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ANALYSIS

Cost-effective emission abatement in agriculture in the presence of interrelations: cases for the Netherlands and Europe

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Abstract

Agriculture contributes to global warming through emissions of nitrous oxide (N_2O), and methane (CH_4), and to acidification mainly through emissions of ammonia (NH_3). Measures to reduce one of these gases may affect emissions of others. Policies neglecting these interrelations may be suboptimal. This study investigated interrelations between abatement of ammonia, nitrous oxide, and methane from European agriculture. We first studied how emission reduction technologies simultaneously affect the emissions of these three gases. Next, we analyzed for the Netherlands how the costs of emission reduction are affected when these interrelations are included in the analysis. Cost-effectiveness analysis of emission reductions in agriculture in the Netherlands indicates that increased nitrous oxide emissions due to ammonia abatement can be avoided at low cost. Finally, we calculated at the European level the side effects on ammonia emissions and the greenhouse gases nitrous oxide and methane of various emissions scenarios for European agriculture. We estimated that nitrous oxide emissions from European agriculture may increase as a side effect of ammonia abatement, whereas ammonia emissions may decrease due to nitrous oxide and methane mitigation. The conclusion is that simultaneous reductions in emissions can be realized at lower overall costs using an integrated approach.

Keywords: Cost-effectiveness; Emission abatement; Global warming; Acid rain; Integrated assessment; Agriculture

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1. Introduction

In Europe, agricultural activities are an important source of the greenhouse gases nitrous oxide (N_2O) and methane (CH_4), and also of ammonia (NH_3), which contributes to acidification and eutrophication

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of soils and water. Emissions of these gases are associated with both animal and crop production. Many European countries agreed to reduce ammonia emissions in the Gothenburg Protocol (UNECE, 1999) in order to reduce acidification and eutrophication. Moreover, governments committed themselves to reduce greenhouse gas emission levels in the coming decade in the Kyoto Protocol (UNFCCC, 1997). Several studies have indicated that the agricultural sector can make an important contribution to these emission reductions (Mosier et al., 1998a and 1998b; McCarl and Schneider, 2000), and emission reductions of nitrous oxide and methane are important policy options for reducing emissions of greenhouse gases[1].

Nitrous oxide, methane, and ammonia have common sources in agriculture. Reducing emissions of one of these gases may have an impact on emissions of the others (Brink et al., 2001a). These interrelations change the effectiveness of environmental policy and also the total costs of achieving environmental targets, but are often ignored (Davis et al., 2000). In general, taking into account the side effects of policy measures will favor measures with beneficial side effects.

In this study, we investigated interrelations between abatement of the greenhouse gases nitrous oxide and methane and of ammonia in the agricultural sector in the Netherlands and Europe. For this purpose, we used data on abatement options and their impacts on emissions of ammonia, nitrous oxide, and methane. We studied for a case study on the Netherlands how the abatement costs are affected if the side effects of abatement options on other gases are considered. Therefore, we determined abatement cost curves representing cost-effective abatement strategies for various combinations of restrictions on emissions of nitrous oxide, methane, and ammonia. In the second part of the study, we analyzed at the European level in a number of scenarios how the emissions of other gases are affected if a policy for reducing one of the gases is implemented. Cost-effective abatement strategies to reduce nitrous oxide, methane, and ammonia from agriculture were determined for European countries considering side effects of abatement technologies.

Emissions were calculated using information on the European agricultural sector included in the RAINS[2] model databases. In addition to earlier work (Brink et al., 2001a,2001b), in this study, we included in the analysis newly collected information on technical measures to reduce emissions of nitrous oxide and methane, and estimated possible side effects of these abatement technologies. Moreover, we applied a new model that is largely based on the specifications of the RAINS model (Brink et al., 2001c). In this study, we restricted our analysis to cost minimization in a first-best context. We would like to indicate that the required incentive structures for introducing these first-best options and the game theoretical analysis thereof are beyond the scope of this paper.

2. Background: emissions of nitrous oxide, methane, and ammonia from agriculture

During the 1990s, agriculture was responsible for about 8% of total greenhouse gas emissions in Europe, with a share of about 50% of agricultural greenhouse gas emissions as methane and about 50% as nitrous oxide (derived from UNFCCC, 2000). The share of ammonia emissions in total European emissions of acidifying compounds was about 20% during the 1990s, and more than 90% of total

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[1] We used direct Global Warming Potentials (GWPs) relative to carbon dioxide for a 100-year time horizon, in line with Houghton et al. (1996). For nitrous oxide and methane, these GWPs are 310 and 21, respectively.

[2] 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). The RAINS model was developed to analyze cost-effective abatement strategies for air pollution in Europe. It includes abatement options for reducing emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia, and volatile organic compounds (VOC) for most European countries (36 countries in total). It is capable of minimizing total abatement cost given a set of deposition constraints for acidification. It has been used in the preparation and analysis of scenarios for the EU acidification and ozone strategy (Amann et al., 1998; Tuinstra et al., 1999) as well as for the discussion of reduction targets for the Gothenburg Protocol (Amann et al., 1999; UNECE, 1999).

ammonia emissions were related to agriculture (derived from UNECE/EMEP, 2000). Main sources of ammonia are livestock farming, fertilizer use, and fertilizer production. Ammonia emissions from livestock occur during animal housing, during outside storage of manure, after application of manure to soils, and during grazing (Klaassen, 1994). Nitrous oxide is emitted from agricultural fields after the application of nitrogen fertilizers and from animal waste management systems. Indirect nitrous oxide emissions occur at remote sites after atmospheric deposition of nitrogen oxides (NO_x) and ammonium (from ammonia), and in aquatic systems after nitrogen leaching and runoff (Mosier et al., 1998c). Nitrous oxide is also emitted during the production of nitric acid, which is mainly produced as an intermediate in synthetic fertilizer production (Oonk and Kroeze, 1998) Agricultural emissions of methane mainly result from enteric fermentation and manure management. Rice cultivation, which is a considerable source of methane globally, is a minor source in Europe (UNFCCC, 2000). Thus, the main driving forces behind these agricultural emissions are animal production (nitrous oxide, methane, ammonia) and use and production of synthetic fertilizers (nitrous oxide, ammonia).

In this study, emissions of nitrous oxide, methane, and ammonia from European agriculture were estimated for 2010 using data from the ammonia module of the RAINS model and our newly obtained information on emissions of greenhouse gases nitrous oxide and methane. The RAINS model includes information on agricultural activities in European countries (which are exogenous to the model), ammonia emission factors, and technical measures for ammonia emission reductions in order to estimate ammonia emissions in Europe and determine cost-effective ways to reduce these emissions (Klaassen, 1991). We extended the specifications of the RAINS model to consider the effects of technical abatement measures on various pollutants (cf. Brink et al., 2001c). Moreover, agricultural emissions of nitrous oxide and methane were estimated according to the Revised IPCC Guidelines for National Greenhouse Gas Inventories for methane (IPCC, 1997) and nitrous oxide (Mosier et al., 1998c), adapted to be used with the information on European agriculture in the RAINS model (cf. Brink et al., 2001a).

3. Emission abatement options

Several technical measures are available for reducing emissions of nitrous oxide, methane, and ammonia from agriculture. This study included a selection of these abatement options and an estimate of their respective cost by the year 2010. We excluded cutting output as a control option because this might be very expensive and the focus so far is on technical options. Measures to reduce emissions of nitrous oxide and methane were taken from existing studies for the European Union (Bates, 1998a,1998b; Hendriks et al., 1998; Bates, 2000). Options for ammonia reduction were taken from the RAINS model (Klaassen, 1991; Amann et al., 1998). These studies provide information on costs and effects on emissions that the measures primarily aim at. Costs are in euros_{1990}[3] and effects on emissions are given as percentage changes in unabated emissions from the source to which the control option is applied. For each of the technical measures included, we estimated their impact on emissions of other pollutants. Costs for ammonia reduction measures, which were taken from the RAINS model, are country-specific. These costs will affect the profitability of farms, depending on the extent to which they increase output prices. Information on costs of nitrous oxide and methane mitigation options was available only for the EU, assuming equal costs throughout the EU (Hendriks et al., 1998)[4]. No data were available to estimate costs for countries outside the EU. We assumed that abatement options that were available for EU countries could also be applied in other European countries at the same cost. When more information becomes available, we will be able to relax this assumption. The following is a short description of the abatement options included. Tables 1–3 present costs and effects of abatement options for nitrous oxide, methane, and ammonia, respectively.

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[3] EUR_{1990} prices were determined assuming that 1 EUR_{1990}=1 ECU_{1990}.

[4] This assumption deserves relaxation in further studies by specification for costs of technologies in various regions of Europe. However, after the introduction of the euro, some harmonization of costs of specific technologies over Europe is rapidly taking place. Note that in our study, cost differences occur at the aggregated level depending on the structure of the agricultural sector.

Table 1

Costs of technologies primarily aimed at reducing nitrous oxide, their technical potential to reduce nitrous oxide emissions, and estimated side effects on emissions of methane and ammonia (effects are presented as percent (%) change in emissions from source to which applied)[a,b]

Abatement technologies	Cost[c] (EUR$_{1990}$ per animal per year)	Emissions of nitrous oxide[c]					Emissions of methane		Emissions of ammonia			
		Direct soil emissions (%)	Animal waste management (%)	Nitrogen deposition (%)	Leaching and runoff (%)	Fertilizer production (%)	Enteric fermentation (%)	Manure management (%)	Animal housing (%)	Manure storage (%)	Fertilizer application (%)	Grazing (%)
Catalytic conversion N_2O in nitric acid production	0.4–4.2	0	0	0	0	−80	0	0	0	0	0	0
Substituting inorganic with organic N fertilizer	918–941	−15	0	−15 to −11	−15	0	0	0	0	0	−15	0
Restrictions on timing of fertilizer application	>0–1.8	0	20	0 to 10	−15	0	0	20	0	20	1	0
Fertilizer efficiency improvements	>0	−20	0	−20 to −15	−20	0	0	0	0	0	−20	0
Adjusting groundwater levels for grassland	0.5–1.3	−20	0	0	0	0	0	0	0	0	0	0
Restrictions on grazing	>0 to 34	1 to 700	−46 to −2	−15 to +41	0	0	0	1 to 335	1 to 335	1 to 335	1 to 335	−50

[a] A detailed specification of the numbers provided in this table and estimated effects of measures on methane and ammonia emissions is given in Brink (2003).

[b] Ranges indicate differences between sources.

[c] Values presented in this table for cost and effects on nitrous oxide emissions are based on Bates (1998b, 2000), Hendriks et al. (1998), Hendriks and Bode (2000), and Velthof et al. (1998).

Table 2

Costs of technologies primarily aimed at reducing methane, their technical potential to reduce methane emissions, and estimated side effects on emissions of nitrous oxide and ammonia (effects are presented as percent (%) change in emissions from source to which applied)[a,b]

Abatement technologies	Cost[c] (EUR$_{1990}$ per animal per year)	Emissions of methane[c]		Emissions of nitrous oxide				Emissions of ammonia			
		Enteric fermentation (%)	Manure management (%)	Direct soil emissions (%)	Animal waste management (%)	Nitrogen deposition (%)	Leaching and runoff (%)	Animal housing (%)	Manure storage (%)	Fertilizer application (%)	Grazing (%)
Propionate precursors	25–60	−25 to −10	−5	−5	−5	−5	−5	−5	−5	−5	−5
Probiotics	15–35	−8 to −3	−8 to −3	−8 to −3	−8 to −3	−8 to −3	−8 to −3	−8 to −3	−8 to −3	−8 to −3	−8 to −3
Daily spread of manure	8–75	0	−90	80	0	−20 to +5	80	0	−50	10	0
Anaerobic digestion of manure — centralized plant	2–26	0	−75 to −50	0	0	0	0	0	0	0	0
Anaerobic digestion of manure—small-scale plant	11–155	0	−75 to −50	0	0	0	0	0	0	0	0

[a] A detailed specification of the numbers provided in this table and estimated effects of measures on nitrous oxide and ammonia emissions is given in Brink (2003).

[b] Ranges indicate differences between sources.

[c] Values presented in this table for cost and effects on methane emissions are based on Bates (1998a, 2000).

Table 3

Costs of technologies primarily aimed at reducing ammonia, their technical potential to reduce ammonia emissions, and estimated side effects on emissions of methane and nitrous oxide (effects are presented as percent (%) change in emissions from source to which applied)[a,b]

Abatement technologies	Cost[c] (EUR_{1990} per animal per year)[d]	Emissions of ammonia[c]					Emissions of methane		Emissions of nitrous oxide			
		Animal housing (%)	Manure storage (%)	Fertilizer application (%)	Grazing (%)	Fertilizer production (%)	Enteric fermentation (%)	Manure management (%)	Direct soil emissions (%)	Animal waste management (%)	Nitrogen deposition (%)	Leaching and runoff (%)
Low nitrogen feed	0.1– 46	−20 to −10	−20 to −10	−20 to −10	−20	0	0	0	−20 to −10	−20 to −10	−20 to −10	−20 to −10
Cleaning air from animal housing	1.3–85	−80	0	0	0	0	0	0	0	2 to 295	−54 to −10	0
Animal housing adaptations	0.2–206	−80 to −45	−70 to –60	0	0	0	0	−90 to −10	1 to 99	45 to 900	−68 to −1	2 to 36
Covered outdoor storage of manure	>0 –105	0	−80 to −50	0	0	0	0	10	1 to 26	−10	−33 to −1	1 to 13
low ammonia application manure	>0 –71	0	0	−80 to −30	0	0	0	0	60 to 100	0	−39 to −1	1 to 18
Substitution of urea with ammonium nitrate	19 – 1620	0	0	−93 to −80	0	0	0	0	0	0	−92 to −77	0
End-of-pipe options in fertilizer plants	3–77	0	0	0	0	−50	0	0	0	0	−50	0

[a] Values presented in this table are based on Brink et al. (2001a).

[b] Ranges indicate differences between sources.

[c] Information on costs and ammonia emission reduction potentials was taken from the RAINS model (Amann et al., 1998; Klimont and Brink, 2004).

[d] For fertilizer use and production, costs are given in EUR_{1990} /ton fertilizer-nitrogen per year.

3.1. Measures to reduce nitrous oxide

The following measures to reduce nitrous oxide emissions related to agricultural activities were included in this study:

- *catalytic conversion of nitrous oxide in nitric acid production* can reduce nitrous oxide emissions from industrial nitric acid production processes by up to 80%, converting nitrous oxide to N_2 and H_2O (Oonk and Kroeze, 1998; Hendriks and Bode, 2000). Catalytic converters for this purpose are not yet commercially available, but we assume that they will be available in 2010 (based on Bates, 1998b).
- *substituting inorganic with organic nitrogen fertilizer* may reduce the total amount of nitrogen in the system (and hence nitrous oxide emissions) if inorganic fertilizer is replaced with manure, which is otherwise disposed of as a waste product (Hendriks et al., 1998). In Europe, emissions of nitrous oxide and ammonia from synthetic fertilizer application could be reduced by an estimated 15% by reducing the use of synthetic fertilizers (Bates, 1998b).
- *restrictions on timing of fertilizer application* (i.e., not in fall or winter) may reduce nitrous oxide emissions from nitrogen leaching in Europe by an estimated 15% (Hendriks et al., 1998). Ammonia emissions are minimized when manure is applied under cool, humid conditions, before or during rain, and not in June, July, or August. These conditions are the opposite of conditions for low-nitrogen leaching. It is not clear what the effect of this practice would be on ammonia emissions. We assume that restrictions on fertilizer application timing will cause a small increase in ammonia emissions (1%). Longer manure storage times and greater capacities are required (Bates, 1998b). As a result, emissions of ammonia, nitrous oxide, and methane during manure storage may increase by an estimated 20% (Hendriks et al., 1998).
- *fertilizer efficiency improvements* can reduce the amount of nitrogen fertilizer applied to agricultural soils, and hence the associated emissions of nitrous oxide as well as ammonia. Various measures, such as ensuring uniform spreading of fertilizers, maintaining a fertilizer-free zone, and optimizing fertilizer distribution geometry, are available at no direct cost (Mosier et al., 1998a; Bates, 2000). However, transaction costs and increased uncertainties in crop yield are not included in these cost estimates (Bates, 2000). It was not possible to make a reasonable estimate for these costs, but to account for them, we tentatively assumed costs of EUR_{1990} 5 million per kiloton nitrous oxide abated. Furthermore, we assumed that a 20% reduction in ammonia and nitrous oxide emissions from synthetic fertilizer application could be achieved in Europe.
- *adjusting groundwater levels for grassland* and preventing large fluctuations in groundwater levels could reduce nitrous oxide emissions from agricultural soils in several parts of Europe (Oenema et al., 1998; Velthof et al., 1998). In these studies, the cost and effect of this option were, however, not quantified. Because it was not possible to make reasonable estimates for the costs and effects, we tentatively assumed a reduction in nitrous oxide emissions from agricultural soils by 10% and costs of EUR_{1990} 5 million per kiloton nitrous oxide abated. As a side effect, this option may promote emissions of methane from agricultural soils (Velthof et al., 1998). In our analysis, agricultural soils are, however, not included as a source of CH_4.
- *restrictions on grazing* can reduce nitrous oxide emissions from animal waste, which are much higher for grazing animals than for animals in houses with anaerobic storage of manure (Mosier et al., 1998c). Therefore, restrictions on grazing can reduce nitrous oxide emissions from dairy farming systems by a shift from high nitrous oxide emissions during grazing to lower emissions from animal housing (Velthof and Oenema, 1997; Oenema et al., 1998). This implies, however, that more manure is collected, stored, and applied as fertilizer to agricultural fields because cattle will be inside for a longer time. Therefore, this option may increase ammonia and methane emissions from manure management, as well as nitrous oxide and ammonia emissions after application of manure (Velthof and Oenema, 1997). Costs associated with additional manure storage capacities are based on Bates (1998b).

3.2. Measures to reduce methane

The following measures to reduce methane emissions from agriculture were included in the study:

- *propionate precursors* can be introduced as a feed additive for livestock receiving concentrates to reduce methane production within the rumen (Bates, 2000). Reductions in methane emissions from enteric fermentation of up to 25% can be obtained (Bates, 2000). Moreover, due to increased animal productivity, feed requirements are reduced and, as a consequence, emissions of methane, nitrous oxide, and ammonia associated with manure produced by animals may decrease by up to 5% (Bates, 2000).
- *probiotics* are microbial feed additives that improve animal productivity for milk and growth (Bates, 2000) and hence can reduce methane from ruminants (Mosier et al., 1998b). An increase in the production per animal implies that fewer animals are needed to satisfy the demand for agricultural products because total production of milk and meat is assumed constant. Although emissions per animal may increase, the reduction in livestock may reduce emissions of methane and also of ammonia and nitrous oxide by up to 7.5% (Bates, 2000).
- *daily spread of manure* may reduce emissions of methane from manure management considerably (up to 90%) because the storage period is minimized (Bates, 1998a). However, the concomitant emissions of nitrous oxide and ammonia may increase substantially (up to 80%), depending on factors such as manure application techniques, crop nitrogen needs, rainfall, and time of the year (Mosier et al., 1998c). Costs for this measure are associated with increased labor requirements (Bates, 1998a).
- *anaerobic digestion of manure* results in methane emissions, which can be recovered and used for energy purposes (Hendriks et al., 1998; Mosier et al., 1998b). This may reduce methane emissions from manure management in Europe by 50–75% (Bates, 2000). Following Bates (2000), we distinguish between small-scale and large-centralized anaerobic digestion plants, with different costs. Possibly, because of controlled anaerobic storage conditions, ammonia and nitrous oxide emissions from animal waste systems will decrease. This has, however, not yet been studied (Bates, 2000). In addition, the net effect of using the digested manure as a fertilizer on emissions of nitrous oxide and ammonia is unclear.

3.3. Measures to reduce ammonia

Technical measures to reduce ammonia emissions, and information on costs and reductions in ammonia emissions, included in the RAINS model are described in Klaassen (1991) and Amann et al. (1998). The estimated impact of these measures on nitrous oxide and methane emissions is discussed in more detail in Brink et al. (2001a). Options included are:

- *low-nitrogen feed* assumes changes in the composition of the feed such that the nitrogen content decreases. Because of the reduction in nitrogen excretion, emissions of nitrous oxide also will decrease. Emission reductions of 10–20% can be obtained by this measure for both ammonia and nitrous oxide.
- various techniques can be applied to *clean the air in animal housing*. Ammonia is absorbed from the air and converted into nitrite and nitrate. During this process nitrous oxide emissions may occur. Ammonia emissions from animal housing may potentially decrease by 80% whereas nitrous oxide emissions from animal housing may increase by almost 300%.
- *livestock housing 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 animal house. Besides a decrease in ammonia emissions from manure management (up to 80%), these processes bring about an increase in nitrous oxide emissions from agricultural soils (up to 99%), manure management (up to 900%), and nitrogen leaching (up to 36%), and a decrease in methane emissions from manure management (up to 90%).
- *covering outdoor storage of manure* prevents the escape of ammonia during storage, resulting in a decrease in associated emissions (up to 80%). Depending on the manure type and the storage conditions, this option may change manure storage

conditions from aerobic into anaerobic, which may result in a decrease in nitrous oxide emissions (about 10%) and an increase in methane emissions (about 10%).

- various techniques are available for *manure application with low ammonia emissions*, mainly manure injection techniques. With manure injection, the manure is placed in the soil as opposed to spreading it over the surface. This reduces ammonia emissions during application (up to 80%) and is assumed to result in an increase in nitrous oxide emissions from agricultural soils (up to 100%).
- *substituting urea fertilizers with ammonium nitrate* reduces ammonia emissions from synthetic fertilizer use (up to 93%), without an effect on nitrous oxide and methane.
- several *end-of-pipe measures in fertilizer plants* are available to remove ammonia that is emitted during the production of synthetic fertilizers, resulting in a 50% reduction in ammonia emissions from this source.

4. Cost-effectiveness of emission control in the Netherlands

Interactions between policies for different environmental problems can affect the cost-effectiveness of these policies. To illustrate the possible effect of such interrelations on total abatement costs, we performed an analysis for increasing restrictions on emissions of nitrous oxide, methane, and ammonia from agriculture in the Netherlands. For a sequence of increasing emission reduction targets, we calculated the minimum costs required to achieve these targets and identified the abatement options applied in this optimum, given the costs and effects of abatement measures presented in Tables 1–3. This resulted in abatement cost curves, representing the relationship between emission reduction levels and the costs of realizing these reductions.

4.1. Cost curves for ammonia abatement

Cost curves for ammonia abatement in the Netherlands were determined for two cases: (*a*) ammonia abatement *without* constraints on nitrous oxide and methane emissions, and (*b*) ammonia abatement *with* the additional constraint that emissions of nitrous oxide and methane from agriculture may not increase above their initial levels.

4.1.1. Case a

In case *a* (no restrictions on nitrous oxide and methane), ammonia abatement resulted in increasing nitrous oxide emissions and unaffected or decreasing methane emissions (Fig. 1). Nitrous oxide and

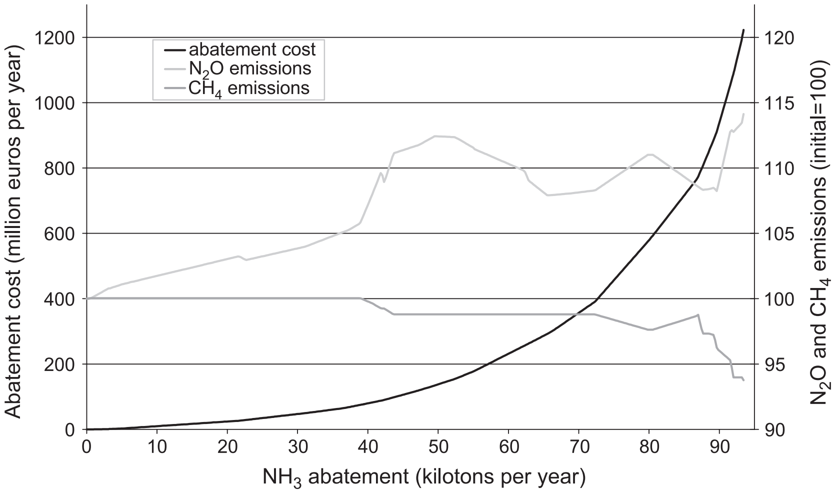

Fig. 1. Costs of ammonia abatement and associated nitrous oxide and methane emissions (initial emissions =100) in the agricultural sector in the Netherlands without a restriction on nitrous oxide and methane emissions (case *a*).

methane emissions vary for different ammonia abatement levels, because they depend on the specific ammonia abatement options applied. Therefore, it is interesting to analyze which abatement technologies are responsible for the changes in nitrous oxide and methane emissions at various ammonia abatement levels. The first 50 kilotons of ammonia can be abated at lowest costs by manure application techniques with low ammonia emissions (e.g., manure injection), which cause an increase in nitrous oxide emissions and do not affect methane emissions (Fig. 1). The relatively small reduction in nitrous oxide emissions associated with the 22nd kiloton of ammonia reduced (Fig. 1) is caused by the introduction of low-nitrogen feed for laying hens, which also has no effect on methane. When reducing ammonia emissions by 40–44 kilotons, nitrous oxide emissions increase relatively quickly whereas methane emissions decrease (Fig. 1) due to the introduction of adaptations to poultry housing. For ammonia abatement of 53–66 kilotons, nitrous oxide emissions decrease along with ammonia emissions (Fig. 1) because of low-nitrogen feed options. Ammonia abatement of 66–80 kilotons is obtained by adapting animal houses, causing an increase in nitrous oxide emissions and a reduction in methane emissions (Fig. 1). For ammonia abatement of 80–88 kilotons, nitrous oxide emissions decrease (Fig. 1) because, in this stage, techniques to clean the air from pig housing systems are applied instead of housing adaptations. Air-cleaning techniques have a higher ammonia reduction potential and a smaller impact on nitrous oxide emissions than housing adaptations, so nitrous oxide emissions are reduced with respect to the emission level in an earlier stage of the cost curve. The decrease in methane emissions at the end of the curve (Fig. 1) is caused by the introduction of propionate precursors and animal housing adaptations. Propionate precursors increase animal productivity and hence reduce emissions of ammonia, nitrous oxide, and methane simultaneously. Total nitrous oxide emissions, however, increase at the final stage of the cost curve (Fig. 1) because of the effects of animal housing adaptations and air-cleaning techniques, which are also applied in this stage.

4.1.2. Case *b*

In case *b*, in addition to the ammonia reduction targets of case *a*, both nitrous oxide and methane emissions may not exceed their initial levels. With the additional restriction in case *b*, total abatement costs are higher than in case *a* (Fig. 2). The difference in abatement costs between cases *a* and *b* is relatively small: <EUR 1 million per year for ammonia abatement up to 40 kilotons, EUR 1–6 million for 40–90 kilotons ammonia abatement, and increasing to EUR 35 million for higher ammonia abatement levels (Fig.

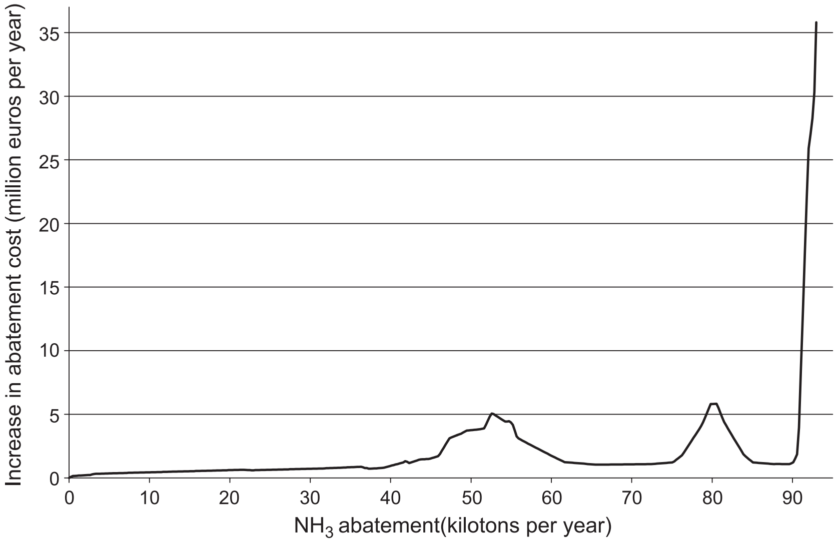

Fig. 2. Increase in cost for various levels of ammonia abatement with a restriction on nitrous oxide and methane emissions (case *b*) compared to the cost without a restriction on nitrous oxide and methane emissions (case *a*).

2). Abatement costs are higher in case *b* than in case *a* because (i) nitrous oxide abatement options with no effect on ammonia are applied to cancel out increases in nitrous oxide emissions; (ii) abatement options are applied at an earlier stage in the cost curve; and (iii) abatement options are replaced by options that are less cost-effective but also have a smaller impact on nitrous oxide emissions. All three reasons were observed in analyzing differences between cases *a* and *b*; that is, (i) application of catalytic reduction of nitrous oxide in industrial production of nitric acid for fertilizer production, introduction of restrictions on timing of synthetic fertilizer application, and adjusting groundwater levels for grasslands; (ii) early introduction of low-nitrogen feed, cleaning air from animal houses, fertilizer efficiency improvements, end-of-pipe abatement technologies in fertilizer production, and propionate precursors; and (iii) covering outdoor storage of manure instead of applying animal house adaptations. These changes prevent nitrous oxide and methane emissions from exceeding their initial level at relatively low additional abatement costs.

4.2. Cost curves for nitrous oxide and methane abatement

Cost curves for reducing the sum of nitrous oxide and methane (in CO_2-equivalents) emissions from agriculture in the Netherlands were determined, as was their effect on ammonia emissions. First, we calculated costs to reduce agricultural emissions of nitrous oxide and methane in the Netherlands *without* a restriction on ammonia emissions (case *c*). Furthermore, we analyzed the effect of a reduction target for ammonia on costs to reduce agricultural emissions of nitrous oxide and methane in the Netherlands in two cases: with a predetermined abatement strategy for ammonia (case *d*), and with a cost-effective strategy for ammonia, nitrous oxide, and methane abatement simultaneously (case *e*).

4.2.1. Case c

In case *c*, a reduction in nitrous oxide emissions from agriculture in the Netherlands by up to 1500 kiloton CO_2-equivalents can be achieved cost-effectively by catalytic reduction of nitrous oxide in industrial production of nitric acid (Fig. 3). This technology reduces nitrous oxide emissions and has no effects on ammonia and methane emissions (Fig. 3). For reductions of more than 1500 kiloton CO_2-equivalents, abatement options had to be applied that also affected emissions of ammonia. For abatement levels from 1500 to 1700 kiloton CO_2-equivalents, ammonia emissions are calculated to increase a little as a result of introducing restrictions on fertilizer timing (Fig. 3). Abatement levels beyond 1700

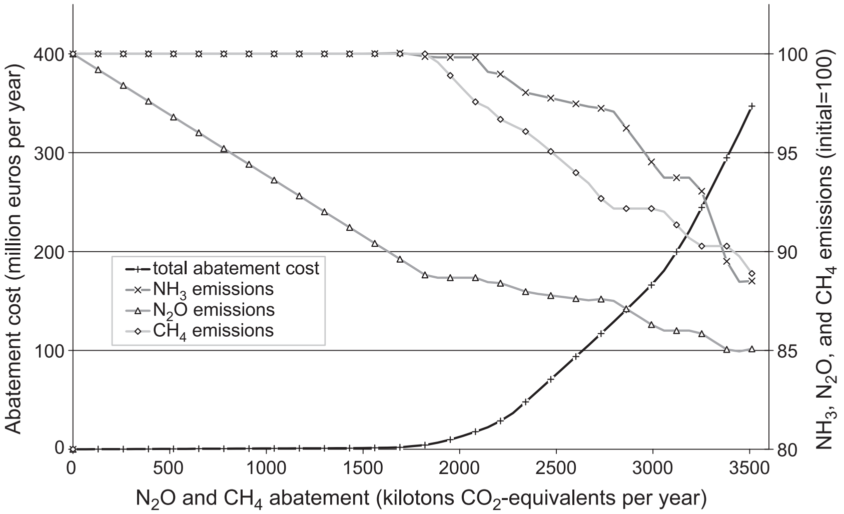

Fig. 3. Total costs for reducing the sum of nitrous oxide and methane emissions (CO_2-equivalents) from agriculture in the Netherlands and resulting emissions of nitrous oxide, methane, and ammonia (initial emissions =100) without a restriction on ammonia emissions (case *c*).

kiloton CO_2-equivalents are realized by abatement options that simultaneously reduce ammonia emissions, resulting in a more than 10% reduction in ammonia emissions for a reduction of nitrous oxide and methane emissions of 3500 kiloton CO_2-equivalents (Fig. 3).

4.2.2. Case d

In case *d*, we first determined a cost-effective abatement strategy for reducing ammonia emissions by 63 kilotons (to meet the emission target of 128 kilotons of NH_3 for the Netherlands in 2010 as included in the Gothenburg Protocol (UNECE, 1999)) without restrictions on nitrous oxide and methane emissions (in the following discussion, this abatement strategy is referred to as the predetermined abatement strategy). This ammonia reduction level can be obtained at EUR 270 million (see Fig. 1). Subsequently, we analyzed what additional abatement options have to be applied to cost-effectively reduce nitrous oxide and methane emissions at an increasing rate while maintaining the abatement options that are applied in the predetermined abatement strategy for ammonia. The resulting cost curve starts from a cost level of about EUR 270 million (i.e., the costs for reducing ammonia emissions by 63 kilotons; Fig. 1). Total and marginal costs of reducing nitrous oxide and methane emissions are higher, and the maximum level of nitrous oxide and methane abatement (about 1.7 megaton CO_2-equivalents) is lower in case *d* than in case *c* (Fig. 4). This is because not all abatement options that are available in case *c* can be applied in case *d*. Some options related to reducing nitrous oxide and methane emissions cannot be applied together with ammonia abatement options that are in the predetermined abatement strategy. Moreover, reductions in ammonia emissions due to abatement options for nitrous oxide and methane cannot be used to replace options to reduce only ammonia emissions that are in the predetermined abatement strategy. Consequently, there is less flexibility in choosing abatement strategies to reduce nitrous oxide and methane emissions, resulting in higher abatement costs and a lower reduction potential.

4.2.3. Case e

In case *e*, we also determined cost-effective abatement strategies for nitrous oxide and methane with a reduction target for ammonia emissions of 63 kilotons. Unlike case *d*, the initial ammonia abatement strategy is not maintained in case *e*. For increasing nitrous oxide and methane reduction levels, abatement strategies were determined such that the emission reduction targets for ammonia as well as nitrous oxide

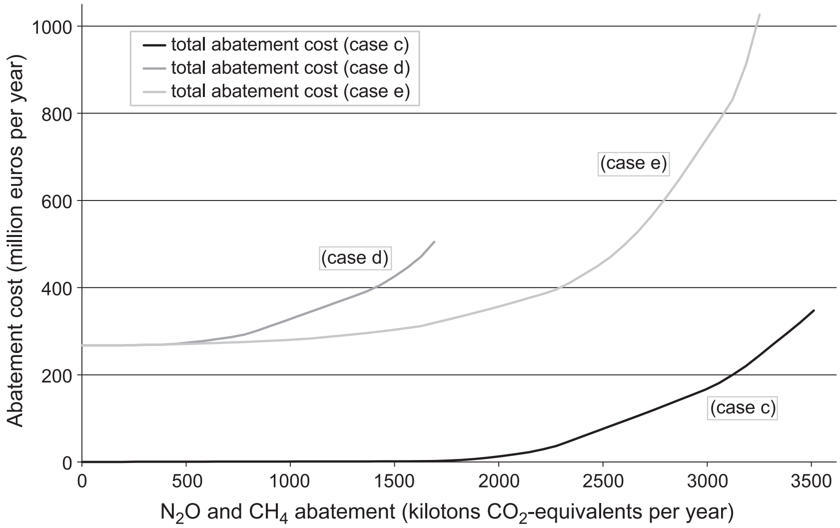

Fig. 4. Total cost for reducing the sum of nitrous oxide and methane emissions (CO_2-equivalents) from agriculture in the Netherlands (i) without a restriction on ammonia emissions (case *c*), (ii) with a reduction target for ammonia emissions of 63 kiloton maintaining the initial ammonia abatement strategy (case *d*), and (iii) with a reduction target for ammonia emissions of 63 kiloton and unrestricted abatement strategies (case *e*).

and methane were achieved at least costs. In case *e*, the abatement cost curve also starts from EUR 270 million and, as in case *d*, total and marginal abatement costs are higher and the maximum feasible reduction in nitrous oxide and methane emissions is lower than in case *c* (Fig. 4) because of the additional ammonia reduction target. However, total and marginal costs of reducing nitrous oxide and methane emissions are lower, and the maximum level of nitrous oxide and methane reduction (about 3.3 megaton CO_2-equivalents) is higher in case *e* than in case *d* (Fig. 4). This is because changes can be made in the initial ammonia abatement strategy, applying options to reduce ammonia and nitrous oxide or methane together, instead of abatement options related only to reducing ammonia emissions (and possibly even increasing nitrous oxide or methane emissions).

5. Side effects at the European level: scenarios for European agriculture

Agricultural emissions of ammonia, nitrous oxide, and methane in Europe were estimated for 2010, using information in the RAINS model. The model includes data on agricultural activities in Europe in 1990 and 1995, and a set of forecasts for activities up to 2010. This study used the baseline projection for 2010 described in Amann et al. (1998). Table 4 presents aggregated trends in animal numbers and fertilizer use in Europe from 1990 to 2010 based on Amann et al. (1998).

Emissions in 2010 were estimated for five scenarios that were based on the same projections for agricultural activities, but with different emission reduction strategies (Table 5). First, emissions were determined for a no-control strategy (NOC), which assumes that in 2010 no technical abatement measures for any of the pollutants will be applied. This scenario was used as a reference against which emissions resulting from other control strategies could be compared. Differences between emissions in the NOC strategy and emissions in other scenarios are the result of assumptions about implementation of abatement options and their estimated impact on emissions.

Next, the environmental targets scenario (ENV) and the maximum feasible reduction scenario (MFR) focus on ammonia abatement. Possible changes in nitrous oxide and methane emissions in these scenarios were calculated as side effects. The ENV scenario includes a control strategy for ammonia that is based on calculations for the 'medium ambition level' scenario described by Amann et al. (1999, p. 25). They specify targets for reducing environmental damage due to acid deposition, eutrophication, and ground-level ozone concentrations in Europe, identify the cost-minimal allocation of emission abatement for all contributing pollutants over European countries to meet these targets simultaneously, and calculate the resulting emission levels for each country. The ENV scenario is based on these emission levels for ammonia in each country (Amann et al., 1999, p. 27). Thus, the scenario shows the effect on agricultural emissions of ammonia reductions needed in Europe to achieve certain realistic targets for acid deposition in 2010 in a cost-effective way. The MFR scenario shows the highest possible reduction of

Table 4
Animal numbers and nitrogen fertilizer use in Europe: data for 1990 and projections for 2010 according to the RAINS 'baseline' projection, Amann et al. (1998) (10^6 animals and 10^6 tons N year^{-1})

	Western Europe		Eastern Europe		Total Europe	
	1990	2010	1990	2010	1990	2010
Dairy cattle	32	23	41	32	72	56
Other cattle	62	62	70	55	132	117
Pigs	111	108	123	126	234	234
Poultry	990	1065	1267	1187	2257	2253
Fertilizer consumption	11	10	10	9	21	19

Table 5
Scenarios for which emissions in 2010 were estimated

Scenario	Restrictions on emissions
NOC	no restrictions
ENV	Reductions in ammonia emissions according to the 'medium ambition level' scenario to reduce acidification and eutrophication (Amann et al., 1999, p. 25)
MFR	Highest possible reduction in ammonia emissions by technical measures included in the model
NOM	Nitrous oxide mitigation by the most effective abatement technologies for this gas (12.7% reduction)
CHM	Methane mitigation by the most effective abatement technologies for this gas (9.6% reduction)

ammonia emissions in Europe by technical abatement measures as included in the RAINS model (Table 3), irrespective of the costs.

Finally, we analyzed nitrous oxide mitigation (NOM) and methane mitigation (CHM) by the most effective technical abatement options for these gases (Tables 1 and 2). In the NOM scenario, total agricultural nitrous oxide emissions in Europe are 12.7% lower than in the NOC scenario, and in the CHM scenario total agricultural methane emissions are 9.6% lower than in the NOC scenario.

6. Results: side effects of emission control in Europe

Emissions of nitrous oxide, methane, and ammonia from European agriculture were estimated using the RAINS ammonia module that we extended to include agricultural emissions of nitrous oxide and methane (cf. Brink et al., 2001a), and measures to reduce these emissions. Cost-effective abatement strategies—that is, abatement options that have to be applied in order to achieve emission reduction targets at least cost to farmers—were determined. The estimated emissions are presented in Table 6[5]. Comparing emissions in scenarios focusing on ammonia abatement (ENV and MFR) with emissions in the NOC scenario reveals that ammonia abatement in Europe may as a side effect increase agricultural nitrous oxide emissions in Europe. In the MFR scenario, nitrous oxide emissions were more than 9% higher than emissions in the NOC scenario. Agricultural emissions of methane decreased by 0.4% (ENV) and 5.4% (MFR) compared with NOC emissions. Furthermore, abatement of nitrous oxide (NOM) in European agriculture was calculated to reduce ammonia emissions by 8%, whereas calculated methane emissions are almost 4% higher than the NOC emissions. Abatement of methane (CHM) was calculated to reduce ammonia emissions by more than 6%, whereas calculated nitrous oxide emissions are almost 6% higher than the NOC emissions.

Table 6
Estimated emissions from European agriculture (million tons ammonia, nitrous oxide, and methane per year; in brackets emissions as a percentage of emissions in NOC scenario) and total abatement cost (billion euros$_{1990}$/year) for several scenarios in 2010[a]

Scenario	Ammonia	Nitrous oxide	Methane	Total abatement cost
NOC	6.7 (100%)	1.7 (100%)	16.6 (100%)	0
ENV	5.7 (86%)	1.7 (103%)	16.5 (100%)	3.5
MFR	4.2 (62%)	1.8 (109%)	15.7 (95%)	38.1
NOM	6.2 (92%)	1.5 (87%)	17.2 (104%)	21.0
CHM	6.3 (94%)	1.8 (106%)	15.0 (90%)	7.3

[a] Emissions 2010 estimated for a scenario without technical abatement measures (NOC), two scenarios assuming ammonia abatement (ENV and MFR), a scenario assuming abatement of nitrous oxide (NOM), and a scenario assuming abatement of methane.

7. Discussion and conclusions

In Europe, agriculture is an important source of the greenhouse gases nitrous oxide and methane and also of ammonia, which contributes to acidification and eutrophication. Emissions are associated with livestock farming, fertilizer use, and fertilizer production. Many European countries intend to reduce greenhouse gas emissions as well as emissions of acidifying compounds by 2010. Emissions can be reduced by several abatement options. Options for one gas, however, may have side effects on emissions of other gases, either beneficially or adversely.

We estimated for several control options primarily aimed at ammonia, nitrous oxide, or methane the effects on emissions of all three gases. Next, in an optimization analysis for agriculture in the Netherlands, we showed that abatement costs for ammonia were higher if greenhouse gas emissions were not allowed to increase, than if the effect on greenhouse gas emissions was not considered. Costs to maintain greenhouse gas emissions in the Netherlands at their initial level were, however, small (<EUR 6 million for the largest part of the reduction potential) because in the Netherlands, relatively inexpensive control options are available to reduce nitrous oxide emissions from fertilizer production. We found that abatement of nitrous oxide and methane emissions from

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[5] Uncertainties in emissions from agriculture are relatively large (Van Aardenne et al., 2000; Suutari et al., 2001). 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.

agriculture in the Netherlands was more expensive if there was also a reduction target for ammonia emissions, in particular, if the cost-effective strategy for ammonia reduction was determined first, and subsequently cost-effective strategies were chosen to reduce nitrous oxide and methane emissions.

At the European level, emissions in 2010 were calculated for scenarios with different assumptions about the abatement options applied. We calculated that in Europe, a 14% reduction in ammonia emissions may have an impact on agricultural emissions of nitrous oxide (3% increase) and methane (0.5% reduction). More stringent ammonia emission reductions (38%) have a larger calculated impact on agricultural emissions of nitrous oxide (9% increase) and methane (5% reduction). A reduction in nitrous oxide emissions from agriculture (13%) reduced ammonia emissions (7%), but increased methane emissions from agriculture (4%). A reduction in methane emissions from agriculture (9%) reduced ammonia emissions (6%), but increased nitrous oxide emissions from agriculture (6%).

Although the data we used require further study, the results of our study show that they may have important policy implications. We argue that in the design of policies for emission reduction at the national and the European level, these interrelations should be taken into account. This implies, ceteris paribus, avoiding technologies that are doing a good job in reducing acidification, but at the same time are causing complications for global warming. We agree that, in practice, first-best solutions can never directly be implemented because strategic behavior of actors may be prohibitive or because it is impossible to introduce the correct incentive structure at acceptable transaction costs. In the preparation of environmental policy, however, it is essential to be aware of the first-best options. Other studies are devoted to the incentive structures and the game theoretical aspects of implementing policies for transboundary problems (including the fact that the first-best solution may well not be a Nash equilibrium), but that is not the primary focus of this paper.

This study has illustrated the importance of explicitly considering side effects of abatement activities in environmental policymaking in the agricultural sector because substantial increases in emissions may occur as a side effect of emissions reduction strategies that focus on a single gas. The next step in this research area may be to apply the optimization analysis for several countries in Europe, and to analyze the effects of the existence of interrelations with nitrous oxide and methane emissions on cost-effective allocation of emission reduction strategies over European countries. Eventually, the analysis may be extended to include interrelations between acidification and greenhouse gas mitigation policies in sectors other than agriculture.

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