

Cost-effective N₂O, CH₄ and NH₃ abatement in European agriculture: interrelations between global warming and acidification policies

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Abstract

In Europe agriculture is an important contributor to emissions of the acidifying compound ammonia (NH₃) and the greenhouse gases nitrous oxide (N₂O) and methane (CH₄). Measures to reduce one of these gases may also have an impact on emissions of the others. This study investigates the effects of control options for NH₃, N₂O, and CH₄ that are available for the European agriculture on the emissions of all three gases. We found that NH₃ abatement in the European agriculture may have an adverse effect on N₂O emissions while abatement of N₂O results in a net decrease in emissions of NH₃. Reductions in CH₄ emissions slightly increase in N₂O emissions. An optimisation analysis for the Dutch agriculture shows that a shift to other NH₃ abatement options is possible to avoid the increase in N₂O emissions, but at considerable costs. If N₂O control options are available, it may be more cost-effective to apply these options to reduce the N₂O emissions to the initial level.

Introduction

In Europe, agriculture is an important source of the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). Agricultural activities are also the major source of ammonia (NH_3) emissions, which contribute to acidification and eutrophication of soils and waters. Emissions of these gases are associated with both animal and arable production. Many European countries committed themselves to reduce NH_3 emissions. Moreover, most countries also have agreed to reduce their greenhouse gas emission levels in the coming decade on the basis of the Kyoto Protocol (Conference of the Parties, 1998). Several studies have indicated that the agricultural sector can make a contribution to these emission reductions (De Jager et al., 1998; McCarl and Schneider, forthcoming).

Since CH_4 , N_2O and NH_3 have common sources in agriculture, reducing emissions of one of these gases may have an impact on the emissions of others, either beneficially or adversely. These interrelations affect the effectiveness of environmental policy and also the total costs of achieving environmental targets, but are often ignored. In general, taking into account the side effects of policy measures will make measures with a beneficial side effect more attractive and measures with an adverse side effect less. This study investigates interrelations between greenhouse gas mitigation policies and policies for acidification in the European agriculture. First, we provide some background on emissions of CH_4 , N_2O , and NH_3 from agriculture, describe the methodology for estimating emissions, and present options available for reducing these emissions. Next, we estimate (i) the possible side effects of various control options for NH_3 on N_2O and CH_4 , (ii) the possible side effects of CH_4 and N_2O abatement on NH_3 emissions, and (iii) possible interactions between CH_4 and N_2O control options. We present estimates for emissions of NH_3 , N_2O , and CH_4 from agriculture in Europe for 1990 and 2010 for various scenarios with different assumptions about abatement measures implemented, taking into account the estimated side effects of control options. Furthermore, we analysed the cost-effective emission reductions of NH_3 and greenhouse gases in the Dutch agricultural sector, their side effects, and potential costs of avoiding these side effects. Finally, we will present some conclusions.

Background

In 1990, agriculture was responsible for about 7% of total greenhouse gas emissions in Europe, with about 75% of agricultural greenhouse gas emissions being CH_4 and about 25% N_2O (derived from the EDGAR database, Olivier et al., 1996). In Europe NH_3 emissions are about 20% of total emissions contributing to acidification (derived from Amann et al., 1998).

Most NH₃ emissions in Europe are related to agriculture (Klaassen, 1994). Main sources of NH₃ are livestock farming, fertiliser use, and fertiliser production. NH₃ emissions from livestock occur in stables, during outside storage of manure, after application of manure to soils, or during grazing. The main source of N₂O is the application of nitrogen fertilisers to soils, which are converted to N₂O by micro-organisms. Moreover, N₂O emissions occur directly from animal waste management systems and during grazing. Indirect N₂O emissions occur at remote sites after atmospheric deposition of agricultural nitrogen oxides (NO_x) and NH₃ and in aquatic systems after nitrogen leaching and runoff. Finally, N₂O is also emitted during nitric acid production, which is related to agricultural activities since nitric acid is mainly produced as an intermediate in synthetic fertiliser production. Agricultural emissions of CH₄ are mainly caused by enteric fermentation by ruminants and by manure management. Rice cultivation, which is a considerable source of CH₄ globally, is a minor source in Europe. Thus, the main driving forces behind these agricultural emissions are animal production (CH₄, N₂O, and NH₃) and synthetic fertiliser use and production (N₂O and NH₃).

Several options are available for reducing these emissions from agriculture. Direct soil emissions of N₂O can be mitigated by reducing nitrogen inputs to soils, e.g. by a more efficient use of nitrogen in agriculture (Hendriks et al., 1998; Mosier et al., 1998a). CH₄ emissions from enteric fermentation can be controlled by increasing the rumen efficiency and by improving the animal productivity (Hendriks et al., 1998; Meeks and Bates, 1999). CH₄ emissions from manure management can be reduced either by prevention of anaerobic decomposition of manure or by stimulating the (controlled) fermentation of manure in special reactors with the recovery of CH₄ which can be used for heat and electricity production (Hendriks et al., 1998; Meeks and Bates, 1999).

NH₃ emissions from animals can be reduced by changes in the nitrogen content of the feed, changes in manure management, and substituting urea fertiliser by ammonium nitrate (Klaassen, 1991; Cowell and ApSimon, 1998). NH₃ from fertiliser production processes can be reduced by stripping and absorption techniques (Tangena, 1985; Klaassen, 1991).

Methodology for emission calculation

We used data from the NH₃-module of the RAINS model¹ to calculate the emission levels of CH₄, N₂O, and NH₃ from the agricultural sector in Europe² for the years 1990 and 2010. This

¹ Regional Air Pollution INformation and Simulation model, developed at the International Institute for Applied Systems Analysis (IIASA), Austria (Alcamo et al., 1990; Amann et al., 1998).

part of the RAINS model was developed to calculate NH_3 emissions in Europe and determine the costs and effectiveness of possibilities to reduce these emissions. For each country, the model includes information on agricultural activities and on costs and effects of several NH_3 reduction techniques (Klaassen, 1991). We calculated NH_3 emissions in 1990 and 2010 using the RAINS model. Moreover, we calculated emissions of CH_4 and N_2O from agriculture for these years by applying the Revised IPCC Guidelines for National Greenhouse Gas Inventories for CH_4 (IPCC, 1997) and the emission inventory method for N_2O described by Mosier et al. (1998b) to the information on the European agricultural sector in RAINS. Details of the calculation of CH_4 and N_2O emissions are described in Brink and Kroeze (in prep.).

Options for emission control

In order to establish the effect of control options for one pollutant on emissions of other pollutants, we selected a number of control options for NH_3 (Table 1), N_2O (Table 2), and CH_4 (Table 3) that are expected to be available in Europe in 2010. The effect on emissions is presented as a percentage change in emissions from the animal category to which the control option is applied³. Below, we will give a short description of the control options included.

Control options for NH_3 and information on costs and associated emission reductions are directly taken from RAINS (Klaassen, 1991). The estimated impact on N_2O and CH_4 emissions is discussed in more detail in Brink en Kroeze (in prep.). *Low nitrogen feed* assumes changes in the composition of the feed such that the nitrogen content decreases. Because of the reduction in nitrogen excreted emissions of N_2O will also decrease. *Biofiltration* absorbs NH_3 in the stable air and converts it to nitrite and nitrate. During this process N_2O emissions may occur. *Stable adaptations* imply a quick removal of the manure from the stable floor to a closed storage system. Manure from pigs and poultry is aerated and dried after removal from the stable. This process causes a large increase in N_2O emissions and a reduction in the emissions of CH_4 . *Covering storage of manure outside* prevents the escape of NH_3 during storage. In some countries this option will make manure storage conditions anaerobic, which results in a decrease in N_2O emissions and an increase in CH_4 emissions.

² The RAINS model covers most of Europe, including the European part of the former USSR (36 countries in total).

³ For example, the effect of hexose partitioning on CH_4 from enteric fermentation is -15% (Table 1). If hexose partitioning is applied to dairy cattle in the Netherlands in 2010, CH_4 emissions from enteric fermentation from this source (132 kiloton CH_4) are reduced by 15% (i.e. 20 kiloton CH_4).

With *manure injection* the manure is placed in the soils as opposed to spreading it over the surface. We assumed that this option causes an increase in emissions of N₂O from agricultural soils (Kroeze, 1994). *Substituting urea fertiliser by ammonium nitrate* reduces NH₃ emissions from synthetic fertiliser use. Finally, there are some *stripping and absorption techniques* available to remove NH₃ that is emitted during the production of synthetic fertilisers.

N₂O emissions can be reduced by *replacing synthetic fertilisers by manure*. This implies a more efficient use of manure that is otherwise disposed of as waste products (Hendriks et al., 1998). Emissions of N₂O as well as emissions of NH₃ will decrease because of a reduction in the use of synthetic fertilisers. *Restrictions on the timing of fertiliser application* will reduce N₂O emissions from soils as well as from nitrogen leaching. This option will also reduce NH₃ emissions from manure application⁴. This option requires longer manure storage times and greater capacities (AEA Technology Environment, 1998b). As a result, emissions of NH₃ and CH₄ may increase. Hendriks et al. (1998) mention a number of measures to *improve the fertiliser use efficiency*. Hence, a smaller amount of synthetic fertilisers is required, which causes a reduction in emissions of N₂O and NH₃ associated with synthetic fertiliser use. Velthof et al. (1998) mention some options to *improve grassland management* that will reduce N₂O emissions from soils, like an adjustment of the groundwater level. This option will promote the emissions of CH₄ from agricultural soils (Velthof et al., 1998). Another option to reduce N₂O emissions from dairy farming systems is to *restrict grazing* (Velthof et al., 1998). However, when grazing is restricted, the cattle will be in the stable for a longer time and more manure will be collected and stored. Therefore, this option will increase both NH₃ and CH₄ emissions (Velthof, 1997, p.166). Velthof et al. (1998) also indicate that N₂O emissions can be reduced by reducing the total nitrogen intake of the animals. As discussed earlier, this option is also included for the reduction of NH₃ (*low nitrogen feed*). N₂O emissions from nitric acid production in industry can be reduced by *catalytic reduction*, which converts N₂O to N₂ and O₂ (Hendriks et al., 1998)⁵.

Information on mitigation options included for CH₄ is taken from Meeks and Bates (1999). *Hexose partitioning* reduces CH₄ emissions by changes in the diet, which manipulate the amount of the feed carbohydrate going directly into microbial growth as opposed to

⁴ In some countries the application of fertilisers to soils is already restricted to a certain period of the year because of the associated reduction of NH₃ emissions.

⁵ These catalytic converters are not yet commercially available, but it is assumed that they will be available in 2010 (ECN and RIVM, 1998; AEA Technology Environment, 1998b) .

fermentation (Meeks and Bates, 1999). This technology enhances protein utilisation and hence also reduces NH_3 emissions. Moreover, animal productivity increases. *Propionate precursors* such as organic acids, malate or fumarate can be introduced as a feed additive for livestock. By increasing the presence of propionate precursors within the rumen, more of the hydrogen is used to produce propionate, and hence the CH_4 production is reduced (Meeks and Bates, 1999). *Probiotics* are microbial feed additives containing live cells and a growth medium, which improve animal productivity and hence reduce emissions of CH_4 and possibly also of NH_3 and N_2O ⁶ (Meeks and Bates, 1999). *Daily spreading of manure* reduces emissions of CH_4 from manure management because the storage period is shortened. However, this option may cause an increase in emissions of N_2O and NH_3 depending on factors such as manure application techniques, crop nitrogen needs, rainfall, and time of the year (Meeks and Bates, 1999). Moreover, because of existing regulation on timing of fertiliser application this option may not be fully applicable in each European country. *Anaerobic digestion of manure* in special reactors will produce biogas, which for the most part consists of CH_4 and CO_2 . When the biogas is used for heat and electricity production most of the CH_4 is converted to CO_2 before being released to the atmosphere (Hendriks et al., 1998; Meeks and Bates, 1999). Following Meeks and Bates (1999) we distinguish small scale and large centralised anaerobic digestion plants. Because of the controlled anaerobic storage conditions, NH_3 and N_2O emissions from animal waste systems may decrease. It is not clear what will be the effect of the remainder of the manure (that mostly will be applied to agricultural soils as a fertiliser) on emissions of N_2O and NH_3 .

The estimated effects of each of these control options on NH_3 , N_2O , and CH_4 emissions are presented in tables 1, 2, and 3. Also included are the costs of control options. Cost figures for control options taken from RAINS (Table 1) are country specific. Costs of N_2O mitigation options are taken from Hendriks et al. (1998) and AEA Technology Environment (1998b), who present costs for the EU-15 countries. Both studies assume that costs are equal throughout the EU. Hendriks et al. (1998) indicate that a follow-up study should identify cost differences in the various EU-15 countries (Hendriks et al., 1998, p.3). Costs of CH_4 mitigation options are taken from AEA Technology Environment (1998a), which presents

⁶ It is assumed that the total production of milk and meat in a country is kept constant. Consequently, when the production per animal is increases, fewer animals are needed to satisfy the demand for agricultural products. Although the emissions per animal may increase, in most cases the reduction in livestock will reduce total emissions.

costs per tonne CH₄ reduced for EU countries expressed in 1995 ECUs⁷. Different figures are given for countries with cool and countries with temperate climates because of differences in emission factors for CH₄ from manure waste management. Since we only had data for the EU and lacked the data to estimate country specific costs of mitigation options for N₂O and CH₄ for all European countries, we assumed costs to be equal throughout Europe. In future research we will relax this assumption.

Emissions in Europe in 1990 and 2010

On the basis of the estimated impact of several control options on CH₄, N₂O, and NH₃ as presented in Tables 1, 2, and 3, we calculated agricultural emissions of CH₄, N₂O, and NH₃ in Europe in 1990 and in 2010. Projections of agricultural activities in 2010 are taken from RAINS (viz. the 'Baseline' projection, described in Amann et al., 1998, p. 60-61). For the year 2010 we formulated several scenarios differing in the assumptions on the implementation of abatement strategies for the three gases. First, emissions were determined for a no control strategy (NOC), which assumes that in 2010 no abatement of any of the pollutants will take place. This scenario is used as a reference with which emissions resulting from other control strategies will be compared. Differences between emissions in the NOC scenario in 2010 and emissions in 1990 are exclusively the result of the (exogenous) changes in agricultural activities⁸. The other scenarios are based on the same projections for agricultural activities, but differ with respect to emission control strategies. Therefore, differences between emissions in the NOC strategy and emissions in other scenarios are only the result of the assumptions about the implementation of abatement options.

The second scenario (EQM) includes a control strategy for NH₃ that is based on targets for reducing environmental damage in Europe due to acid deposition. The deposition targets are taken from the 'medium ambition level' scenario described by Amann et al. (1999, p. 25). They identify the cost-minimal allocation of emission abatement measures for all acidifying compounds over European countries to meet the deposition targets and calculate the resulting emission levels for each country. The EQM scenario is based on these emission levels for NH₃ in each country (Amann et al., 1999, Table 3.3). Thus, the scenario analyses the effect on agricultural emissions of NH₃ reductions needed in Europe to achieve certain realistic targets

⁷ The conversion rate from ECU to Euro is 1:1.

⁸ Both in Western and Eastern Europe the population of most animal categories and also the consumption of synthetic fertilisers decrease between 1990 and 2010. Only poultry in Western Europe and pigs in Eastern Europe have an increasing population. The effect however is a decrease in total emissions.

for acid deposition in 2010 in a cost-effective way. Third, the maximum feasible reduction scenario (MFR) shows the impact of the highest possible reduction of NH_3 emissions in all European countries by the control options presented in table 3 on the emissions of CH_4 , N_2O , and NH_3 . Thus the EQM and MFR scenarios are scenarios focusing on NH_3 abatement, for which we calculated the emissions of N_2O and CH_4 . In addition, we determined the impact of N_2O mitigation (NOM) and CH_4 mitigation (CHM) by the most effective mitigation techniques for these gases on agricultural emissions of CH_4 , N_2O , and NH_3 . The N_2O mitigation scenario results in a reduction in N_2O emissions from European agriculture in 2010 by 19% compared to the situation without abatement. The CH_4 mitigation scenario reduces total CH_4 emissions from agriculture in Europe in 2010 by 12% compared to the emission level without abatement.

The calculated emissions are displayed in

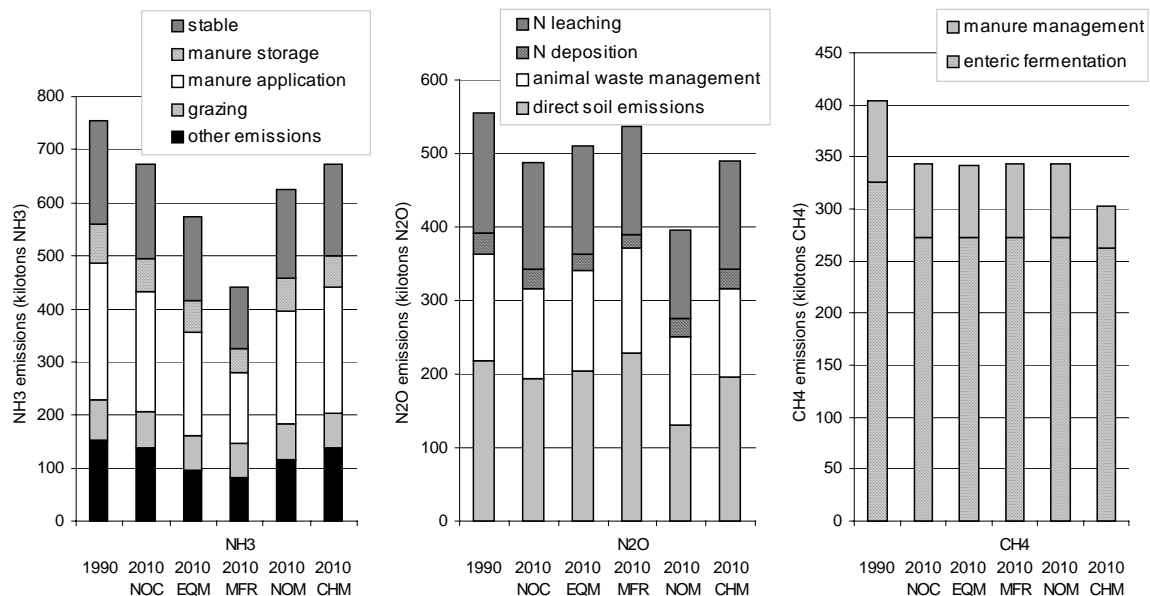


Figure 1⁹. We calculated a decrease in emissions of all three gases between 1990 and 2010. This is due to the expected decreases in livestock numbers and synthetic fertiliser use in Europe, which are incorporated in the projections for agricultural activities. Comparing emissions calculated for scenarios reflecting NH_3 abatement (EQM and MFR) with emissions in the NOC scenario shows that NH_3 abatement in Europe may not simultaneously reduce emissions of CH_4 and N_2O but may in fact increase agricultural N_2O emissions in Europe.

⁹ There are large uncertainties in estimating emissions of from agriculture (see e.g. Van Aardenne et al. (2000) for an analysis of uncertainties in estimating N_2O emissions from agriculture). Moreover, there are uncertainties in estimating the impact of control options. However, since we were not able to determine all uncertainties involved, the results are presented without an uncertainty range.

N₂O emissions for the MFR scenario are more than 10% higher than emissions for the NOC scenario in 2010. The net effect on agricultural emissions of CH₄ is almost zero. Furthermore, we found that abatement of N₂O (scenario NOM) in the European agriculture may simultaneously reduce emissions of NH₃ to about 7% below the level of NH₃ emissions in 2010 for the NOC scenario. The net effect of CH₄ abatement in the European agriculture (scenario CHM) on NH₃ emissions is negligible. The net effects of CH₄ mitigation on N₂O and of N₂O mitigation on CH₄ are very small increases in emissions.

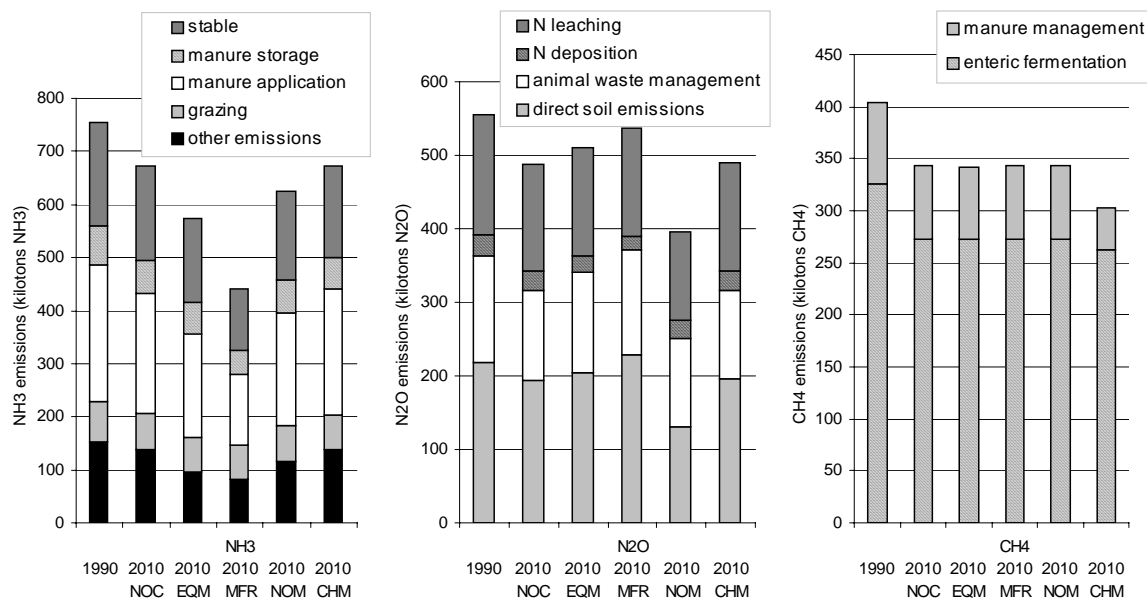


Figure 1 Emissions of NH₃, N₂O, and CH₄ from European agriculture in 1990 and 2010 for a scenario without control (NOC), two scenarios assuming NH₃ abatement (EQM and MFR), a scenario assuming abatement of N₂O (NOM), and a scenario assuming abatement of CH₄ (see text for explanation of the scenarios; results are preliminary estimates and need further research)

Cost-effectiveness of emission control

As mentioned earlier, interactions between different areas of environmental policy may affect the cost-effectiveness of these policies. To show the possible effect of such interrelations on total abatement costs, we performed an optimisation analysis for increasing restrictions on NH₃ emitted by the Dutch agricultural sector. In this optimisation analysis we determined the costs of abatement techniques that have to be implemented in order to achieve a certain emission reduction target at minimum abatement costs. This results in an abatement cost curve which represents the relation between a certain reduction in emissions and the costs that have to be made to realise this emission reduction. We analysed different cases: (1) abatement of NH₃ using NH₃ control options only (Table 1) without restrictions on greenhouse gas emissions and (2) with the additional constraint that emissions of N₂O and CH₄ from agriculture are not allowed to increase above the initial level; (3) abatement of NH₃ using

control options for NH₃ (Table 1) as well as for N₂O and CH₄ (Tables 2 and 3) and (4) with the additional constraint that emissions of N₂O and CH₄ from agriculture are not allowed to increase above the initial level. Figure 2 presents the results of cases 1 and 2 and Figure 3 of cases 3 and 4.

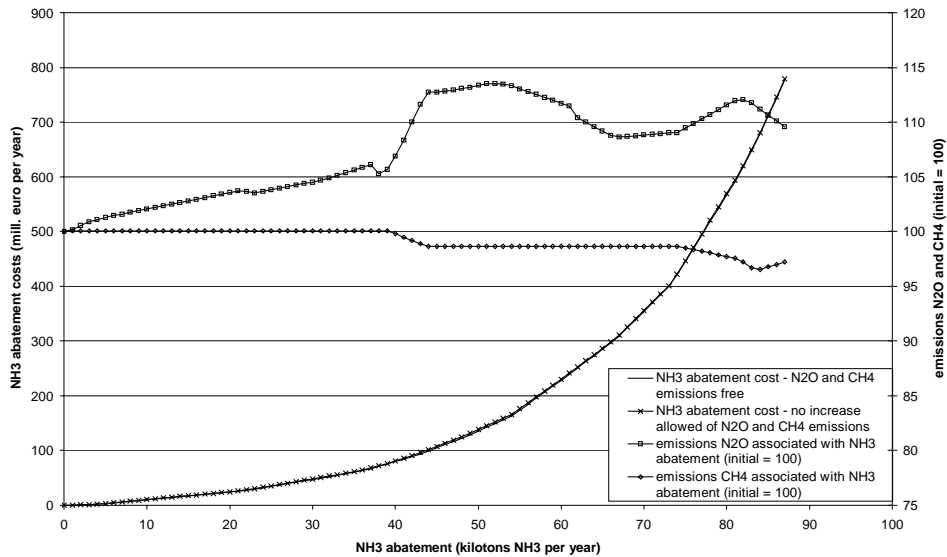


Figure 2 Costs of NH₃ abatement in the Dutch agricultural sector by NH₃ control options only in case N₂O and CH₄ emissions are not restricted (case 1) and in case N₂O and CH₄ emissions are not allowed to increase above the initial level (case 2). Also shown are the relative changes in N₂O and CH₄ emissions associated with NH₃ abatement in case 1.

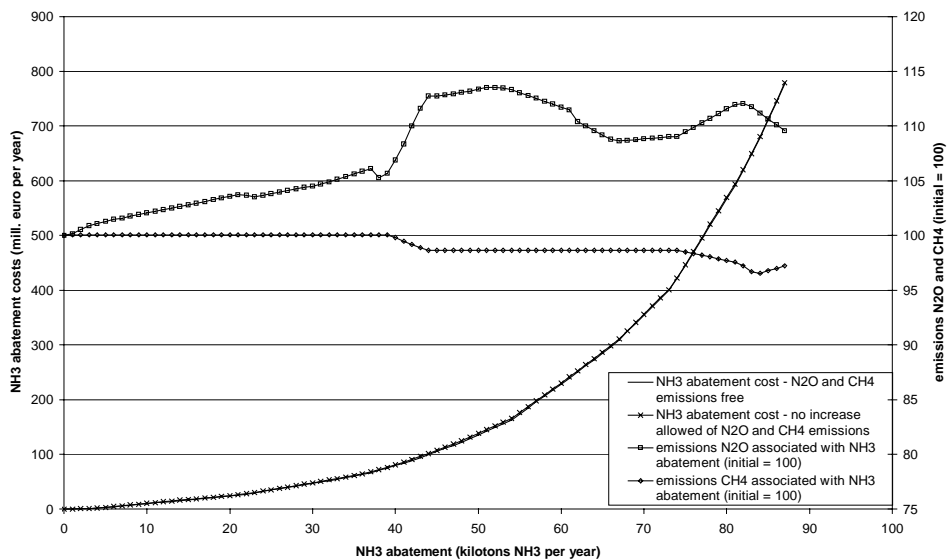


Figure 3 Costs of NH₃ abatement in the Dutch agricultural sector in case N₂O and CH₄ emissions are not restricted (case 3) and in case N₂O and CH₄ emissions are not allowed to increase above the initial level (case 4). Also shown are the relative changes in N₂O and CH₄ emissions associated with NH₃ abatement in case 3.

In both cases without constraints on greenhouse gas emissions (cases 1 and 3), N₂O emissions increase with higher NH₃ abatement levels. In cases 2 and 4 this increase is not allowed. To meet the constraints on N₂O and CH₄ emissions, either other NH₃ control options have to be applied (viz. control options with no effect on N₂O and CH₄ or control options which result in a decrease in emissions of N₂O or CH₄) or additional control options for N₂O and CH₄ have to be implemented. In case 2, only NH₃ control options are available to meet the constraints. Therefore, to prevent an increase in N₂O emissions in this case, NH₃ control options have to be applied that have no effect on N₂O emissions or that reduce N₂O emissions instead of or in addition to control options which result in an increase in N₂O emissions (for the Dutch agriculture we found a shift mainly from injection of manure, which causes an increase in N₂O, to low nitrogen feed, which simultaneously reduces NH₃ and N₂O). Since these control options are less cost-effective, abatement costs for a certain reduction of NH₃ emissions in case 2 are higher than in case 1. Costs for a 50 kiloton reduction of NH₃ emissions are about 80 million Euro higher in case 2 than in case 1 and for a reduction of 70 kilotons the difference is even more than 400 million Euro. Moreover, given the constraints on N₂O and CH₄ in case 2, the maximum feasible reduction of NH₃ is about 70 kilotons, while the maximum feasible reduction of NH₃ in case 1 is about 85 kilotons.

If control options for N₂O and CH₄ are included in the analysis (cases 3 and 4), the differences in costs are not so large anymore. To prevent an increase in N₂O emissions as a result of NH₃ abatement in case 4, some inexpensive control options can be applied that result in a reduction of N₂O emissions (in our analysis the reduction is mainly achieved by catalytic reduction of N₂O in nitric acid production processes, which is a very cost-effective control option for N₂O). The largest difference between abatement costs in cases 3 and 4 is about 2.5 million Euro for a reduction of 50 kilotons NH₃ (which is less than 2% of the total abatement costs).

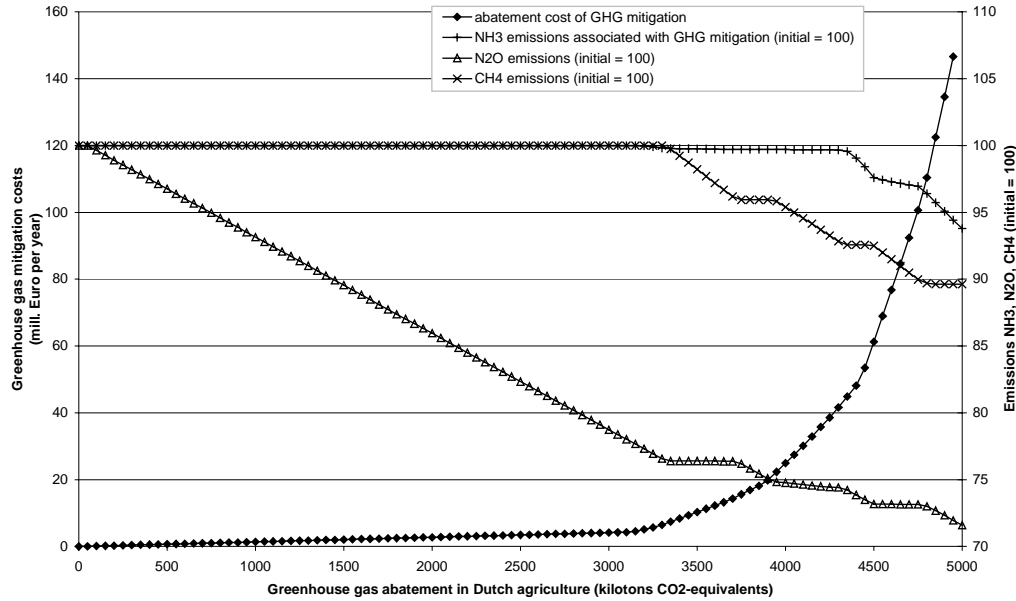


Figure 4 Costs of greenhouse gas abatement in the Dutch agriculture and attendant relative changes in emissions of NH_3 , N_2O , and CH_4 .

Furthermore, we determined the abatement cost curve for total greenhouse gas emissions from the Dutch agriculture and the effect on NH_3 emissions (Figure 4). We found that up to a reduction of 3000 CO_2 -equivalent greenhouse gas emission reductions can be achieved by catalytic decomposition of N_2O from nitric acid production processes, which is an inexpensive control option with a large reduction potential. Then some other control options are applied which also have an impact on emissions of NH_3 and CH_4 . The effect on NH_3 emissions is a small reduction of about 6% compared to the initial level of 191 kiloton in 2010.

Conclusions

In Europe, agriculture is an important source of emissions of the greenhouse gases CH_4 and N_2O and also of NH_3 , which contributes to acidification and eutrophication. Emissions are associated with livestock farming, fertiliser use, and fertiliser production. Many European countries committed themselves to reductions in greenhouse gas emissions, as well as in emissions of acidifying compounds. We analysed trends in emissions of N_2O , CH_4 , and NH_3 from European agriculture in 1990 and 2010 using data from the RAINS model. We found that between 1990 and 2010 emissions of N_2O , CH_4 , and NH_3 decrease by 12%, 15%, and 12% respectively as a result of expected reductions in livestock numbers and in fertiliser use.

Moreover, emissions can be reduced by several control technologies. In Europe, emissions of NH_3 can be reduced by at least 34% by means of end-of-pipe measures. European emissions of N_2O and CH_4 from agriculture may be reduced by 12% and 19% respectively.

However, several interrelations exist between policies for global warming and acidification in the agricultural sector in Europe since control options for one gas may have side effects on emissions of other gases, either beneficially or adversely. We estimated for a number of control options primarily aimed at NH_3 , N_2O , or CH_4 the effects on emissions of all three gases. These estimates were taken into account in our estimates of emissions of NH_3 , N_2O and CH_4 from the European agriculture. Emissions were calculated for various scenarios with different assumptions about the control options applied. In fact, we found that an NH_3 reduction in Europe by 14% (EQM scenario) and 34% (MFR scenario) may cause, as a side effect, an increase in N_2O emissions by 5% and 11% respectively. On the other hand, our results indicate that a 19% reduction in N_2O (NOM scenario) may simultaneously reduce NH_3 emissions by about 7%. A reduction in CH_4 emissions of 12% (CHM scenario) hardly affects emissions of NH_3 , but slightly increases emissions of N_2O (<0.5%). We found no effect of N_2O reduction on CH_4 emissions.

European countries face reduction targets for both acidifying compounds and for greenhouse gas emissions. Because of side effects, measures to achieve one target can make it more difficult to achieve another target. Therefore, it is important to take into account side effects of emission reduction measures. An optimisation analysis for the Dutch agricultural sector shows that abatement costs for NH_3 are higher if greenhouse gas emissions are not allowed to increase than in case the effect on greenhouse gas emissions is not taken into account. Costs to avoid an increase in greenhouse gas emissions are substantial if this is done by choosing NH_3 control options that have no negative side effects on greenhouse gas emissions. If control options for N_2O and CH_4 are also available, total abatement costs will also increase, but to a much smaller extent since relatively inexpensive control options are available to reduce N_2O emissions. In any case, however, the emission reductions come in addition to the existing commitments for greenhouse gas emission reductions in Europe, so total costs of greenhouse gas reductions in agriculture will increase as a result of the side effects of NH_3 abatement.

The results presented in this paper are preliminary and further research is needed on the side effects of the control options in the agricultural sector. Nevertheless, our study illustrates the importance of taking into account side effects of abatement activities in environmental policy making, which are not only present in the agricultural sector, but also in other sectors of the economy.

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Table 1 Costs of options primarily aimed at reducing NH₃ and tentatively estimated effect on emissions of NH₃, N₂O, and CH₄ (% change in emissions from animal category to which applied)¹

control options NH ₃	costs (mill. euro/ kton NH ₃ /yr)	sources of NH ₃ ²					sources of CH ₄ ³		sources of N ₂ O ³			
		stable	manure storage	fertiliser application	grazing	fertiliser production	enteric fermentation	manure management	direct soil emissions	animal waste management	nitrogen deposition	leaching and runoff
low nitrogen feed	1.1 to 22.6	-10 to -20	-10 to -20	-10 to -20	-20	0	0	0	-10 to -20	-10 to -20	-10 to -20	-20
biofiltration of stable air	6.5 to 74.9	-80	0	0	0	0	0	0	0	2 to 295	-7 to -55	0
stable adaptations	0.8 to 42.9	-45 to -80	-60 to -70	0	0	0	0	-10 to -100	1 to 99	45 to 900	-1 to -68	2 to 36
covering manure storage	0.0 to 90.3	0	-50 to -80	0	0	0	0	1 to 10	1 to 19	-1 to -10	-1 to -27	1 to 10
injection of manure	0.3 to 946.1	0	0	-30 to -80	0	0	0	0	60 to 100	0	-1 to -32	1 to 13
substitution of urea by ammonium nitrate	0.4 to 1.0	0	0	-80 to -93	0	0	0	0	0	0	-80 to -93	4 to 17
stripping and absorption	7	0	0	0	0	-50	0	0	0	0	-50	0

¹ Ranges indicate differences between the country-specific estimates for emission reduction from different sources of emissions and their costs

² Taken from RAINS (Amann et al., 1998)

³ Estimated effects described in Brink and Kroeze (in prep.)

Table 2 As Table 1, but for control options primarily aimed at reducing N₂O emissions

control options N ₂ O	costs (mill. euro/ kton N ₂ O/yr)	sources of N ₂ O					sources of CH ₄ ¹		sources of NH ₃ ¹			
		direct soil emissions	animal waste management	nitrogen deposition	leaching and runoff	fertiliser production	enteric fermentation	manure management	stable	manure storage	fertiliser application	grazing
replacing synthetic fertilisers by manure ²	243	-20 ³	0	0	-20 ³	0	0	0	0	-20 ³	0	
restrictions on timing of fertiliser application ²	6	-10 ⁴	0	- ⁵	-10 ⁴	0	0	+ ⁶	0	+	-	0
improved fertiliser use efficiency ²	<1 ⁷	-20 ³	0	-	-20 ³	0	0	0	0	-20 ³	0	
improvement of grassland management ²	5 ⁸	-20 ⁹	0	0	0	0	0 ¹⁰	0	0	0	0	
restricted grazing ²	6 ¹¹	0	-25 ⁹	+	0	0	0	+	+	+	-	
catalytic decomposition ²	0.43	0	0	0	0	-80 ¹²	0	0	0	0	0	

Notes:

¹ The estimates of the effects on CH₄ and NH₃ emissions are preliminary

² Information on costs and effects on N₂O emissions based on Hendriks et al (1998), Mosier et al. (1998a), and Velthof et al. (1998).

³ 20% reduction of emissions induced by synthetic fertilisers application.

⁴ 10% reduction of emissions from application of manure and synthetic fertilisers.

⁵ A '-' indicates a decrease in emissions that we could not yet quantify; in our calculations we assumed a decrease in emissions of 10%.

⁶ A '+' indicates an increase in emissions that we could not yet quantify; in our calculations we assumed an increase in emissions of 10%.

⁷ This control option includes options with net benefits (because of the savings from reduced application of inorganic fertiliser nitrogen) and options with net costs (AEA Technology Environment, 1998b). Therefore, we assumed a very low total net cost for this option.

⁸ This is a rough estimate of costs associated with lower crop productivity levels and higher labour requirements (as mentioned in AEA Technology Environment, 1998b, p.24).

⁹ Reduction of emissions from dairy cattle only.

¹⁰ This option will increase CH₄ emissions from soils (Velthof et al., 1998), which are not included in the model.

¹¹ As in the case of restrictions on timing of fertiliser application, costs are associated with greater storage capacities required; we assumed equal costs for these options.

¹² 80% reduction of emissions during industrial production of nitric acid.

Table 3 As Table 1, but for control options primarily aimed at reducing CH₄ emissions¹

control options CH ₄	costs (mill. euro/ kton CH ₄ /yr)	sources of CH ₄		sources of N ₂ O ²				sources of NH ₃ ²			
		enteric fermentation	manure management	direct soil emissions	animal waste management	nitrogen deposition	leaching and runoff	stable	manure storage	fertiliser application	grazing
hexose partitioning ³	1 ⁴	-15	0	? ⁵	?	-5	?	-5	-5	-5	-5
propionate precursors ³	2.73 - 5.69	-10 to -25	0	?	?	?	?	?	?	?	?
probiotics ³	5.44 - 11.33	-3 to -8	0	?	- ⁶	-	?	-	-	?	-
daily spread ^{3,7}	2.26 - 4.12	0	-90	++ ⁸	-- ⁹	+ ¹⁰	++	-	--	++	0
anaerobic digestion - centralised ³	2.29 - 7.88	0	-50 to -85	?	-	?	?	0	-	?	0
anaerobic digestion - small scale ³	0.29 - 0.70	0	-50 to -85	?	-	?	?	0	-	?	0

¹ Ranges indicate differences between the country-specific estimates for emission reduction from different sources of emissions and their costs.

² The estimates of the effects of CH₄ control options on N₂O and NH₃ emissions are preliminary.

³ Information on costs and effects on CH₄ emissions taken from AEA Technology Environment (1998a) and Meeks and Bates (1999).

⁴ Insufficient data is available to make an adequate assessment of the cost of hexose partitioning (AEA Technology Environment, 1998a). According to Meeks and Bates (1999) costs are likely to be minimal as productivity increases will partly offset the additional feed costs associated with this option. Therefore we assume a low cost of 1 million euro/kton CH₄ removed/year.

⁵ A '?' indicates that we do not know if there is an effect on emissions; in our calculations we assumed that there is no effect on these emissions.

⁶ A '-' indicates that we expect a decrease in emissions that we could not yet quantify; in our calculations we assumed a decrease in emissions of 10%.

⁷ The applicability of this control option may be limited in some countries because of existing regulations on timing of fertiliser application (AEA Technology Environment, 1998a, p.44).

⁸ A '++' indicates that we expect a large increase in emissions that we could not yet quantify; in our calculations we assumed an increase in emissions of 50%.

⁹ A '--' indicates that we expect a large decrease in emissions that we could not yet quantify; in our calculations we assumed a decrease in emissions of 50%.

¹⁰ A '+' indicates that we expect an increase in emissions that we could not yet quantify; in our calculations we assumed an increase in emissions of 10%.