, particularly Europe, showing a reverse to the global trend as the area of woodlands is expected to increase annually by 7,400 (developed countries) and 13,720 km^2 (Europe), (Zhang *et al.,* 2006).

Brazil experienced a deforestation of 93,700 km^2 between 2001 and 2004 (Morton *et al.,* 2006). The deforestation occurred at a rate of between 10,000 and 30,000 $km^2\ yr^{-1}$ since 1978. There is no consistent trend, but the rate is linked to macroeconomic factors. A rising demand for soybean and beef contributed to increased Brazilian deforestation rate from 2001 to 2004 (Fearnside, 2005) (Morton *et al*., 2006). Similarly, Southeast Asia lost 23,000 km^2 between 1990 and 2000 for timber harvest and agricultural expansion. In contrast, forests are being replanted in East Asia with China increasing its woodland area by almost 100% (from 127,400 to 231,100 km^2) (Zhao *et al.,* 2006). This trend, though to a lesser extent, can also be observed in Japan and South Korea. However, a reduction in the water surface through building of dams and drainage of wetland areas can be observed all over the Asian continent (Zhao *et al.,* 2006).

Table 6: Agricultural land use in the last four decades

	Area (M km²)					Change 2000s/1960s	
	1961-70	1971-80	1981-90	1991-00	2001-03	%	M km²
1. World							
Agricultural land	45.38	46.51	47.94	49.49	49.80	10	4.4
Arable land	13.01	13.35	13.79	13.97	14.03	8	1.0
Permanent crops	0.91	0.99	1.10	1.30	1.38	51	0.50
Permanent pasture	31.46	32.18	33.05	34.23	34.39	9	2.9
Forest and Woodland[a]	43.52	42.91	42.87	42.12	0.00	-3	-1.4
Other Land[a]	41.50	40.98	39.59	38.68	0.00	-7	-2.8
Non-arable and -permanent[b]	0.00	0.00	0.00	114.72	114.63	-0.08	-0.1
2. Developed countries							
Agricultural land	18.85	18.82	18.69	18.58	18.24	-3	-0.6
Arable land	6.46	6.48	6.51	6.32	6.10	-6	-0.4
Permanent crops	0.32	0.31	0.30	0.30	0.30	-7	-0.02
Permanent pasture	12.06	12.03	11.88	11.96	11.85	-2	-0.2
Forest and Woodland[a]	19.94	19.93	20.09	19.36	0.00	-3	-0.6
Other Land[a]	15.64	15.68	15.65	16.04	0.00	3	0.4
Non-arable and -permanent[b]	0.00	0.00	0.00	47.46	47.61	0.33	0.15
3. Developing countries							
Agricultural land	26.53	27.69	29.25	30.91	31.56	19	5.0
Arable land	6.55	6.87	7.30	7.65	7.94	21	1.4
Permanent crops	0.59	0.67	0.80	1.00	1.08	84	0.49
Permanent pasture	19.40	20.15	21.18	22.27	22.54	16	3.1
Forest and Woodland[a]	23.58	22.98	22.78	22.75	0.00	-4	-0.8
Other Land[a]	25.86	25.31	23.94	22.64	0.00	-13	-3.2
Non-arable and permanent[b]	0.00	0.00	0.00	67.27	67.02	-0.36	-0.25

Source: FAOSTAT; data archive – land use, accessed 30.05.2007 [a] until 1994; [b] from 1995 onwards

4. Impacts of intensive animal farming on the global climate

Generally, animal farming produces significant GHG emissions resulting from emissions from the animals themselves and activities associated with the farming of animals. Sources are:

1. Direct livestock emissions
2. Manure management
3. Use of agrochemicals (fertiliser, pesticides and antibiotics)
4. Land use
5. The use of fossil fuels for a variety of applications

We examine these in more detail below.

4.1 Direct livestock emissions

When farming ruminant animals, the animals themselves produce the greatest amount of GHGs (up to 60%) through enteric fermentation in the rumen. Other components of the overall GHG emissions contribute roughly similar amounts, with the use of diesel and electricity being at the lower end (Casey and Holden, 2006). Globally, livestock is the most important anthropogenic source of methane emissions (US-EPA, 2006a). Methane is a powerful GHG with ≈ 20 times the global warming potential of CO_2.

There are considerations when comparing intensive versus non-intensive livestock production, not least animal welfare issues. Whereas non-intensive systems can be shown to be far more desirable in terms of animal welfare, the position with respect to GHG emissions is less clear. The amount of methane emitted by animals is directly related to the number of animals, so that a more intensive farm will have higher emissions (http://ec.europa.eu/research/environment/newsanddoc/article_2087_en.htm), though the emissions per unit of product (e.g. meat, milk) might be lower (IPCC WGIII Ch.8, 2007). The demand for meat products determines the number of animals that need to be raised. An intensive farm may spare land for other purposes by optimising yield on high quality land and, hence, minimising the area that is used for agriculture (Mooney *et al.*, 2005, Dorrough *et al.*, 2007). However, it is argued that using less land directly for agriculture will still have an effect on surrounding lands due to high concentrated emissions and different requirements to the infrastructure (Matson and Vitousek, 2006). Furthermore, the length of time it takes to rear an animal has decreased dramatically in intensive farming systems (e.g. from 72 days in 1960 to 48 days in 1995 for broiler chickens). Generally, chickens and pigs use concentrated feed (high protein) more efficiently compared to cattle, which enabled a considerable reduction in the rearing time. As a result, the production of these meats has also increased (Naylor *et al.*, 2005). Given that the demand of meat has to be met (expecting large, unforeseen global shifts in projected consumption patterns), intensive farming reduces the time necessary to produce the same quantity of product, hence reducing GHG emissions per unit of product. Furthermore, the increase in the production of chickens and pigs may also be favourable considering that these animals produce much less GHG (pig: 1 – 1.5 kg CH_4 head^{-1} yr^{-1}) by enteric fermentation compared to cattle (dairy cattle: 36 – 100 kg CH_4 head^{-1} yr^{-1}) and sheep (5 – 8 kg CH_4 head-1 yr^{-1}) (US-EPA, 1998).

4.2 Manure management

There are several ways of managing animal manure, which can either be stored wet (e.g. slurry) or dry (e.g. farm yard manure). Methane emissions occur mainly when the manure is managed in liquid forms (lagoon or holding tanks) or remain wet. Generally, intensive livestock systems use liquid manure management due to the large quantity of manure produced and the method of collection (Reid *et al.*, 2004). A typical system for large scale pig operations are lagoons (although not in Europe). Manure deposited on fields and pastures or otherwise handled in dry form do not produce significant amounts of methane (Reid *et al.*, 2004). Emissions also depend on the animal's diet: Higher energy feed produces manure with more volatile solids, i.e. decomposable organic matter that may emit more GHG depending on surrounding environmental conditions. Pig production produces the largest share of manure, followed by dairy (Steinfeld *et al.*, 2006). If the liquid manure is used for methane production (biogas plants) that is used for energy to replace fossil fuels then the net GHG emissions could be significantly less for pig production than ruminant production.

4.3 Use of agrochemicals

GHG emissions associated with the production and use of fertiliser have been discussed is section 2. Intensive animal farming will have a high demand on the supply of feed crops, hence, furthering the use of fertiliser. Here, even crops that are associated with N fixing organisms (such as soybean) and require less additional nitrogen, are fertilised (Steinfeld *et al.*, 2006). Feed crops will also receive pesticides to ensure the protection against pests, which may reduce yields. The production of pesticides is also energy-intensive and hence adds to the overall GHG budget of intensive animal farming (Table 2) (Lal, 2004c).

Intensive conventional farms may also make use of antibiotics as a preventive measure rather than for treating actual diseases. Considering the high density of livestock, this measure is perceived to be necessary to avoid the development of devastating epidemics. Furthermore, drugs, such as antibiotics and steroids, are often given to speed up the fattening process (Centner, 2003), though these are banned in some regions. These extra resources have associated energy and GHG costs.

4.4 Land use

Livestock is the world's largest user of land with a shift from grazing to the consumption of feed crops. Industrial livestock systems are now often separated from feed crops and the end consumer to take advantage of lower costs and potentially less rigid environmental regulations (Naylor *et al.*, 2005). This results in further emissions from transport. The great demand of feed and space for animal farming furthers cultivation of land, especially deforestation of rain forest.

Generally, intensive farming uses more supplement feed rather than feeding the livestock on grassland (Eickhout *et al.*, 2006). Some of these feeds are often not produced in the same country. Here, soya plays an important role as a high energy feed for which Brazil is one of the main producing countries (FAOSTAT, 2007). Intensive animal farming indirectly supports the deforestation of Brazilian rain forest for soya plantation (Fearnside, 2005) with some European countries showing a negative carbon / GHG balance due to livestock feed imports (Janssens *et al.*, 2005). On the other hand, the use of supplement feed for ruminants is known to reduce methane emissions from enteric fermentation (IPCC WGIII Ch.8, 2007). The impact of feed crops can be reduced if industrial food waste (e.g. mash from ethanol production or residue from vegetable oil milling), which is not suitable for human consumption, is used as animal feed. This approach covers about 70% of the animal feed in the Netherlands (Nonhebel, 2004).

Intensive animal farming may also result in overgrazing of grassland, which may then reduce the carbon stocks and even lead to desertification (Steinfeld *et al.*, 2006).

4.5 Fossil Fuel use

Energy consumption varies widely between different practices and farming systems. Generally, more modern systems use the bulk of total energy input on the production of feed. Apart from fertiliser, this includes seed, pesticides, machinery and electricity (water supply, heating, drying). The on-farm energy consumption of intensive systems can exceed the carbon dioxide emissions of the N fertiliser production.

On the other hand, processing of the agricultural product may often be less efficient at a smaller scale, so that intensive systems may conserve energy (Barrett *et al.*, 2001). Generally, the dairy sector is one of the highest energy-consuming sectors due to pasteurization, cheese making and dried milk. Furthermore, the required refrigerated transport is energy intensive and vehicles are often not loaded to full capacity (Steinfeld *et al.*, 2006).

4.6 Effect of increasing meat (and animal feed) demand on future agricultural emissions of greenhouse gases

Economic growth is usually accompanied by an increasing demand for meat, as more people can afford it (Eickhout *et al.*, 2006). In addition, populations are still increasing in developing countries which will fuel an increased demand for food even in the absence of dietary changes. The UN predicts that the world population will continue to increase from the present about 6.5 billion and stabilise at over 9 billion (UN, 2004).


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Currently, meat consumption is still greater in developed countries than in developing countries (Table 7). However, the demand for animal products is rapidly increasing in developing countries and rose from 11 to 24 kg capita^{-1} yr^{-1} during the period 1967-1997, corresponding to an annual growth rate of more than 5% (IPCC WGIII Ch.8, 2007). IPCC WGIII Ch.8 (2007) concluded that

- Growing demand for meat may induce further changes in land use (e.g., from forestland to grassland), often increasing CO_2 emissions, and increased demand for animal feeds (e.g., cereals). Larger herds of beef cattle will cause increased emissions of CH_4 and N_2O, although use of intensive systems (with lower emissions per unit product) is expected to increase faster than growth in grazing-based systems. This may attenuate the expected rise in GHG emissions.
- Intensive production of beef, poultry, and pork is increasingly common, leading to increases in manure with consequent increases in GHG emissions. This is particularly true in the developing regions of South and East Asia, and Latin America, as well as in North America. (IPCC WGIII Ch.8, 2007)

The FAO (2002) forecasts a further increase of 60 % in global meat demand by 2030, mostly in South and Southeast Asia, and Sub-Saharan Africa. The greatest increases in demand are expected for poultry (83% by 2020; Roy *et al.,* 2002).

Annual GHG emissions from agriculure are expected to increase in the coming decades (included in the baseline) due to escalating demands for food and shifts in diet (IPCC, WGIII Ch.8, 2007).

Table 7: Per capita food supply in developed and developing countries

						Change 2000s/1960s	
	1961-70	1971-80	1981-90	1991-00	2001-02	%	cal day^{-1} or g day^{-1}
1. Developed countries							
Energy, all sources (cal day^{-1})	3049	3181	3269	3223	3309	+9	261
% from animal sources	27	28	28	27	26	-2	–
Protein, all sources (g day^{-1})	92	97	101	99	100	+9	8
% from animal sources	50	55	57	56	56	+12	–
2. Developing countries							
Energy, all sources (cal day^{-1})	2032	2183	2443	2600	2657	+31	625
% from animal sources	8	8	9	12	13	+77	–
Protein, all sources (g day^{-1})	9	11	13	18	21	+123	12
% from animal sources	18	20	22	28	30	+67	–

Taken from IPCC 2007; Source: FAOSTAT, 2006.

5. Greenhouse gas emissions from intensive versus non-intensive agricultural practices

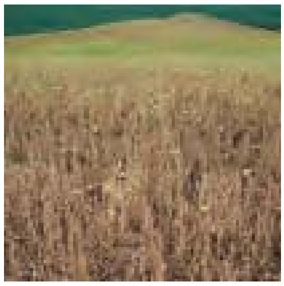
The emissions of GHGs from agriculture depend on the combination of production system and site factors. The same production system can have different impacts on different soil types, etc. On mineral soils, the amount of standing biomass (above - and below ground) and annual input of organic matter to the soil will determine carbon storage. The most important carbon mitigation mechanism in the short term is to avoid deforestation, primarily in tropical countries (IPCC WGIII Ch.8, 2007). This strategy has other environmental benefits as well. Any practice that can give rural income without more use of land, or by taking degraded land back into production, should therefore be encouraged. All benefits obtained on a per hectare basis of one land use type - have to be seen in connection with the total area of land required to produce the amount of food or other product needed.

Activities such as agroforestry may be useful to increase soil fertility as well as carbon stocks (Cacho *et al.*, 2003), though this depends on the initial land condition and use and the management methodology. The highest benefits can be obtained if degraded soils can be reclaimed (IPCC WGIII Ch.8, 2007). Some estimates of carbon mitigation potential are given by Bloomfield and Pearson (2000). Targeting small-holders for carbon sequestration programmes can be a good strategy, both in terms of carbon sequestration and poverty alleviation, but the transaction costs (administration, verification) may be higher for smallholdings (Cacho *et al.*, 2003). Generally, forest projects are relatively inexpensive and cost e.g. around 40 to 100 times less than Activities Implemented Jointly (AIJ) energy projects (Table 8). However, forest projects are less standardised in regard to baselines and actual costs so that values given in Table 8 should be considered with caution. It still becomes clear that a larger scale makes the costs much more economic with the biggest project (target area 750 km^2) costing much less (0.25 \$ Mg CO_2^{-1}) compared to the smaller projects (10 – 60 km^2) at a price of around \$ 3.5 per Mg of carbon dioxide.

Smallholder farms may often store more carbon than commercial arable agriculture due to more trees (Roshetko *et al.*, 2002), but it is not known if they also use a larger area to produce the same amount of food (see below).

There are not many studies where small scale and intensive farming systems are compared. Mrini *et al.,* (2002) compares energy use under traditional and intensive farming systems in Morocco, and concludes that the energy use is less in the traditional system, which uses less energy per unit produced (0.73 and 1.10 MJ kg^{-1} respectively). The main reason for the difference in energy use between the two systems was the irrigation system used. However, they also compared their results with other studies of intensive and traditional farming systems, and they found that generally, the traditional farming systems used less energy per unit of product. Although it can be difficult to compare systems, it does suggest that traditional systems may be more energy efficient (at least measured on per product rather than per ha basis). The reasoning for this may be less use of machinery.

In developed countries, organic agriculture has been championed as the most sustainable form of agriculture. Williams *et al.*, (2006) performed a life cycle analysis of the global warming potential of some food products in England and Wales (Table 9). They found clear GHGs benefits for some products, but not all. While organic milk, eggs and poultry showed no benefits in terms of GHGs, organic wheat bread, oil seed rape and potatoes showed benefits (lower global warming potential) than conventional ones (Table 9, Williams *et al.,* 2006).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Organic field crops and animal products generally consume less primary energy than non-organic counterparts, owing in part to the use of legumes to fix N rather than fuel to make synthetic fertilisers (Williams *et al.,* 2006). In relation to this, many studies have found that the emissions related to crop production are lower in organic farms than in conventional farms when measured as a per hectare basis, but this advantage of organic production is less clear in units of crop yield, since yields are lower for some crops in organic farms (Flessa *et al.,* 2001, Tzilivakis *et al.,* 2005, Petersen *et al.,* 2006).

Organic farmers usually apply practices that promote carbon sequestration in the soil and could favour GHG savings from organic cropping. Common organic practices like the use of cover crops, growing trees and shrubs around croplands and avoiding bare soils are all proposed mitigation options for agriculture (IPCC WGIII Ch.8, 2007) already in place in many organic farms worldwide. More scientific research is needed to evaluate the specific carbon benefits of these practices in organic farms.

Table 9: Global warming potential (CO_2 equivalents) for some foods produced organically and non-organically.

	Non-organic (g CO_2)	**Organic** (g CO_2)
Wheat bread (kg)	804	786
Oil seed rape (kg)	1,710	1,620
Potatoes (kg)	215	199
Poultry (kg)	4,570	6,680
Eggs (20)	5530	7000
Milk (10 l)	10,600	12,300

(Williams *et al*., 2006)

Table 8: A selection of AIJ (Activities Implemented Jointly) reforestation projects.

Project:	**Profafor**	**Scolel Te**	**Klinki**	**SIF**	**Virilla**
Country	Ecuador	Mexico	Costa Rica	Chile	Costa Rica
Land type	Andean highlands	Highland (>2800m) tropical communities	Pastures and and lowland	Pastures and marginal farmland	Pastures
Duration (yr)	25	30	25	51	25
Target area (km^2)	750	20	60	70	10
Area planted (km^2)	225	5	0.48	na	1.31
CO_2 sequestered (Tg)	35	1.21	7.22	1.41	0.85
CO_2 per year (Pg km^{-1} yr^{-1})	0.0019	0.002	0.0048	0.0002	0.0009
Project cost ($1000)	8810	3681	10703	20600	3395
Annual cost ($ km^{-2} yr^{-1})	470	613.5	387.8	577.0	13,581
Carbon cost ($/Mg CO_2)	0.25	3.05	1.47	14.61	4.02

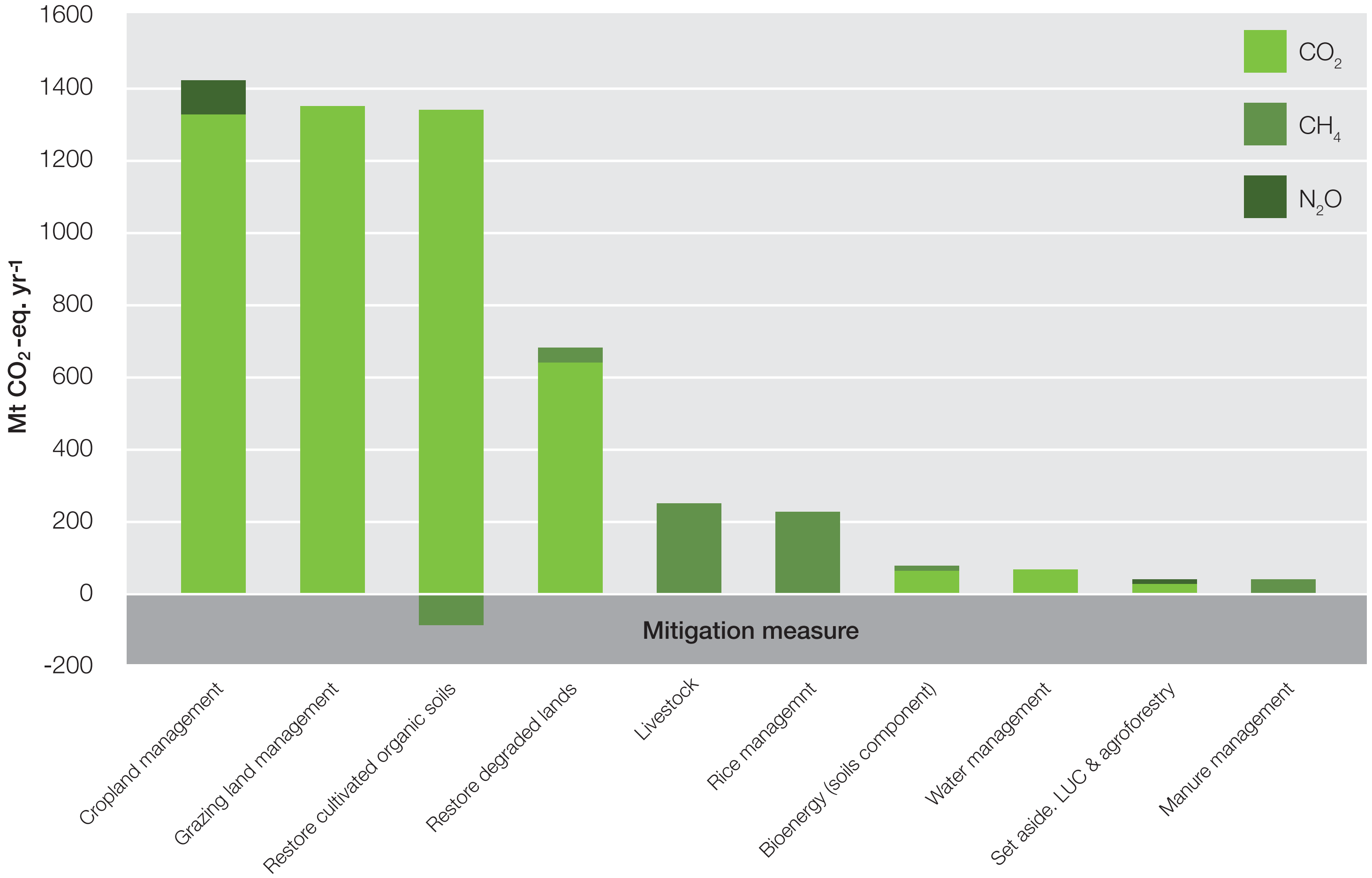
They show examples of the benefits that can be obtained in terms of carbon sequestration, as well as the costs (from Cacho *et al*., 2003).

6. Potential for the mitigation of greenhouse gas emissions from agriculture

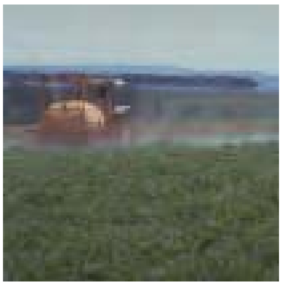
Agriculture has a significant mitigation potential, which could change the position of agriculture from one of the largest emitters to a much smaller emitter or even a net sink. The potential has been estimated by several researchers and has been summarised by the IPCC, 2007 (Figure 8). Mitigation is defined by the IPPC WGIII (2007) as a technological change or substitution which reduces the GHG emissions or enhances carbon sinks. The potential can be calculated by comparing the current or projected emissions/sink under a given baseline (e.g. business as usual with no mitigation put in place) with the emissions/sink occurring if a change in management (i.e. mitigation) were put in place. Much of the information contained in this section is drawn from IPCC WGIII Ch.8 (2007).

The most recent estimate of mitigation potential from agriculture by Smith *et al.,* (2007), which is also one of the only two global estimates, gives a maximum global mitigation potential of 6 Pg CO_2-eq yr^{-1}. However, not all of the technical potential can be realised. The economic potential is a maximum of 4.3 Pg CO_2-eq yr^{-1} at a carbon price of 100 US$ t CO_2-eq (Smith *et al.*, in press). Here, by far the greatest mitigation contribution originates from soil carbon sequestration (89%) and only some potential in mitigating methane (9%) and nitrous oxide (2%) emissions (Smith *et al.*, in press) (Figure 8).

Figure 8. Global technical mitigation potential by 2030 of each agricultural management practice showing the impacts of each practice on each GHG.



Global technical mitigation potential by 2030 of each agricultural management practice showing the impacts of each practice on each GHG (taken from IPCC, 2007); 1000 Mt = 1 Pg. Source: Drawn from data in Smith *et al.*, 2007.



Generally, the impact of mitigation measures is very versatile. They can act on mainly one GHG or more than one GHG. In the latter case, there may be positive impacts on more than one GHG, or there may be trade-offs between gases. Consequently, a combined effect of all the gases has to be considered. In addition, the effectiveness will depend on region and climate (with the exception of livestock mitigation) so that the same measure may have opposite effects in different parts of the globe. The length of mitigation impact will also vary, with some effects being indefinite and others reaching saturation over time. This means that mitigation practices are not universally applicable but need to be assessed individually for each agricultural environment (IPCC WGIII Ch.8, 2007). In the following sections, the potential of several mitigation options is described separately. Generally, several options may operate via similar mechanisms.

Where a practice affects radiative forcing through other mechanisms such as aerosols or albedo, those impacts also need to be considered (Marland *et al.*, 2003; Andreae *et al.*, 2005), though these impacts are small relative to the impact on GHGs.

6.1 Mitigation potential from increasing carbon sinks.

There are several options to increase carbon sinks; these can be divided into two main approaches: 1) restoration of natural vegetation and 2) sustainable management practices of the farmed land.

6.1.1 Restoration of natural vegetation

Croplands contain the lowest concentration of carbon (apart from deserts and semideserts) compared to any other land use (Table 5 & Figure 5). Therefore, the reversion of cropland to another land cover, typically one similar to the native vegetation is one of the most effective methods of reducing emissions / increasing carbon sinks. Considering that the opposite land use change, from natural to cropland contributes considerably (20%) to global GHG emissions, it would also be desirable to conserve the current natural vegetation.

Generally, land use change is limited by the available land, which is usually limited to surplus agricultural land or croplands of marginal productivity. A conversion may either occur “over the entire land area (set-asides or abandoned farms)”, or “in localized spots, such as grassed waterways, field margins, or shelterbelts” (Follett, 2001; Freibauer *et al.*, 2004; Lal, 2004b; Falloon *et al.*, 2004; Ogle *et al.*, 2003)”.

Within the restoration of natural vegetation one can distinguish between two fundamentally different types: a) dry vegetation and b) wetlands.

The conversion of arable cropland to grassland or forest typically acts as a carbon sink (Guo and Gifford, 2002). This is a result of less soil disturbance and reduced carbon removal, which would usually take place in the form of harvest. Uncultivated grasslands and forests will also usually emit less N_2O provided that the previous cropland was fertilised, higher rates of CH_4 oxidation, but recovery of oxidation may be slow (Paustian *et al.*, 2004).

Converting drained croplands back to wetlands can result in an even greater carbon sink (Table 5 & Figure 5). On the other hand it may stimulate CH_4 emissions because water-logging creates anaerobic conditions (Paustian *et al.*, 2004).

6.1.2 Sustainable management practices

The low carbon concentration in croplands (Table 5) means that it has a great potential to increase in carbon content through beneficial management practices. In contrast, grazing lands already have higher carbon stocks as they are usually less intensely managed and disturbed. General approaches to increase soil carbon stocks in croplands are:

- Increase of yield
- Reduction of soil disturbance
- Agroforestry
- Avoiding bare soil.

6. Potential for the mitigation of greenhouse gas emissions from agriculture

Increase of yield:

An increased yield will also increase the amount of carbon that is sequestered by the plant and released into the soil during growth, or when incorporating plant residues into the soil. Furthermore, less land may be required, which may then be available for land use change to natural vegetation, as discussed above.

Apart from fertilisation (discussed below), there are several means through which the crop yield can be increased. These include water management, improved locally adapted crop varieties, and the introduction of legumes into grassland. The effectiveness of irrigation will depend on the energy that is required to deliver the water and its availability. Furthermore, soil with higher water content may also be a greater source of nitrous oxide (Liebig *et al.,* 2005, Schlesinger 1999, Mosier *et al.*, 2005, Follett, 2001; Lal, 2004a). Crop varieties could be improved in a number of ways to increase their yield, which may not necessarily increase the net photosynthesis but addresses other issues. The crop could, e.g., have a greater water or nutrient use efficiency, increasing the yield at the same input, or enabling a reduction in external inputs, and the associated energy required to supply this input whilst maintaining the same yield. For example, water intensive varieties of maize could be replace by other locally adapted varieties that need less water or nutrients and produce the same yield. Similarly, the introduction of leguminous species into grassland will increase the productivity or reduce the amount of fertiliser that is required (Sisti *et al.*, 2004; Diekow *et al.*, 2005, Soussana *et al.*, 2004).

Reduction of soil disturbance and residue management:

Soil disturbance by tillage aerates the soil which enhances microbial decomposition, and hence the loss of carbon. The traffic by machinery or livestock and the tillage will also lead to soil erosion and compactions and poor drainage. These disturbances can be reduced by minimal (conservation) or no till practices and less intensive grazing. The carbon benefits from no-till agriculture may be offset by increasing reliance in herbicides and machinery (both practices contribute to GHG emissions) and may affect biodiversity negatively (CBD Technical series no. 10).

With regard to grazing, there is an optimal stocking rate, at which the carbon accrual will be greater than on ungrazed land. (Liebig *et al.*, 2005; Rice and Owensby, 2001). The effects are inconsistent, however, owing to the many types of grazing practices employed and the diversity of plant species, soils, and climates involved (Schuman *et al.*, 2001; Derner *et al.*, 2006). The influence of grazing intensity on emission of non-CO_2 gases is not well-established, apart from the direct effects on emissions from adjustments in livestock numbers.

Systems that retain crop residues also tend to increase soil carbon because these residues are the precursors for soil organic matter, the main carbon store in soil. Avoiding the burning of residues (e.g., mechanising sugarcane harvesting, eliminating the need for pre-harvest burning (Cerri *et al.*, 2004) also avoids emissions of aerosols and GHGs generated from fire, although CO_2 emissions from fuel use may increase (IPCC WGIII Ch.8, 2007).

Agro-forestry:

Agro-forestry is the production of livestock or food crops on land that also grows trees for timber, firewood, or other tree products. It includes shelter belts and riparian zones/buffer strips with woody species. The standing stock of carbon above ground is usually higher than the equivalent land use without trees, and planting trees may also increase soil carbon sequestration (Oelbermann *et al.*, 2004; Guo and Gifford, 2002; Mutuo *et al.*, 2005; Paul *et al.*, 2003). But the effects on N_2O and CH_4 emissions are not well known (Albrecht and Kandji, 2003).

Avoiding bare soil:

Bare soil is prone to erosion and nutrient leaching. In regard to soil carbon it will always be lower than the same crop with vegetation due to the carbon in the above and belowground biomass. This can be reduced by using “catch” and “cover” crops which will cover the soil in between the actual crop or in fallow periods, respectively. (Barthès *et al.*, 2004; Freibauer *et al.*, 2004)

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The sequestration of carbon into agricultural soils contributes the largest part (89%) of the total agricultural mitigation potential (Smith *et al.*, 2007). Here, management practices will be able to store more than twice as much carbon than land use change to wetland and other natural vegetation. This is due to the greater proportion of land available for this management change. Within land use change, restoration of organic soils contributes by far the greatest mitigation potential due to the high per-area potential.

6.1.3 Mitigation potential from grazing land, livestock, and manure management

Grazing land management

The management of grazing land for the mitigation of carbon emissions has been partly covered in the previous section. An additional significant practice is the management of fire on grasslands. This is carried out to renew the grass. The fire itself will release GHGs as well as reactive hydrocarbon and nitrogen gases. The smoke aerosols will also have a complex effect on the atmosphere. The effect on woody biomass can be either positive or negative, depending on the occurrence of spontaneous fires or the purpose of the fire to clear woody biomass. Therefore, the mitigation can either involve 1) the reduction of the frequency or extent of fires through more effective fire suppression; 2) or the reduction of the fuel load by vegetation management; and burning at a time of year when less CH_4 and N_2O are emitted (Korontzi *et al.*, 2003). Although most agricultural-zone fires are ignited by humans, there is evidence that the area burned is ultimately under climatic control (Van Wilgen *et al.*, 2004). In the absence of human ignition, the fire-prone ecosystems would still burn as a result of climatic factors. Reducing the frequency or intensity of fires typically leads to increased tree and shrub cover, resulting in a CO_2 sink in soil and biomass (Scholes and van der Merwe, 1996). This woody-plant encroachment mechanism saturates over 20-50 years, whereas avoided CH_4 and N_2O emissions continue as long as fires are suppressed.

Livestock management

There are several approaches by which the direct livestock emissions can be reduced.

Improved feeding practices: Methane emissions can be reduced by feeding more concentrates, normally replacing forages (Blaxter and Claperton, 1965; Johnson and Johnson, 1995; Lovett *et al.*, 2003; Beauchemin and McGinn, 2005). Although concentrates may increase daily methane emissions per animal, emissions per kg-feed intake and per kg-product are almost invariably reduced. The magnitude of this reduction per kg-product decreases as production increases. The net benefit of concentrates, however, depends on reduced animal numbers or younger age at slaughter for beef animals, and on how the practice affects land use, the N content of manure and emissions from producing and transporting the concentrates (Phetteplace *et al.*, 2001; Lovett *et al.*, 2006). Other practices that can reduce CH_4 emissions include: adding certain oils or oilseeds to the diet (e.g., Machmüller *et al.*, 2000; Jordan *et al.*, 2006); improving pasture quality, especially in less developed regions, because this improves animal productivity, and reduces the proportion of energy lost as CH_4 (Leng, 1991; McCrabb *et al.*, 1998; Alcock and Hegarty, 2006); and optimising protein intake to reduce N excretion and N_2O emissions (Clark *et al.*, 2005).

Specific agents and dietary additives: A wide range of specific agents, mostly aimed at suppressing methanogenesis, has been proposed as dietary additives to reduce CH_4 emissions. They include vaccines (Wright *et al.*, 2004), probiotics (McGinn *et al.,* 2004), halogenated compounds (Wolin *et al.*, 1964; Van Nevel and Demeyer, 1995), ionophores (Benz and Johnson, 1982; Van Nevel and Demeyer, 1996; McGinn *et al.*, 2004), and others. Some of them are still under development and their indirect effects for health and the environment are not certain (Steinfeld *et al.*, 2006).

Longer-term management changes and animal breeding: Increasing productivity through breeding and better management practices, such as a reduction in the number of replacement heifers, often reduces methane output per unit of animal product (Boadi *et al.*, 2004). Although selecting cattle directly for reduced methane production has been proposed (Kebreab *et al.*, 2006), it is still impractical due to difficulties in accurately measuring methane emissions at a magnitude suitable for breeding programmes. With improved efficiency, meat-producing animals reach slaughter weight at a younger age, with reduced lifetime emissions (Lovett and O'Mara, 2002). However, the whole-system effects of such practices may not always lead to reduced emissions. For example in dairy cattle, intensive selection for higher yield may reduce fertility, requiring more replacement heifers in the herd (Lovett *et al.*, 2006).

Manure management

Animal manures can release significant amounts of N_2O and CH_4 during storage, but the magnitude of these emissions varies. Methane emissions from manure stored in lagoons or tanks can be reduced by cooling, use of solid covers, mechanically separating solids from slurry, or by capturing the CH_4 emitted (Amon *et al.,* 2006; Clemens and Ahlgrimm, 2001; Monteny *et al.,* 2001, 2006; Paustian *et al.*, 2004). The manures can also be digested anaerobically to maximise CH_4 retrieval as a renewable energy source (Clemens and Ahlgrimm, 2001; Clemens *et al.*, 2006). Handling manures in solid form (e.g., composting) rather than liquid form can suppress CH_4 emissions, but may increase N_2O formation (Paustian *et al.*, 2004). Preliminary evidence suggests that covering manure heaps can reduce N_2O emissions, but the effect of this practice on CH_4 emissions is variable (Chadwick, 2005). For most animals worldwide there is limited opportunity for manure management, treatment, or storage; excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and methane emissions are negligible (Gonzalez-Avalos and Ruiz-Suarez, 2001). To some extent, emissions from manure might be curtailed by altering feeding practices (Külling *et al.*, 2003; Hindrichsen *et al.*, 2006; Kreuzer and Hindrichsen, 2006), or by composting the manure (Pattey *et al.*, 2005; Amon *et al.*, 2001), but if aeration is inadequate CH_4 emissions during composting can still be substantial (Xu *et al.*, 2007). All of these practices require further study from the perspective of their impact on whole life-cycle GHG emissions.

In comparison with managing croplands and grassland as carbon sinks, the direct potential carbon mitigation by livestock management is relatively small (only 10% rather than 89%). However, livestock require feed and as such have an indirect effect on cropland and grassland management.

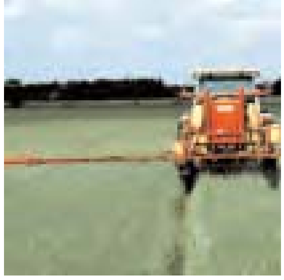
6.1.4 Other mitigation possibilities and implications for sustainable development.

There are several other mitigation potentials that have not been covered by the previous points and will be discussed here.

Rice management

Cultivated wetland rice soils emit significant quantities of methane (Yan *et al.*, 2003). Emissions during the growing season can be reduced by various practices (Yagi *et al.*, 1997; Wassmann *et al.*, 2000; Aulakh *et al.*, 2001). For example, draining wetland rice once or several times during the growing season reduces CH_4 emissions (Smith and Conen, 2004; Yan *et al.*, 2003; Khalil and Shearer, 2006). This benefit, however, may be partly offset by increased N_2O emissions (Akiyama *et al.,* 2005), and the practice may be constrained by water supply. Rice cultivars with low exudation rates could offer an important methane mitigation option (Aulakh *et al.*, 2001). In the off-rice season, methane emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding water-logging (Cai *et al.*, 2000, 2003; Kang *et al.*, 2002; Xu *et al.*, 2003). Increasing rice productivity can also enhance soil organic carbon stocks (Pan *et al.*, 2006). Methane emissions can be reduced by adjusting the timing of organic residue additions (e.g., incorporating organic materials in the dry period rather than in flooded periods; Xu *et al.*, 2000; Cai and Xu, 2004), by composting the residues before incorporation, or by producing biogas for use as fuel for energy production (Wang and Shangguan, 1996; Wassmann *et al.*, 2000).

The system of rice intensification (SRI) was developed in Madagascar to help farmers increase rice production without extra inputs (Stoop and Kassam, 2006). The cultivation system involves growing the rice plants widely spaced without flooding and with only organic amendments as fertilisers. There are anecdotal reports of high yield using the system (Uphoff, 2004). However, the merits of the system remain controversial (Sinclair, 2004). No investigation of the GHG emission from the system are known to us, but based on general knowledge about the practices that promote and reduce emissions we predict that methane emissions will be greatly reduced, as it is not flooded. Some nitrous oxide emissions are expected, but they may not be large as mineral nitrogen is not added. Organic amendments may increase nitrous oxide emissions, but this is not always



observed (Wassmann *et al.*, 2004). The most important point may be the downstream effects. Sinclair (2004) notes that large quantities of organic fertilisers are needed to maintain high yields. It is important from the point of view of a total GHG balance, where and how this organic material is grown.

Management of organic/peaty soils

Organic or peaty soils contain high densities of carbon accumulated over many centuries because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, which aerates the soil, favouring decomposition, and therefore high CO_2 and N_2O fluxes. Methane emissions are usually suppressed after draining, but this effect is far outweighed by pronounced increases in N_2O and CO_2 (Kasimir-Klemedtsson *et al.*, 1997). Emissions from drained organic soils can be reduced to some extent by practices such as avoiding row crops and tubers, avoiding deep ploughing, and maintaining a shallower water table. But the most important mitigation practice is avoiding the drainage of these soils in the first place or re-establishing a high water table (Freibauer *et al.*, 2004).

Restoration of degraded lands

A large proportion of agricultural lands has been degraded by excessive disturbance, erosion, organic matter loss, salinisation, acidification, or other processes that curtail productivity (Batjes, 1999; Foley *et al.*, 2005; Lal, 2001a, 2003, 2004b). Often, carbon storage in these soils can be partly restored by practices that reclaim productivity including: re-vegetation (e.g., planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids, and composts; reducing tillage and retaining crop residues; and conserving water (Lal, 2001b; 2004b; Bruce *et al.*, 1999; Olsson and Ardö, 2002; Paustian *et al.*, 2004). Where these practices involve higher nitrogen amendments, the benefits of carbon sequestration may be partly offset by higher N_2O emissions.

6.2 Mitigation potential from fertiliser management, especially from improved efficiency and reduced over-use of fertilisers

The addition of fertiliser increases crop productivity but may also increase nitrous oxide emissions. Therefore, crop fertilisation can be positive or negative in regard to the total GHG budget.

The effect of increased productivity has been discussed earlier and as such the addition of fertiliser will have the same mitigation potential if the cropland is nutrient deficient (Schnabel *et al.*, 2001; Conant *et al.*, 2001). As such, fertiliser additions will have a beneficial effect in extremely nutrient deficient regions like large parts of Africa (Sanchez, 2002). However, the use of fertiliser will equally generate more GHG emissions during production (CO_2) (Schlesinger, 1999; Pérez-Ramírez *et al.*, 2003; Robertson, 2004; Gregorich *et al.*, 2005), and often after application (N_2O) (Conant *et al.*, 2005) thereby offsetting some of the benefits.

The reduction of the reliance on fertilisers by adopting cropping systems that maintain high yields has a high mitigation potential (Paustian *et al.*, 2004). An important example is the use of rotations with legume crops (West and Post, 2002; Izaurralde *et al.*, 2001). This reduces the requirement of external N inputs although legume-derived N can also be a source of N_2O (Rochette and Janzen, 2005). This approach is usually acquired by organic practices.

Nitrogen applied in fertilisers (but also other input such as manures) is not always used efficiently by crops (Galloway *et al.*, 2003; Cassman *et al.*, 2003). The surplus N is particularly susceptible to emission of N_2O (McSwiney and Robertson, 2005). Consequently, improving N use efficiency can reduce N_2O emissions and indirectly reduce GHG emissions from N fertiliser manufacture (Schlesinger, 1999). By reducing leaching and volatile losses, improved efficiency of N use can also reduce off-site N_2O emissions. Practices that improve N use efficiency include: adjusting application rates based on precise estimation of crop needs (e.g., precision farming); using slow- or controlled-release fertiliser forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); applying N when least susceptible to loss, often just prior to plant uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crops' roots; or avoiding N applications in excess of immediate plant requirements (Robertson, 2004; Dalal *et al.*, 2003; Paustian *et al.*, 2004; Cole *et al.*, 1997; Monteny *et al.*, 2006).

Generally, fertiliser production has a potential to reduce its global GHG emissions by more than half from 0.283 to 0.119 Pg CO_2-eq yr^{-1}. Improvements would be related to greater energy efficiency in ammonia plants (29%), introduction of new nitrous oxide reduction technology (32%) and other general energy-saving measures in plants (39%) (Kongshaug, 1998).

6.3 Changing diet and consumption patterns – impact of consuming less meat

A vegetarian diet produces much less GHG over a lifetime. The average consumption of grain and forage for production of one kg of animal products in Table 10 shows that producing lamb and beef requires between four and ten times more grain than producing pigs or chicken (see details Table 10). For ruminants, methane production further increases GHG emissions per unit of food. Therefore, the consumption of less meat will save GHG, and so will consuming poultry instead of beef or lamb (Table 10). The average amount of kcal fossil energy used per kcal of meat produced is 25. This is more than 11 times that of plant-based products, with an average input/output ratio of 2.2 (Pimentel and Pimentel, 2003). Using numbers from Pimentel and Pimentel (2003) we calculated that 385 kcal of fossil fuel per person per day could be saved by substituting just 5% of the meat in the diet with vegetarian products, assuming an average US diet as baseline. Considering that fossil fuels emit different amounts of CO_2 per kcal (Sims *et al.*, 2006), this amounts to between 95 and 126 g of CO_2.

Foster *et al.,* (2006) calculate that the energy needed to produce one kg of sheep meat is 23 MJ, one kg of poultry is 12 MJ and one kg of potatoes is 1.3 MJ in the UK. Whilst both a plant-based and a meat-based diet in developed countries require significant quantities of non-renewable fossil fuel, a meat based diet requires more (Pimentel and Pimentel, 2003) (Table 11). If developing countries were to eat as much meat as developed countries per capita, the amount of agricultural land required world wide would be about two thirds larger than today (Jackson *et al.*, 2005). For individuals wishing to reduce their GHG footprint, adopting a vegetarian diet, or at least reducing the quantity of meat products in the diet, would have beneficial GHG impacts.

Table 10: Average consumption of grain and forage (kg) for production of one kg of animal product in US agriculture.

Livestock	Grain	Forage
Lamb	21	30
Beef cattle	13	30
Eggs	11	
Swine	5.9	
Turkey	3.8	
Broiler	2.3	
Dairy (milk)	0.7	1

(US department of Agriculture, 2001)

Table 11: Global warming potential of the main meat categories, as well as milk and selected plant products for comparison.

Product	Global warming potential kg CO_2 -eq per kg of product
Sheep	17.4
Beef	12.98
Pig	6.35
Poultry	4.57
Milk	1.32
Bread wheat	0.80
Potato	0.21

(kg CO^2 equivalents on a 100 year time scale per kg product). Calculations were based on UK data (Foster et al., 2006).

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