Introduction

The availability of plant nutrients in sufficient quantities and their correct balance is a prerequisite for plant growth and hence yield. The use of mineral fertilizer as a source of plant nutrients is essential for sustainable agriculture. Mineral fertilizers are applied to balance the gap between the permanent export of nutrients from the field with the harvested crops and the nutrients supplied by the soil and by available organic sources (see Fig. 1).

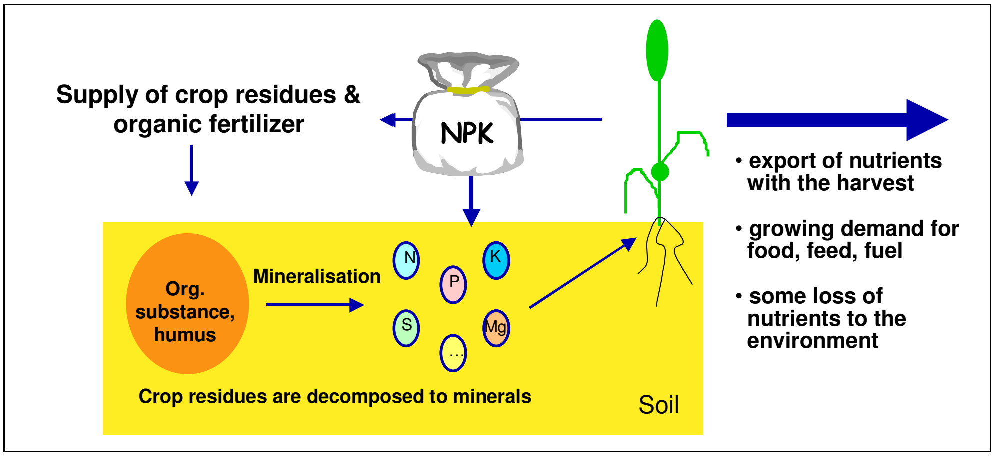

Figure 1: Mineral fertilizers close the gap between the nutrient supply from soil and organic sources and the nutrient demand for optimum crop development

An increasing world population will demand increasing food production (FAO, 2006) that needs to be produced from a limited agricultural area (FAO, 2003). As a consequence the agricultural productivity in terms of yield per hectare has to be improved to sustain sufficient global supply of food, feed and bio-energy. Intensive crop production with economically optimum fertilizer input is an option to support this development because it allows utilizing the yield potential of agricultural crops.

As all human activities also intensive crop production and in particular the use of mineral fertilizer has an "environmental footprint". With regards to N fertilizers this is mainly related to eutrophication and acidification of natural and semi-natural ecosystems, and the release of greenhouse gases (GHG). This paper investigates the GHG emissions ("carbon footprint") of crop production in general and the intensity of mineral N fertilizer use in particular.

Climate change – the contribution of agriculture in general and of mineral fertilizer in particular

Figure 2 shows the contribution of different sectors to the global GHG emissions in 2004 (IPCC, 2007; Bellarby, 2008). According to IPCC (2007), agricultural GHG emissions include:

- Methane (CH_4) emissions from enteric fermentation (cattle farming)
- CH_4 from rice cultivation
- Nitrous oxide (N_2O) from application of organic and mineral N sources
- N_2O and CH_4 from manure handling (storage etc.), and
- N_2O and CH_4 from burning of crop residues etc.

Mineral fertilizers are mainly involved in N_2O emissions from soils. According to Bellarby et al. (2008) agricultural soils emit 2128 Tg CO_2-equivalents (CO_2eq) as N_2O. In order to distinguish between N_2O from mineral fertilizer application and N_2O from organic N sources the

IPCC estimation methodology (IPCC, 2006) was applied. A global consumption of 90 Tg mineral N (IFA statistics for 2004/2005) gives combined direct and indirect N_2O emission from mineral fertilizer application of 561 Tg CO_2eq, which is 1.2% of the total global GHG budget or 26% of the N_2O emissions from agricultural soils. The remaining 1567 Tg CO_2eq have to be allocated to organic N sources such as manure, crop residues and sewage sludge.

Agricultural GHG emissions according to IPCC (2007) have a share of 13.5% in the total GHG emission. There are also GHG emissions assigned to other sectors than agriculture that are directly linked to agricultural production. The production of N fertilizer releases 410 Tg CO_2eq per year, which is equivalent to 0.8% of the global GHG emissions. The loss of carbon due to land use change from natural area (mainly forest) into agricultural land contributes on average about 12% (uncertainty range of 6 - 17%) to the global GHG emissions (Bellarby et al., 2008). In total all GHG emissions related to agriculture amount on average to 26% of the total global GHG emissions with a range between 17 and 32% because of the uncertainty of the land use data.

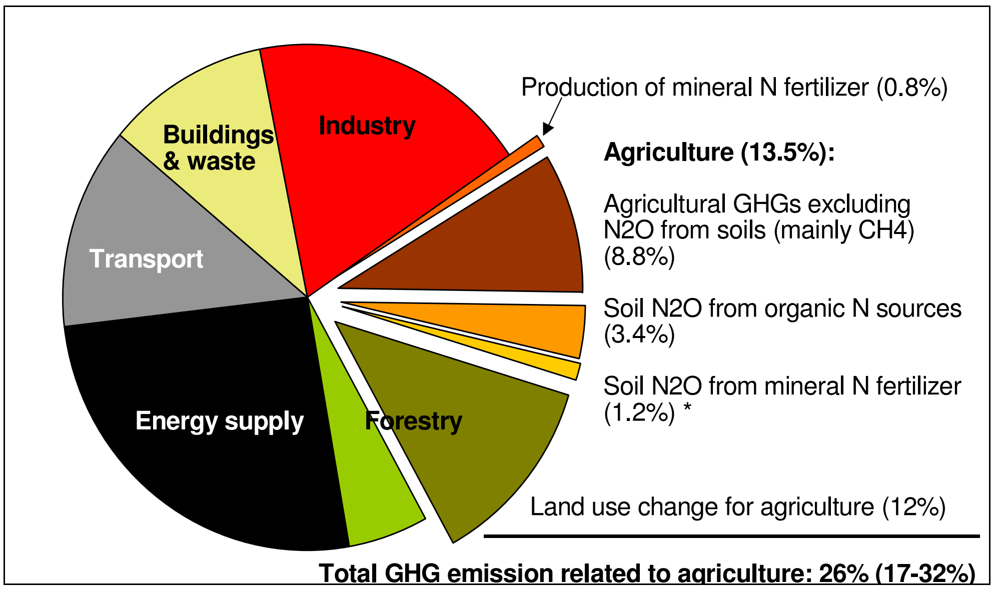

Figure 2: Contribution of all activities related to agriculture to the global GHG emissions in 2004 (IPCC, 2007; Bellarby et al., 2008; * own calculations)

These data show that the production and use of mineral and organic N fertilizer contributes significantly to the global GHG budget, but the major contribution related to agriculture is the expansion of agricultural land into forests and wetlands. Intensification of crop production can have an impact on both aspects. It can increase GHG emissions per area because of increased fertilizer application rates. But it may also protect natural and carbon-rich areas from being converted into agricultural land because intensive crop production allows for high yields per hectare.

Materials and methods – "carbon footprint" calculation based on life-cycle assessment (LCA) principles

A carbon footprint is "the total set of GHG (greenhouse gas) emissions caused directly and indirectly by an individual, organization, event or product" (Carbon Trust, 2007). This study calculates the carbon footprint per ton of winter wheat. The calculation is based on life-cycle assessment (LCA) principles. It includes all on-farm activities to produce wheat grain, the production and supply of seeds, pesticides, machinery, and fertilizers as well as the extraction and processing of any raw materials needed (Brentrup et al., 2004).

The results presented in this paper are based on a life-cycle assessment (LCA) study (Brentrup et al., 2004) that uses data from a long-term comparison of increasing rates of ammonium nitrate (AN) application to winter wheat ("Broadbalk Experiment" in Rothamsted, UK). The grain yield increased from 2.1 t/ha at zero N application to a maximum of 9.3 t/ha at 240 kg N/ha. The economic optimum N application rate is at about 195 kg N/ha. The following analysis will focus on four production intensities, which are "without N" (0 kg N/ha, 2.07 t grain/ha), "50% of optimum N" (96 kg N/ha, 7.11 t grain/ha), "economic optimum N rate" (192 kg N/ha, 9.25 t grain/ha), and "optimum N + 50%" (288 kg N/ha, 9.11 t grain/ha). The N fertilizer used in this field trial is ammonium nitrate (33.5% N).

Results

Figure 3 shows the emissions of GHG per ha. For fertilizer production average European technology for ammonium nitrate production according to Jenssen & Kongshaug (2003) has been assumed.

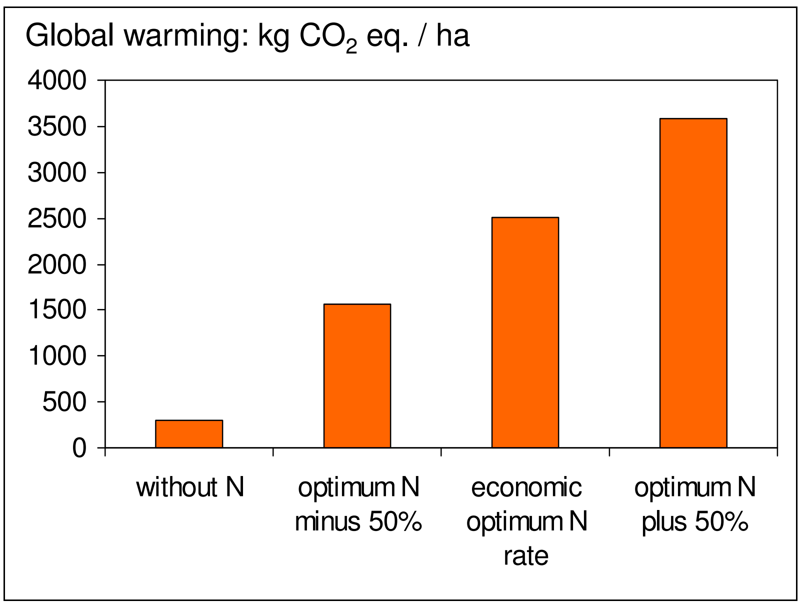

Figure 3: Greenhouse gas emissions of wheat production in kg CO_2eq per ha (including production and transport of farming inputs) at different N fertilizing intensities

The GHG emission for "optimum N + 50%", "economic optimum N rate", "optimum N – 50%", and "without N" is 3588, 2516, 1569, and 295 kg CO_2eq/ha, respectively. The "optimum N + 50%" treatment shall not be considered further, since any N application beyond the economic optimum increases GHG emissions without increasing grain yield.

Crop production causes GHG emissions, but at the same time the crops fix about 1.6 tonnes of carbon dioxide per tonne of biomass through photosynthesis (Greef et al., 1993). At a yield of 18.5 t/ha (grain plus straw at economic optimum N rate) this amounts to 29.6 t CO_2 fixation per ha, i.e. almost 12 times the CO_2 emissions. If this biomass is used as bio-fuel (e.g. for direct incineration) and thereby avoids the use of fossil fuels, a substantial net saving of CO_2 emissions can be achieved. However, by far most of the grain is still consumed as food or feed and in this case the CO_2 fixation is only short- to medium-term and is usually not considered as a credit.

In view of the current and future demand for cereals it can be assumed that any reduction in the production intensity at one place has to be compensated by additional production at another place. In many cases this results in land use changes from nature into agricultural land (IPCC, 2007 and Fig. 1). Figure 4 shows the additional CO_2 emission that occur due to conversion of temperate forest into cropland and cultivation of cereals to compensate for the lower yields in the treatments "without N" and "50% of optimum". Bellarby et al. (2008) gives data for CO_2 sequestration per area for different ecosystems. For a temperate forest the value is 560 t CO_2/ha, for arable land it is 300 t/ha, i.e. the conversion from temperate forest into cropland would release 260 t CO_2/ha. In this study the total carbon loss was spread over a time period of 100 years, i.e. the annual CO_2 loss due to land use change is 2600 kg CO_2/ha.

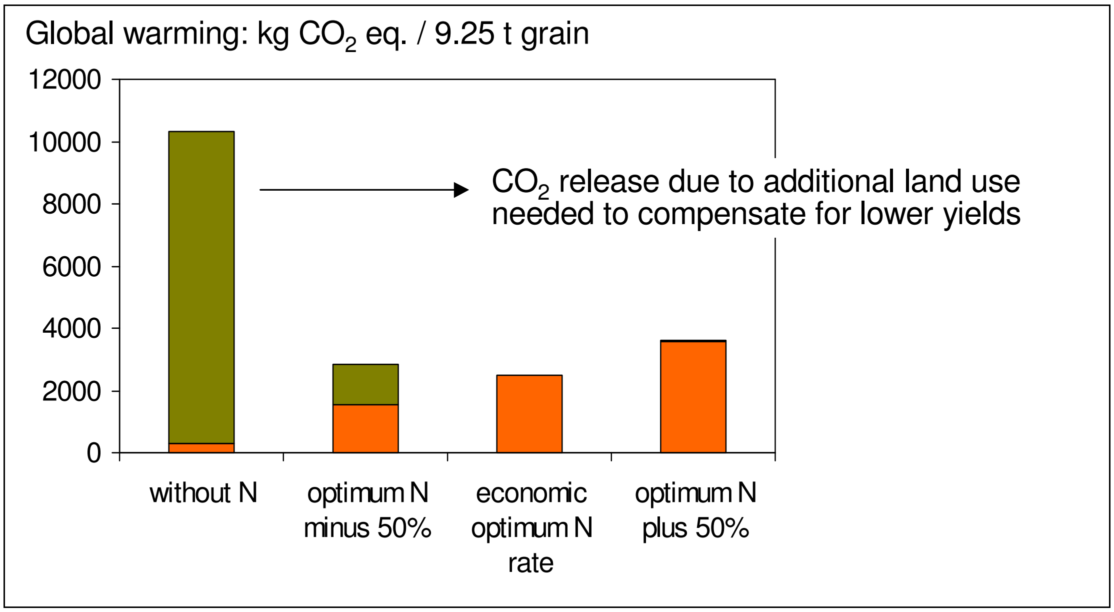

Figure 4: Greenhouse gas emissions of wheat production in kg CO_2eq per ha (including production and transport of farming inputs, <u>and land use change</u>) at different N fertilizing intensities

Without any nitrogen input the grain yield is so low (2.07 t/ha) that the land required to compensate this yield loss would lead to CO_2 emissions that are more than 4 times higher than those of the economic optimum system. Taking further into account the scarce land reserves it becomes obvious that a "zero nitrogen" system is not a viable option. But also the "optimum N minus 50%" treatment shows a higher carbon footprint if the additional land use needed to compensate lower yields is considered. It can be concluded that intensive crop production aiming at most efficient utilization of resources including agricultural land saves GHG emissions because natural land is potentially prevented from being converted into cropland.

From a climate change perspective it is nevertheless important to further reduce the carbon footprint of crop production. Possibilities to reduce the GHG emissions from fertilizer use in crop production are discussed in the following section.

Improving N use efficiency (NUE) to reduce the carbon footprint of crop production
Increasing NUE means to increase the share of N that is taken up by the crop compared to the amount N applied to the soil. The most obvious method to reduce GHG emissions from crop production is to avoid any N application above the economic optimum N rate. Possible measures to improve NUE are for instance to adjust the N application rate to the actual crop N demand by using soil and plant analysis, and to synchronize N application with crop N uptake (e.g. through split application and "just-in-time" fertilization). Figure 5 shows the development of NUE from 1987 to 2005 for Europe based on data from FAO and EFMA statistics. NUE was defined as mineral N input / N removal by harvested crops x 100. NUE increased from 34% in 1987 to more than 60% in 2005. While the strong increase of NUE during the 1990ties was mainly due to the low N application rates in the Eastern European countries after their economic downturn, the increase of NUE during the last years can be attributed to improved N management on farms. More efficient use of organic N sources as well as a more targeted application of mineral nitrogen fertilizers is the explanation for the positive development of NUE in Europe.

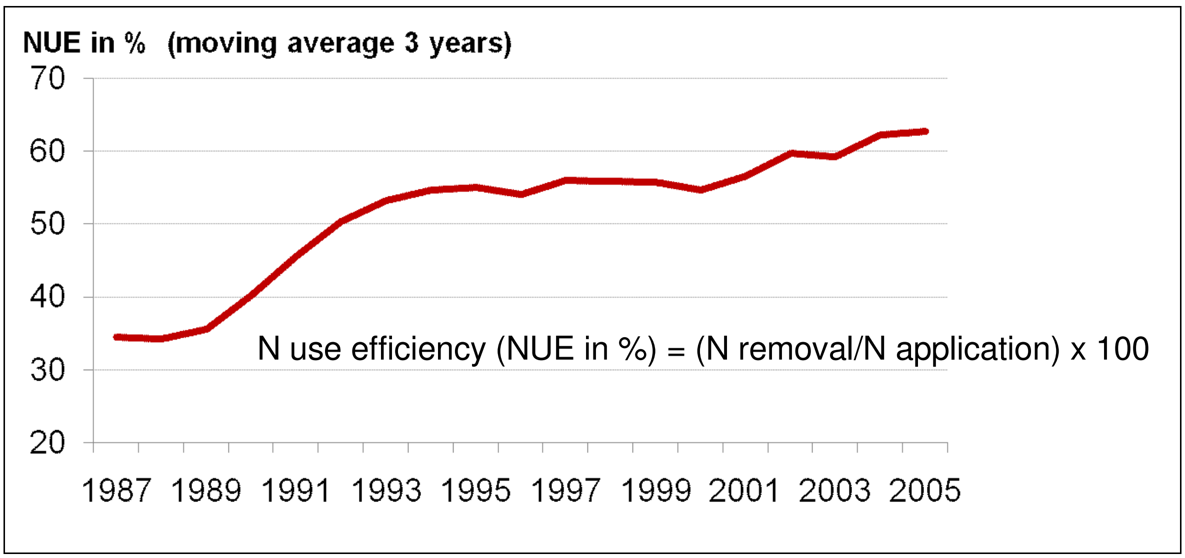

Figure 5: Development of N use efficiency in Europe from 1987 to 2005 (calculation based on FAO and IFA statistics, 2008)

From 1990 to 2006, N_2O emissions from agricultural soils have decreased by 67 Tg CO_2eq (18%; UNFCCC, 2008; Fig. 6). Even though the development during the early 1990ties is mainly driven by decreasing N application in the Eastern European countries, the steadily decreasing N_2O emissions during the last 10 years reveal a clear interdependency between improved NUE and reduced N_2O emissions from soils.

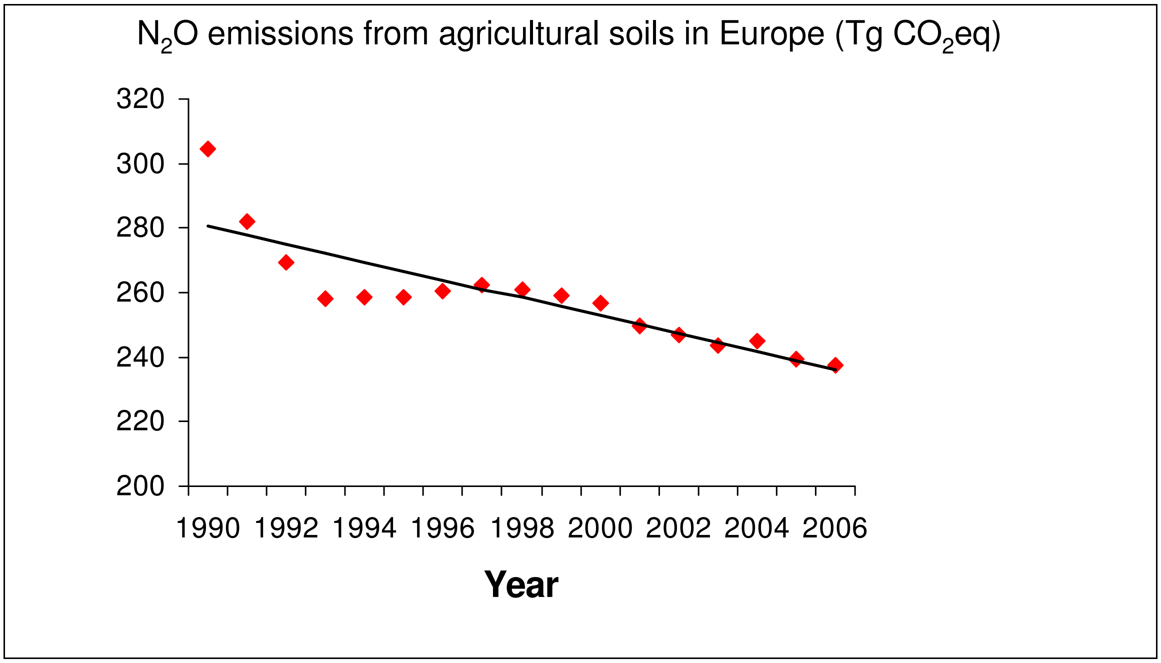

Figure 6: Annual N_2O emissions from agricultural soils in Europe (EU-27) between 1990 and 2006 (UNFCCC database, 2008)

Conclusions

Mineral N fertilizers are essential to sustain optimum yields that are required to satisfy the increasing global need for food, feed and bio-energy.

The agricultural contribution to climate change is substantial, with land use change (CO_2 from deforestation), cattle farming (CH_4 from enteric fermentation), and crop production (N_2O emissions from organic and mineral N inputs) as the major sources.

Intensive crop production aiming at economic optimum N supply helps mitigating GHG emissions by preserving natural land from being converted into cropland.

N use efficiency (NUE) has increased in Europe during the last 20 years. Increasing NUE contributes to decreasing GHG emissions from agriculture by reducing N_2O emissions from soil.

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