

Modelling cost-effectiveness of
interrelated emission reduction strategies
the case of agriculture in Europe

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Abstract

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Agriculture is an important source of ammonia, contributing to acidification and eutrophication, as well as emissions of the greenhouse gases nitrous oxide and methane. Technical measures to control emissions of one of these pollutants may have an impact on emissions of others. These side effects, which may be positive or negative, are usually ignored in policy-making.

This study investigates interrelations in emission reduction strategies for ammonia, nitrous oxide and methane from agricultural activities in Europe and analyses their impact on cost-effective emission reduction strategies. It presents a modelling framework to identify cost-effective strategies for simultaneous reductions in emissions of various pollutants, considering interrelations. The model includes emissions from various sources and atmospheric transport from the location of emissions to the location where the environmental effect occurs. Emissions can be reduced by several abatement options. The effects of these options, including side effects on emissions of various pollutants, are explicitly incorporated in the model.

The model was used for an empirical analysis of interrelations in reducing ammonia, nitrous oxide and methane emissions from the European agricultural sector. In many countries, cost-effective ammonia abatement was found to result in an increase in nitrous oxide emissions. This was caused by measures that effectively reduce ammonia emissions but have adverse side effects on nitrous oxide, such as low ammonia application of manure and animal housing systems with low ammonia emissions. The results also indicated that several measures to reduce nitrous oxide and methane emissions, such as a lower nitrogen content in the fodder, improved fertiliser efficiency and feed additives improving animal productivity in milk and growth, simultaneously reduce ammonia emissions.

Furthermore, the model was used to identify cost-effective emission reduction strategies to achieve geographically specific targets for nitrogen and sulphur deposition, contributing to acidification and eutrophication, combined with reduction targets for nitrous oxide and methane emissions from the European agricultural sector, considering the interrelations in reducing emissions from the agricultural sector. The results indicated that cost savings can be obtained when interrelations are considered, because measures with harmful side effects are substituted with measures with beneficial side effects.

Voorwoord

Het is een bijzonder moment om mijn promotieonderzoek, waar ik een aantal jaren intensief aan heb gewerkt, af te kunnen ronden. Toen ruim een jaar geleden mijn termijn als AIO was verstreken, koos ik ervoor om niet meer fulltime aan mijn proefschrift verder te werken. Ik kreeg een aanstelling bij het RIVM waar ik de gelegenheid kreeg om, naast mijn reguliere werkzaamheden daar, een dag in de week te besteden aan mijn promotieonderzoek. Toen ik begon bij het RIVM had ik de intentie om mijn proefschrift in een jaar af te ronden en ik ben blij dat ik die intentie heb kunnen waarmaken. Dat zou me echter niet zijn gelukt zonder de hulp van anderen, en zeker ook niet zonder de mogelijkheden die het RIVM mij gaf om aan de afronding van mijn proefschrift te werken.

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1

Introduction

1.1 Interrelations in regional air pollution and climate change policies

Regional air pollution in Europe

Human activities – such as fossil fuel consumption, industrial processes and agricultural activities – result in emissions of various pollutants into the atmosphere. For several decades, there has been increasing concern about the environmental impacts of these emissions. Since the early 1970s, acidification has been recognised as a major environmental problem. The main acidifying compounds are sulphur dioxide (SO₂), nitrogen oxides (NO_x) and ammonia (NH₃), which are mainly emitted during fossil fuel combustion (SO₂ and NO_x) and agricultural production (NH₃). Once in the atmosphere, these pollutants are transformed, transported through the atmosphere (possibly over hundreds of kilometres) and subsequently deposited on the earth's surface. Acidifying deposition may be harmful to ecosystems of soil, water and forests and may also cause corrosion of metals and damage to buildings and monuments. Because of the long-distance atmospheric transport, acidifying deposition and its environmental impact in one country is to an important extent the result of emissions in other countries. It is generally recognised that international cooperation is required to efficiently deal with such transboundary problems (see e.g. Mäler, 1989).

In 1979 the Convention on Long-range Transboundary Air Pollution (LRTAP) was signed by countries in Europe and North America. This convention created a framework for international cooperation in controlling and reducing the damage to human health and the environment caused by transboundary air pollution. Under the Convention several international agreements have been reached in Europe to reduce emissions of acidifying pollutants. The first agreements focused on the reduction of emissions of single pollutants (viz. SO₂ in 1985 and NO_x in 1988). In 1991, an agreement was reached on the reduction of emissions of volatile organic compounds (VOC), which together with NO_x emissions contribute to the formation of ground-level ozone. High concentrations of ground-level ozone (also called tropospheric ozone) form another transboundary air pollution problem that can have negative effects on human health, agricultural crops and trees.

The early SO₂, NO_x and VOC protocols established the same reduction rate for each party. It was, however, recognised that a flat-rate approach focusing on a single pollutant will not result in a cost-effective solution of the regional air pollution problem in Europe. In the NO_x and VOC protocols it was stated that negotiations on further reductions in emissions of air pollutants should be based on the links

between their sources and effects. As a first step, the Second Sulphur Protocol (1994) included country-specific emission reduction targets that were established on the basis of the environmental effects of emissions, considering the atmospheric transport of emissions, and regional differences in the sensitivity of ecosystems and costs of emission reduction. The scope of this protocol was limited to SO₂ only. Large-scale integrated assessment models¹, such as the Regional Acidification Information and Simulation (RAINS) model (Alcamo et al., 1990), were used to identify effect-based cost-effective control strategies in European countries.

It was recognised that for the development of a strategy for a second NO_x protocol based on environmental effects, a comprehensive approach was needed with several compounds and effects involved (e.g. Amann et al., 1995; Van Ierland and Schmieman, 1999). NO_x emissions not only contribute to acidification, but also to ground-level ozone and nitrogen eutrophication². Moreover, other pollutants – including SO₂ (acidification), NH₃ (acidification and eutrophication) and VOC (ground-level ozone) – contribute to these regional air pollution problems. Grennfelt et al. (1994) describe several interrelations between air pollution problems. They argue that the various compounds and effects should be considered together because the control of one problem will influence other problems and the control of one compound will affect transport and effects of others (Grennfelt et al., 1994).

Integrated assessment models – in particular the RAINS model – played an important role in the negotiations leading to a multi-pollutant multi-effect protocol in Europe (Amann et al., 1999a). The RAINS model includes emissions of SO₂, NO_x, NH₃ and VOC and control options for these pollutants. The model provides a framework for a comprehensive analysis of emission reduction strategies, focusing on acidification, eutrophication and tropospheric ozone in Europe (Schöpp et al., 1999; Amann and Makowski, 2000). In 1999, the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone was signed (UNECE, 1999a). This protocol sets country-specific emission ceilings for four pollutants (SO₂, NO_x, NH₃ and VOC) in 2010 in order to simultaneously reduce acidification, eutrophication and ground-level ozone concentrations in Europe. Recently, progress has been made in investigating the problem of particulate matter (PM) pollution in Europe, which has adverse effects on human health. This problem is strongly related to the other air pollution problems (Lükewille et al., 2001) and may be included as an additional consideration in a future review of the Gothenburg Protocol (UNECE, 2002).

Climate change

Another environmental issue that has been the subject of widespread public concern since about two decades is the possibility of a climate change due to increasing concentrations of greenhouse gases in the atmosphere. Greenhouse gases are emitted as a result of several human activities, including fossil fuel burning, agricultural activities and deforestation. Important greenhouse gases are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and several fluorinated compounds (such as CFCs, HFCs and SF₆). Although CO₂ is the most important greenhouse gas, several studies show that it is important to consider other greenhouse gases as well (cf. Michaelis, 1999).

¹ According to Hordijk and Kroeze (1997), integrated assessment models aim at covering the whole chain of events, from sources of emissions to environmental effects, with the aim to assist policy makers.

² Eutrophication refers to a strong enrichment of ecosystems by nutrients (mainly nitrogen and phosphorus), which causes some plant species to grow excessively and others to disappear.

Increasing scientific evidence of the potential impact of human activities on the world's climate system and growing public concern over global environmental issues, began to push climate change onto the political agenda in the mid-1980s (UNFCCC, 2002). Possible consequences of climate change are sea level rise, altered precipitation patterns, changes in agricultural yields (either positive or negative) and an increase in the incidence of extreme weather events in some regions, such as floods and droughts. Although there are many uncertainties involved, the Intergovernmental Panel on Climate Change (IPCC) concludes in the Second Assessment Report that 'the balance of evidence suggests that there is already a discernible human influence on global climate' (IPCC, 1996) and in the Third Assessment Report that 'there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities' (IPCC, 2001a).

Unlike air pollutants, the main greenhouse gases are uniformly mixed in the atmosphere because of their relatively long atmospheric lifetime. Therefore, the environmental impact of greenhouse gases does not depend on the location of the emissions. An efficient solution to this problem requires international cooperation at the global scale, because a climate change will have world-wide impacts. In 1992, the world's governments adopted the United Nations Framework Convention on Climate Change (UNFCCC), which provides the foundation for intergovernmental efforts to address the problem of global climate change (UNFCCC, 2002). Parties to this Convention negotiated an agreement to limit or reduce their greenhouse gas emissions. In 1997, they adopted the Kyoto Protocol at the third Conference of the Parties (COP3) in Kyoto. This Protocol contains country-specific targets for greenhouse gas emissions in the period 2008–2012 (UNFCCC, 1997). The reduction target for the EU as a whole is 8% compared to 1990 emissions. In the so-called burden-sharing agreement this reduction target has been shared out amongst the member states to allow for different economic development patterns (European Commission, 1999). Targets for European countries outside the EU range from an 8% reduction to a 1% increase in greenhouse gas emissions compared to 1990 emissions (UNFCCC, 1997, Annex B). In subsequent Conferences of the Parties, further agreements were reached concerning the implementation of the Kyoto Protocol – such as agreements on mechanisms that the parties can use to gain credits for emissions reduced abroad (joint implementation, the clean development mechanism and emission trading) and on the compliance regime – which should enable widespread ratification of the Protocol and its entry into force³ (UNFCCC, 2002).

As for regional air pollution, integrated assessment models, combining key elements of biophysical and economic systems into one integrated system, have been used to analyse the cost and effects of different constraints on greenhouse gas emissions (see e.g. Weyant et al., 1996; Kelly and Kolstad, 1999).

Interrelations between regional air pollution and climate change

There are several interrelations between regional air pollution and climate change (an early overview of possible linkages is provided by White et al., 1989). These interrelations can be subdivided into four categories: (i) emissions of one pollutant may contribute to regional air pollution as well as climate change; (ii) air pollutants and greenhouse gases may be emitted by the same source; (iii) technical measures to reduce emissions of greenhouse gases may affect emissions of air pollutants and technical

³ The US have indicated their intention not to ratify the Kyoto Protocol.

measures to reduce emissions of air pollutants may affect greenhouse gas emissions; and (iv) climate change and regional air pollution may have an effect on each other and on emissions⁴.

An example of interrelations in category (i) is the role of SO₂, which contributes to acidification and also plays a role in climate change, partly offsetting the greenhouse effect due to increased amounts of sulphate aerosols in the atmosphere. This interrelation has been analysed by Alcamo et al. (1995) and Posch et al. (1996).

Category (ii) contains another important linkage between regional air pollution and climate change. Because emissions contributing to regional air pollution and climate change are to a large extent emitted by the same sources, policies focusing on these sources to reduce one of these problems may have an impact on the other. This is in particular the case with policies for climate change, which largely focus on reducing CO₂ emissions. CO₂ emissions are almost entirely produced by burning fossil fuels, which is also an important source of several air pollutants. CO₂ emissions can be limited by reducing the use of fossil fuels through energy efficiency improvements and a shift to renewable sources of energy. Climate policies leading to reduced fossil fuel use will have side benefits, because emissions of air pollutants such as SO₂, NO_x and VOC will also decrease. One of the earliest studies considering these side effects of CO₂ abatement appears to be Ayres and Walter (1991). Since then, a number of studies have dealt with this issue, including Alcamo and De Vries (1992), Pearce (1992), Alfsen et al. (1995), Boyd et al. (1995), Ekins (1996), Burtraw and Toman (1997), Aaheim et al. (1999), RIVM et al. (2001) and Syri et al. (2001). In general, the conclusion from these studies is that benefits of CO₂ abatement that are not directly related to climate, are important and could offset a significant portion of the abatement cost.

Interrelations in category (iii) occur if technical measures to reduce emissions of air pollutants have an effect on emissions of greenhouse gases and the other way around. Interrelations in category (ii) refer to changes in emissions because of changes in the use of the polluting input (e.g. fossil fuels), which are generally in the same direction⁵. Technical measures, however, may have beneficial as well as harmful side effects. Several examples of this have been mentioned in the literature, including scrubbers installed in power plants to reduce SO₂ emissions causing an increase in CO₂ emissions through increased coal use (Martin, 1989) and three-way catalysts in cars reducing NO_x and VOC but at the same time causing an increase in N₂O emissions (Michaels, 1998).

Finally, there are several examples of interrelations in category (iv). Grennfelt et al. (1994) mention the effect of acidification and nitrogen deposition on emissions of CH₄ and N₂O in some ecosystems, and the effect of increased temperatures on nitrate leaching. Moreover, linkages between regional air pollution and climate change may exist because climate change may alter atmospheric transport patterns of air pollutants and the sensitivity of ecosystems for acidifying deposition. These linkages have been investigated in the AIR-CLIM project (Mayerhofer et al., 2001).

Most studies dealing with interrelations between regional air pollution and climate change focus on only one of the categories described. Ignaciuk et al. (2002) indicate the importance of considering

⁴ This subdivision to a large extent corresponds with the types of interactions distinguished by Ignaciuk et al. (2002). They focus on the importance of considering interactions between emissions of air pollutants and greenhouse gases in emission inventories. However, they do not consider the possible contribution of one pollutant to regional air pollution as well as climate change.

⁵ An exception is, for instance, a switch in transportation from gasoline to diesel, which has a lower carbon content but results in higher emissions of particulate matter and associated health impacts (Pearce, 2000).

various kinds of interactions between emissions of air pollutants and greenhouse gases in emission inventories. Van Ierland et al. (2002) propose a model structure for an integrated analysis considering various types of interrelations. In this thesis, we present a model for analysing cost-effective abatement strategies considering interrelations in categories (i), (ii) and (iii).

Integrated analyses in environmental economics

Besides interrelations between regional air pollution and climate change, there are also several interrelations between other environmental problems. In the past decades, several studies in environmental economics have analysed the impact of these interrelations on efficient emission control when multiple pollutants are involved. Although these studies are not specifically dealing with interrelations between regional air pollution and climate change, the conclusions indicate the importance of considering these interrelations in determining optimal emission control strategies. In the following I will briefly review some relevant studies in chronological order.

Beavis and Walker (1979) present a cost-effectiveness analysis for water pollution control, considering several interactive pollutants and several constraints. The combined effect of these pollutants may be additive, but also less-than-additive or more-than-additive, or pollutants may even be working against each other⁶. Moreover, they include joint abatement cost functions, relating any combined level of reductions in emissions of the various pollutants to its total cost. They conclude that optimal tax rates on emissions of different pollutants have to be determined simultaneously and depend on each firm's abatement costs.

Lave (1984) indicates that, if externalities are interdependent, policies pursuing externalities one at a time may produce sub-optimal outcomes or contradictory regulations. This analysis also holds for environmental regulations that aim at specific media (for example, air, land, or water), not considering the overall environmental impact, which typically results in diverting emissions from one medium to another (Hendrickson and McMichael, 1985). Therefore, a broad range of social costs should be considered when formulating regulatory policies in order to make the necessary trade-offs that maximise social welfare (Lave, 1984; Hendrickson and McMichael, 1985).

Baumol and Oates (1988) indicate that, if there are several different types of emissions that are harmful to the environment and control options for some of these emissions may cause an increase in others, maximising social welfare may actually require an increase in the emission of some pollutants that are themselves undesirable, but less damaging than others. As a result, comprehensive policy analysis will be complex. Selection of the optimal policy requires a balancing of the relative marginal valuation of each activity by consumers, the relative marginal damage resulting from emissions due to these activities, and the relative costs of the activities, abatement of their emissions and of substitute and complementary activities and emissions (Baumol and Oates, 1988, p. 106).

Hahn (1989) suggests the use of transferable property rights to achieve a cost-effective solution to problems characterised by multiple objectives. Permits for one objective can be converted to permits for another at a specified exchange rate, which is derived from the trade-off among the objectives decision makers are willing to make. Hahn (1989) indicates, however, that this approach may not result in an efficient solution if the trade-off among objectives is non-linear. Żylicz (1994) shows that in the

⁶ Żylicz (1994) refers to this as synergism, which 'occurs whenever the joint effect of two or more factors is different from the sum of outcomes that would have happened had each of these factors acted alone'. This is, for example, the case with tropospheric ozone, which is formed as a result of interaction between NO_x and VOC.

case of synergistic effects (i.e. if pollutants reinforce each other's effect), an efficient solution can be obtained by a tradable permits approach supplemented with an appropriate additional tax.

Degraeve and Koopman (1998) present an optimisation model used to select a least cost mix of transport policy measures to achieve air quality standards in the EU, considering interdependencies across policy instruments and environmental processes. They describe a methodology for selecting sets of control measures that would achieve the required reductions in emissions of several pollutants at least cost. In their approach, it is possible to take into account effects of sets of control measures on emissions of various pollutants.

Schmieman et al. (2002) present a dynamic analysis of optimal abatement levels for stock pollution (referring to acidification) and flow pollution (referring to tropospheric ozone) simultaneously. Different pollutants contribute to these problems (viz. SO₂, NO_x and VOC) and one of the pollutants contributes to both the stock and the flow pollution (viz. NO_x). They show analytically how in their model optimal abatement levels for SO₂, NO_x and VOC are interdependent because of the ambiguous role of NO_x.

Interrelations in the climate policies debate

Despite the literature on linkages between regional air pollution and climate change, up to now these interrelations have seldom been integrated into the development of policies for these problems (Davis et al., 2000; Pearce, 2000; Mayerhofer et al., 2001). Nevertheless, now that many industrialised countries have started to develop policies for greenhouse gas mitigation, interest in the side effects of greenhouse gas mitigation policies – and particularly in potential ancillary benefits – is growing. The importance of considering effects of greenhouse gas abatement other than those directly related to climate change was already recognised by the IPCC Working Group III in their contribution to the Second Assessment Report (Pearce et al., 1996). In March 2000, an international workshop was held, in Washington D.C. on the issue of ancillary benefits and costs of greenhouse gas mitigation. One of the aims of this workshop was to bring the ancillary benefits and costs of policies more clearly into the climate change debate (Davis et al., 2000). This workshop resulted in an overview of previous studies and ongoing work in this area, and provided information for the IPCC Third Assessment Report of Working Group III (IPCC, 2001b). The Third Assessment Report extensively discusses the issue of side effects of greenhouse gas mitigation and reviews studies on side effects related to human health and side effects in specific economic sectors (Barker et al., 2001; Hourcade et al., 2001; Markandya et al., 2001).

Different terms are used in the literature to refer to the side effects of climate change policies, including co-benefits, ancillary benefits, side benefits, secondary benefits, synergies, collateral benefits and associated benefits (Markandya et al., 2001). In the IPCC Third Assessment Report, a distinction is made between *co-benefits and costs* – that is, those non-climate effects that are intentionally incorporated into the initial creation of climate change policies – and *ancillary benefits or costs*, viz. those side effects that arise incidental to greenhouse gas mitigation (or other) policies (Markandya et al., 2001). In this thesis, we will use the term *ancillary benefits/costs* according to the definition by Markandya et al. (2001) as well as the more neutral term *side effects*.

Policy implications of considering ancillary impacts

In general, ignoring side effects (either positive or negative) in environmental policy-making can lead to important and costly errors concerning the level of abatement (including the balance between

domestic abatement and abatement abroad), policy instruments used and sectors involved (Davis et al., 2000). Reducing greenhouse gas emissions will delay and reduce damages caused by climate change and thereby generate benefits that occur at a global scale and in the long term. As a consequence, for most countries the effects of their national greenhouse gas mitigation policies on global concentrations of greenhouse gases and the impacts of climate change are imperceptible (OECD, 1999). Most ancillary impacts, such as health effects due to local air pollution, are, however, perceived not long after the introduction of policies. In addition, ancillary benefits usually occur relatively close to the sources of emissions (Hourcade et al., 2001). Therefore, ancillary benefits may support an acceleration of climate policies and will make climate change policies easier for decision-makers to enact, and for consumers to accept.

Whereas greenhouse gases affect the global climate regardless of the geographical location of their sources, most ancillary benefits are highly dependent on the geographic location of the emission changes (see e.g. Burtraw and Toman, 1997). For instance, benefits of reductions in local air pollution are likely to be the greatest in densely populated areas, and benefits of reductions in regional air pollution depend on the location of emission reductions, atmospheric transport and exposed population or ecosystems. Consequently, the geographical spread needs to be considered when developing policy responses, in order to maximise the full range of policy benefits (Pearce et al., 1996; OECD, 1999; Pearce, 2000).

Although the main focus in the literature is on ancillary benefits of greenhouse gas mitigation policies, in some cases ancillary costs may arise (Davis et al., 2000). Negative side effects may sometimes be unavoidable, but they should be closely examined for alternative policies that have no or less negative impacts on other policy areas (OECD, 1999).

The choice of policy instruments will be affected by the existence of side effects. Pearce (2000) argues that side effects can very well be incorporated in technology-based standards settings as well as in voluntary and negotiated agreements, whereas more difficulties arise with economic instruments such as taxes and tradable permits because some of the side effects are dependent on the geographic location. Finally, consideration of ancillary impacts in the development of greenhouse gas mitigation policies may also affect sectors the policies are aimed at, and the technical options that are preferred (OECD, 1999; Davis et al., 2000). In general, different policies that result in the same reduction in greenhouse gas emissions can have widely varying ancillary impacts. Considering these impacts makes policy design and selection more complex (Pearce, 2000).

1.2 Scope of the thesis

In addition to several studies mentioned before that deal with interrelations between climate change policies and air pollution associated with fossil fuel use, this thesis will present an economic analysis of interrelations between policies for air pollution and greenhouse gas emissions in the agricultural sector in Europe. Agriculture is 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. 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 CH_4 and about 50% as N_2O (derived from UNFCCC, 2000). The share of NH_3 emissions in total European emissions of acidifying compounds was about 20% during the 1990s, and more than 90% of total NH_3 emissions were related to the agricultural sector (derived from UNECE/EMEP, 2000).

The European agricultural sector will be subject to environmental policy-making in the coming decade, because in the 1999 Gothenburg Protocol (UNECE, 1999a), many European countries agreed on considerable reductions in NH₃ emissions in 2010. Moreover, several studies have indicated that a wide range of options is available in the agricultural sector to reduce greenhouse gas emissions in the near term at modest cost (e.g. De Jager et al., 1998; McCarl and Schneider, 2000; Schneider and McCarl, forthcoming).

This thesis focuses on interrelations of the categories (i), (ii) and (iii) described earlier. Emissions of NH₃, N₂O and CH₄ from agriculture are to a large extent produced by the same activities (viz. animal production and fertiliser use). Consequently, policies aimed at one of these pollutants may also have impacts on emissions of others. Most of the literature on ancillary benefits of climate policies focuses on category (ii) interrelations. As indicated before, CO₂ mitigation mainly depends on energy efficiency improvements and a shift to renewable sources of energy, resulting in a reduction in the amount of fossil fuels consumed. Obviously, this reduces emissions of all pollutants associated with fossil fuel combustion, such as NO_x and SO₂ (which are referred to as ancillary benefits of CO₂ mitigation). Emissions from agricultural sources can also be reduced by limiting agricultural production. In addition to this, emissions of NH₃, N₂O and CH₄ can also to a large extent be reduced by several technical measures. Measures for the reduction of emissions of one of these pollutants may have an effect on emissions of another. Consequently, interrelations of category (iii) may exist in emission reduction strategies for NH₃, N₂O and CH₄, which are specifically considered in this thesis.

Interrelations between policies for climate change and air pollution that have been reported in the literature (i.e. those associated with fossil fuel use) can be characterised mainly as ancillary or *co-benefits*. An interesting aspect of interrelations that may occur in the agricultural sector is that side effects are likely to include positive impacts (e.g. both NH₃ and N₂O emissions decrease with improving the efficiency of fertilisers) as well as negative impacts (e.g. manure application techniques and animal housing systems with low NH₃ emissions may result in an increase in N₂O emissions) (Kroeze, 1998). The analyses in this thesis explicitly include both beneficial and harmful side effects of control measures. Because the size and the direction of the side effects are typical of the various measures that are available for emission control, a bottom-up approach is required for an analysis of interrelations in the agricultural sector. Therefore, for our analyses we apply a bottom-up approach with estimated side effects for the specific measures included in our study.

Hourcade et al. (2001) distinguish three classes of literature regarding the impacts of climate change policies in other areas: (1) literature primarily dealing with climate change mitigation and recognising benefits in other areas; (2) literature primarily focusing on other areas, such as air pollution control, and recognising benefits in the area of climate mitigation; and (3) literature that looks at the combination of policy objectives (climate change and other areas) and looks at the costs and benefits from an integrated perspective. As follows from the foregoing discussion of literature on interrelations between policies for climate change and for regional air pollution problems, most studies can be attributed to class (1). Only a few studies can be attributed to classes (2) and (3). This thesis contributes to class (2) with an analysis of the effects of NH₃ abatement in Europe on emissions of N₂O and CH₄ from the agricultural sector, and to class (3) by presenting an integrated analysis of a simultaneous abatement of emissions of SO₂, NO_x, NH₃, N₂O and CH₄, considering interrelations in abatement efforts in the European agricultural sector.

Models used in the literature on ancillary impacts of greenhouse gas mitigation policies are mostly computable general equilibrium (CGE) models. These models are suitable for estimating CO₂

reductions and their cost, but usually lack the geographical and technical detail that is necessary for a proper estimate of the ancillary impacts (Davis et al., 2000). The model developed and applied in this thesis is a multi-regional optimisation model for the European agricultural sector to determine emission reduction strategies⁷ to achieve multiple geographically specific environmental targets at least cost, incorporating positive as well as negative side effects of specific control measures on emissions considered.

Closely related to this thesis – but focusing on emissions related to energy consumption – is a study by Proost and Van Regemorter (2001). They perform an integrated optimisation analysis for reducing energy-related emissions of air pollutants and greenhouse gases. They adapted the MARKAL model for Belgium to include atmospheric transport and location specific damages from pollution, including damage across the border. They consider monetary values of impacts of Belgian emissions on public health, terrestrial ecosystems and materials. Like most of the literature on ancillary benefits of CO₂ abatement, interactions between greenhouse gas reduction policies and air pollution occur because energy efficiency improvements reducing CO₂ emissions simultaneously reduce emissions of SO₂, NO_x, VOC and PM. In addition, they include specific abatement technologies for air pollutants. The effect of abatement technologies considered by Proost and Van Regemorter (2001) is, however, restricted to one pollutant, whereas an essential contribution of this thesis is that it considers effects of specific abatement measures on several pollutants.

Summarising, this thesis contributes to existing literature by (i) developing a model suitable for an integrated analysis of cost-effective reductions in emissions of NH₃, N₂O and CH₄ from agricultural activities simultaneously; (ii) investigating side effects of specific control measures for NH₃, N₂O and CH₄ emissions from agriculture; (iii) analysing how reductions in NH₃, N₂O and CH₄ emissions from European agriculture influence each other; and (iv) performing an empirical, integrated cost-effectiveness analysis in the context of atmospheric pollution in Europe, considering side effects of specific measures to reduce agricultural emissions, atmospheric transport and geographically specific environmental targets.

1.3 Objectives of the thesis

The aim of this thesis is to investigate how interrelations in abatement of NH₃, N₂O and CH₄ emissions related to agricultural activities in Europe affect cost-effective emission reduction strategies for emissions of both regional air pollutants and greenhouse gases. Particular attention will be given to the allocation of abatement over different sources and countries such that given targets for reductions in acidification and eutrophication in Europe and targets for greenhouse gas emission reductions are met at total minimum cost. To achieve this broad aim, I specified three specific objectives that will be dealt with in the subsequent chapters of this thesis.

The first objective is to identify possible sources of interrelations between policies to reduce NH₃, N₂O and CH₄ emissions from European agriculture. To this end, we develop a methodology to estimate emissions of NH₃, N₂O and CH₄ from European agriculture on the basis of consistent data. Moreover, we examine major options to control these emissions and investigate their effects on emissions of NH₃,

⁷ In this thesis, the term *abatement* or *emission reduction strategy* is used to refer to a set of measures that are applied to reduce emissions allocated over various sources.

N_2O and CH_4 , including possible unintended side effects. Because relevant information on these side effects is hardly available, we estimate these effects.

The second objective is to include these interrelations in an integrated cost-effectiveness analysis for simultaneous reductions in regional air pollution (in particular acidification) and greenhouse gas emissions. To this end, we develop a model that is used to determine what specific abatement measures can be applied in order to meet several environmental targets simultaneously at least cost, considering various side effects of these measures. The model allows for including geographically specific targets for environmental impacts.

The model developed is used to achieve the third objective, that is to analyse side effects of abatement strategies for NH_3 , N_2O and CH_4 in European agriculture and their impact on a cost-effective allocation of emission reductions over various sources in different countries, and on total abatement cost. To this end, we compare model results for various scenarios⁸ with different restrictions on emission or deposition levels.

1.4 Research approach

In this thesis, I gradually develop the model from a simple to more complex structure and present results of calculations with the model. Most of the material presented in this thesis has also been published in or submitted to scientific journals. The structure of the thesis reflects the development in this work. The thesis can be divided into three parts. Each part contains a description of the method used and an application of this method. Table 1.1 gives an overview of the structure of this thesis.

The first part concerns an analysis using an existing model, viz. the Regional Air Pollution Information and Simulation (RAINS) model, developed at the International Institute for Applied Systems Analysis (IIASA) in Austria (a description of this model is given in Alcamo et al. (1990) and Amann et al. (1998)). The part of the RAINS model that deals with NH_3 emissions and their abatement was used as a starting point for our analysis. This part of the thesis first describes a method to estimate emissions of N_2O and CH_4 from European agriculture on the basis of RAINS databases. Moreover, it presents estimated effects of NH_3 control options on N_2O and CH_4 emissions. This method is subsequently applied to analyse side effects of NH_3 abatement in European agriculture on N_2O and CH_4 emissions.

In the second part, the analysis is extended to analyse cost-effective strategies to simultaneously reduce emissions of air pollutants and greenhouse gases considering side effects of emission reduction measures. First, the methodology for an integrated analysis is described by presenting the model developed for integrated cost-effectiveness analysis of reducing emissions of various pollutants simultaneously, considering side effects of emission control options. Furthermore, the model is applied for the European agricultural sector to analyse interrelations in emission reduction strategies for NH_3 , N_2O and CH_4 . Results of the empirical application are presented and discussed.

⁸ A *scenario* refers to a consistent set of assumptions and results that reflect emissions and abatement costs in a future year. Assumptions concern economic activity levels, costs and effects of abatement options in the future, restrictions on emission or deposition levels, and the objective in the optimisation procedure. Scenarios considered in this thesis differ only in the restrictions on emissions or deposition levels or the optimisation objective (i.e. minimisation of the cost or maximisation of emission reduction). Please note that this differs from the usual meaning of scenarios in studies with the RAINS model, where the 'scenario analysis' mode refers to the analysis of regional costs and environmental benefits for alternative combination of economic activity levels and emission control strategies (Amann and Makowski, 2000).

Table 1.1

Overview of the structure of the thesis

| Chapter | Characteristic | Scope of the chapter |
|---------|-----------------|---|
| 2 | Method | Method to calculate N ₂ O and CH ₄ emissions from the agricultural sector in Europe using RAINS databases; estimates for impact of NH ₃ abatement options in RAINS on N ₂ O and CH ₄ |
| 3 | Application | Calculation of NH ₃ , N ₂ O and CH ₄ emissions from the agricultural sector in Europe; determine side effects of NH ₃ abatement on N ₂ O and CH ₄ emissions in Europe for various scenarios |
| 4 | Model | Model for integrated cost-effectiveness analysis of interrelated emission reductions of several pollutants; input data required for application of the model for the agricultural sector in Europe |
| 5 | Application | Integrated cost-effectiveness analysis of simultaneously reducing NH ₃ , N ₂ O and CH ₄ emissions from the agricultural sector in Europe for various scenarios considering interrelations |
| 6 | Model extension | Extension of the model in Chapter 4 to atmospheric transport of air pollutants and location specific deposition targets |
| | Application | Integrated cost-effectiveness analysis of simultaneously reducing emissions of N ₂ O and CH ₄ and deposition levels of SO ₂ , NO _x and NH ₃ considering location specific targets for acidifying and eutrophying deposition levels |

The last part describes an extension of the model to atmospheric transport of air pollutants, linking emission to deposition levels at different locations. Moreover, it presents the results of an application of the extended model for Europe. This analysis also includes non-agricultural emissions of acidifying compounds, viz. SO₂ and NO_x. The model is used to identify cost-effective strategies to reduce acidifying and eutrophying deposition together with N₂O and CH₄ emissions from agriculture.

The model presented in this thesis is a static optimisation model, formulated as a linear programming model. It can be used to identify cost-effective abatement strategies to achieve emission reductions for several pollutants, considering interrelations. The model cannot be used to determine how policies should be implemented. Moreover, it assumes full cooperation between countries to reach the environmental targets at least cost, whereas several environmental economic studies deal with optimal decisions for individual countries in a game theoretical framework (Mäler, 1989; Hoel and Schneider, 1997; Mäler and De Zeeuw, 1998). These aspects are, however, beyond the scope of this thesis. Nevertheless, the first-best solutions provided in this thesis may support decision-makers in developing policies for various interrelated environmental problems.

1.5 Outline of the thesis

To discuss the issue of how interrelations in emission reductions affect cost-effective abatement strategies, this thesis is structured in 7 chapters, starting with the introduction (Chapter 1). This section describes the main contents of the subsequent chapters in this thesis.

Chapter 2 describes a methodology to estimate emissions of NH₃, N₂O and CH₄ from European agriculture on the basis of consistent data. This is an important requirement for an integrated analysis of reducing emissions of these pollutants from European agriculture. On the basis of the IPCC method for estimating national greenhouse gas emissions, we develop a methodology to estimate agricultural emissions of N₂O and CH₄ in Europe using information on the European agricultural sector that is included in the RAINS model for estimating NH₃ emissions. Moreover, Chapter 2 describes estimated side effects of control options for NH₃ emissions included in the RAINS model on emissions of N₂O and CH₄. This chapter has been published in *Atmospheric Environment* (Brink et al., 2001a) and contains the complete text of this article.

Chapter 3 presents emissions of NH_3 , N_2O and CH_4 from agricultural activities in Europe for 1990 and various scenarios in 2010 that were calculated using the methodology and estimated side effects of NH_3 control options that are presented in Chapter 2. To evaluate the methodology, the N_2O and CH_4 emissions calculated for 1990 are compared with other emission inventories. Moreover, in this chapter we analyse ancillary impacts of NH_3 abatement on N_2O and CH_4 emissions by comparing various scenarios for 2010, representing different NH_3 abatement strategies in Europe. This chapter has been published in *Atmospheric Environment* (Brink et al., 2001b) and contains the complete text of this article.

Chapter 4 describes the model that has been developed for integrated cost-effectiveness analyses to achieve multiple environmental targets. The model will primarily be applied to agricultural activities in Europe, but is formulated such that it can possibly be extended to include other sectors as well. Chapter 4 also describes the input data that are used for application of the model to the European agricultural sector. This includes a detailed discussion of the abatement options for N_2O and CH_4 from agriculture considered, as well as their estimated side effects on each other and on NH_3 emissions.

Chapter 5 presents the results of calculations with the model as described in Chapter 4. To this end, the model is implemented in the programming language GAMS (Brooke et al., 1998). A full specification of the model in the GAMS language is provided in Appendix I of this thesis. Emissions of NH_3 , N_2O and CH_4 and abatement costs have been calculated for a number of different scenarios, in order to analyse the role of side effects in cost-effective abatement strategies for different reduction targets. The model identified abatement measures that have to be applied in order to achieve reduction targets at minimum cost. Moreover, we estimate potential cost savings that can be obtained if side effects are considered. To this end we compare cases that separately determine strategies to reduce emissions with strategies determined in an integrated analysis.

In Chapter 6, the model is extended by including atmospheric transport of emissions and by allowing for the specification of deposition targets and emission targets. In addition to NH_3 , emissions of other pollutants contributing to acidification and eutrophication (viz. SO_2 and NO_x), emitted by non-agricultural sources, are included. Abatement cost curves for these pollutants are adopted from the RAINS model. Moreover, the model is extended to include atmospheric transport of NH_3 , NO_x and SO_2 from location of emission to location of deposition (i.e. where the environmental effect occurs). Location specific targets for acidification and eutrophication are specified as maximum nitrogen and sulphur deposition levels, based on the damage to ecosystems they cause. Targets for N_2O and CH_4 are on the sum of total emissions of both greenhouse gases converted to their CO_2 equivalent values. The model is used to determine the cost-effective emission reduction strategies for SO_2 , NO_x , NH_3 , N_2O and CH_4 to achieve targets for nitrogen and sulphur deposition and for agricultural emissions of N_2O and CH_4 in Europe simultaneously. We analyse the impact of considering interrelations in agriculture on the optimal allocation in several scenarios. This chapter has been published in *TheScientificWorld* (Brink et al., 2001c) and contains the complete text of this article.

Finally, Chapter 7 summarises and discusses the main conclusions of the thesis.

2

Ammonia abatement and its impact on emissions of nitrous oxide and methane in Europe – method

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Abstract

Agriculture is an important source of NH₃, which contributes to acidification and eutrophication, as well as emissions of the greenhouse gases N₂O and CH₄. Because of their common sources, emission reduction measures for one of these gases may affect emissions of others. These interrelations are often ignored in policy-making. This study presents an analysis of the effects of measures to reduce NH₃ emissions on emissions of N₂O and CH₄ from agriculture in Europe. The analysis combines information from the NH₃ module of the RAINS model for Europe with the IPCC method for national greenhouse gas inventories. The IPCC method for estimating agricultural emissions of N₂O and CH₄ is adjusted in order to use it in combination with the RAINS database for the European agricultural sector. As an example, we applied the adjusted method to the agricultural sector in the Netherlands and found that application of several NH₃ abatement options may result in a substantial increase in N₂O emissions while the effect on CH₄ emissions is relatively small. In part 2 of this paper we focus on the resulting emissions for all European countries for 1990 and 2010.*

Keywords: Agricultural emissions; Acidification; Global warming; Emission inventory method; Side effects of emission control strategies

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* 'Part 2' refers to Chapter 3 of this thesis.

2.1 Introduction

Many European countries committed themselves to reduce emissions of greenhouse gases as well as other air pollutants. Agricultural activities are an important source of ammonia (NH_3), which contributes to the acidification and eutrophication of soils and waters (Klaassen, 1994; Sutton et al., 1998), and of greenhouse gases such as nitrous oxide (N_2O) (Mosier et al., 1998a) and methane (CH_4) (Safley et al., 1992). Therefore, the agricultural sector is likely to contribute to achieving these reduction.

Several studies have mentioned the existence of side effects of measures to reduce emissions in agriculture. McCarl and Schneider (2000), for instance, list a number of unintended beneficial effects of carbon sequestration, such as reduced soil erosion and improvements in water quality. They also identified detrimental effects, such as a decrease in food and fibre production, resulting in increased consumer prices for crops, meat and fibre. Janzen et al. (1999) judge the influence of various agricultural practices that reduce greenhouse gas emissions on other environmental issues. According to Kroeze (1994a; 1994b), several options for reducing NH_3 emissions may affect emissions of N_2O , either beneficially or adversely. Brink and Kroeze (2000) present preliminary results of a study on the effects of NH_3 abatement in Europe on N_2O and CH_4 emissions. The present paper presents an updated and more detailed description of the method used to determine the side effects of NH_3 abatement on emissions of N_2O and CH_4 in the European agricultural sector. First, it discusses the method and data used to estimate agricultural emissions of NH_3 , N_2O and CH_4 . Next, it describes the NH_3 control options and their estimated effect on N_2O and CH_4 . In part 2 of this paper we will quantify these side effects for European countries (Brink et al., 2001b).

2.2 Calculation of NH_3 , N_2O and CH_4 emissions

Agricultural emissions of NH_3 , CH_4 and N_2O have to a large extent common sources (viz. animal production and fertiliser use) and can largely be estimated on the basis of the same information. This study used information in the RAINS model¹ databases on numbers of animals in several livestock categories, synthetic fertiliser use², production processes in the inorganic chemical industry, waste treatment and disposal and other emissions from anthropogenic sources. The databases include data for 36 European countries for 1990, 1995 and projections up to 2010. This section describes the method and data applied for estimating the emissions.

2.2.1 Emissions of NH_3

Emissions of NH_3 were calculated in the NH_3 module of the RAINS model. For each source category, emissions were estimated using country-specific emission factors. For emissions from animals the

¹ The RAINS (Regional Air Pollution Information and Simulation) model is developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for the integrated assessment of alternative strategies to reduce air pollution in Europe (Alcamo et al., 1990; Amann et al., 1998; Tuinstra et al., 1999). This study uses the same version of the model that has been used in the preparation and analysis of scenarios for the EU acidification and ozone strategy (Amann et al., 1998) as well as for the discussion of reduction targets for the Gothenburg protocol (UNECE, 1999a).

² A distinction is made between urea and other nitrogen fertilisers.

model distinguishes four different stages during which NH₃ losses occur, viz. animal housing, outside storage of animal waste, application of manure and grazing (Klaassen, 1991a)³.

2.2.2 CH₄ emissions

Main agricultural sources of CH₄ include enteric fermentation, animal manure management and rice cultivation. Emissions from enteric fermentation and manure management were estimated following the ‘Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories’ (IPCC, 1997). The animal categories distinguished in the IPCC Guidelines for CH₄ emissions match closely the categories distinguished in the RAINS model (see Table 2.1). A minor difference is that the RAINS model includes sheep and goats in one category, while the IPCC Guidelines make a distinction between the two. Since in most European countries sheep have by far the greatest share in this category (FAO, 1999), the IPCC emission factors for sheep were used. Information on rice production in Europe is not included in the RAINS databases. Therefore, national estimates on CH₄ emissions from this activity were directly taken from the UNFCCC Greenhouse Gas Inventory Database (UNFCCC, 2000)⁴.

Enteric fermentation

CH₄ emission factors for enteric fermentation were directly taken from the IPCC Guidelines (IPCC, 1997). Emission factors for cattle differ between Eastern and Western European countries because of differences in animal management and feeding practices (Table 2.1).

Manure management

Emissions of CH₄ from manure management were estimated according to the IPCC Guidelines using default values for Western and Eastern Europe (IPCC, 1997). Emissions depend on climatic conditions. The IPCC Guidelines provide different emission factors for cool, temperate and warm areas, with annual average temperatures less than 15°C, between 15°C and 25°C, or greater than 25°C. In this study, Albania, Greece, Italy, Portugal and Spain were considered ‘temperate’ and the other European countries ‘cool’ areas.

Manure stored or treated as a liquid tends to produce more CH₄ than manure handled as a solid (IPCC, 1997). Therefore, different emissions factors were used for cattle and pigs kept in solid and liquid waste systems, which are distinguished as separate categories in the RAINS model (Table 2.2).

Table 2.1

CH₄ emission factors for enteric fermentation (kg CH₄ animal⁻¹ yr⁻¹)

| RAINS categories ^b | IPCC categories ^a | Western Europe ^a | Eastern Europe ^{a,c} |
|---|------------------------------|-----------------------------|-------------------------------|
| Dairy cattle (liquid and solid systems) | Dairy cattle | 100 | 81 |
| Other cattle (liquid and solid systems) | Non-dairy cattle | 48 | 56 |
| Pigs (liquid and solid systems) | Swine | 1.5 | 1.5 |
| Sheep and goats | Sheep | 8 | 8 |
| Horses | Horses | 18 | 18 |

^a From IPCC (1997).

^b The RAINS model also includes laying hens, other poultry and fur animals, but the IPCC Guidelines do not provide emission factors for enteric fermentation from these categories.

^c Eastern European emission factors were also used for Greece.

³ This distinction is important in determining the effect of control options on emissions, which is different for the various stages (see Section 2.3).

⁴ In Europe, the contribution of rice cultivation to total CH₄ emissions from agriculture is only about 1.5%. Rice cultivation mainly occurs in Italy, Portugal, and the former USSR (UNFCCC, 2000).

Table 2.2

CH₄ emission factors for manure management (kg CH₄ animal⁻¹ yr⁻¹)^a

| RAINS categories | Western Europe | | Eastern Europe | |
|------------------------------|----------------|-----------|----------------|-----------|
| | Cool | Temperate | Cool | Temperate |
| Dairy cattle (liquid system) | 29.9 | 104.8 | 24.1 | 84.2 |
| Dairy cattle (solid system) | 3.0 | 4.5 | 2.4 | 3.6 |
| Other cattle (liquid system) | 11.2 | 39.3 | 11.2 | 39.3 |
| Other cattle (solid system) | 1.1 | 1.7 | 1.1 | 1.7 |
| Pigs (liquid system) | 5.5 | 19.3 | 5.5 | 19.3 |
| Pigs (solid system) | 0.6 | 0.8 | 0.6 | 0.8 |
| Laying hens | 0.078 | 0.117 | 0.078 | 0.117 |
| Other poultry | 0.078 | 0.117 | 0.078 | 0.117 |
| Sheep and goats | 0.19 | 0.28 | 0.19 | 0.28 |
| Horses | 1.4 | 2.1 | 1.4 | 2.1 |
| Fur animals | Not estimated | | Not estimated | |

^a Derived from IPCC (1997); see Section 2.2.2 for more details.

Emission factors were derived from the IPCC Guidelines (IPCC, 1997), assuming that the solid and liquid systems for cattle and pigs in the RAINS model correspond with the ‘solid storage’ and ‘liquid/slurry’ manure management systems in the IPCC method respectively.

2.2.3 N₂O emissions

N₂O emissions from agriculture are associated with animal and crop production. This study estimated these emissions according to the method described in Mosier et al. (1998a), which is the basis for the 1996 IPCC Guidelines. This method distinguishes between (i) direct N₂O emissions from agricultural fields, (ii) direct emissions from animal production systems and (iii) indirect emissions, that occur when N is lost from agricultural fields and transported to remote sites, where it is subject to denitrification. In addition, this study estimated N₂O from industrial production of fertiliser, since this source is also related to activities in the agricultural sector.

The method in Mosier et al. (1998a) was adapted, where necessary, to enable the use of the information from the RAINS model as input. The notation used in the following description is, to the possible extent, consistent with the notation in IPCC (1997) and Mosier et al. (1998a), but where the data in RAINS diverge from the input data required for the IPCC method an alternative notation is introduced. In case the necessary input data was not available in RAINS, emission estimates were taken from existing national emission inventories directly. Appendix 2.A provides an overview of the equations used. Table 2.6 gives an explanation of the parameters and variables and indicates whether they are based on Mosier et al. (1998a) or on information included in the RAINS model.

Direct emissions from agricultural soils

Direct N₂O emissions from agricultural soils occur after application of organic and synthetic fertilisers and crop residues to agricultural fields and also as a result of biological N₂ fixation and cultivation of organic soils (histosols) (Mosier et al., 1998a). Eq. (A.1) in Appendix 2.A shows how direct N₂O emissions from agricultural soils were calculated for each country. The emission factor for direct soil emissions (EF1 = 0.0125 kg N₂O-N kg⁻¹ N input) was taken from Mosier et al. (1998a). Information on synthetic fertiliser use (NFERT_x), animal numbers (N_y), N excretion during housing (NEXS_y) and NH₃ volatilisation rates (FRACNH3) was taken from the RAINS model. The RAINS model includes no relevant information on crop production, emissions from crop residues and biological N₂ fixation.

Therefore, N₂O emissions from these sources (OTH) were calculated using FAO data on crop production (FAO, 1999). Mosier et al. (1998a) also provide emission factors for N₂O from cultivated histosols. However, this source was not included here because of insufficient input data.

Unlike Mosier et al. (1998a), this study did not use the IPCC default NH₃ and NO_x volatilisation rates for synthetic fertilisers (FRACGASF) and manure (FRACGASM). Instead, category- and country-specific NH₃ volatilisation rates (FRACNH3) from the RAINS model were used. For NO_x, a volatilisation rate (FRACNOX) of 0.3% of the N in synthetic fertiliser and manure was applied (Skiba et al., 1997). The latter may be a conservative estimate, which is, however, justified considering the large uncertainties in NO_x emissions from fertiliser use (Skiba et al., 1997). Since NH₃ volatilisation rates in RAINS are specific for each animal type and fertiliser type, the amount of N applied excluding NH₃ and NO_x volatilisation was determined for each animal category and fertiliser type separately. Total synthetic fertiliser N and total animal waste N that is not lost as NH₃ or NO_x after application (FSN and FAW) was calculated as the sum of the various fertiliser and animal types, respectively.

Mosier et al. (1998a) use default fractions of N excretion during grazing for Western and Eastern Europe to determine the amount of N excreted in the animal houses. Here we use country- and animal category specific estimates of N excretion during housing (NEXS_y) and grazing (NEXM_y) periods, derived from the RAINS model database. These N excretion estimates are known to change with N intake as well as N retention in milk and meat (e.g. Klaassen, 1991a; ECETOC, 1994; Petersen et al., 1998). The RAINS estimates aim at taking this into account, because there are significant differences in feeding strategies, production efficiency and agricultural practices (e.g. number of days animals graze) among the countries. The required information is, however, available only for few European countries (e.g. the Netherlands, Finland, United Kingdom and Denmark). The RAINS model uses data from those countries (Klaassen, 1991a), results of a questionnaire (sent by MAFF⁵ in 1997) and discussions with national experts carried out within the work under the UNECE LRTAP Convention towards preparation of the Gothenburg Protocol (UNECE, 1999a). This information forms the basis for country-specific total N excretion rates and the estimated grazing time for animals, which in turn allowed to estimate the proportion of N excreted during housing and grazing periods.

Direct emissions from animal production

Direct N₂O emissions from animal production stem from animal waste management systems and grazing animals. The IPCC emission factors (EF3) are different for different waste management systems. N₂O emissions from solid systems and grazing are 20 times higher than from liquid systems (Mosier et al., 1998a). Emissions were calculated applying Eq. (A.6) in Appendix 2.A.

Since RAINS distinguishes between N excretion during housing and grazing, the fractions of N excreted in the various waste management systems presented by Mosier et al. (1998a), which include grazing, were recalculated to represent the shares of the various housing types in the total amount of N excreted during housing only (AWMSS_{m,y}, Table 2.3). For cattle and pigs, RAINS includes information on the number of animals kept on liquid and solid waste systems. We assumed for animals in liquid systems AWMSS_{liquid systems,y} = 1 and for animals kept on solid systems AWMSS_{solid storage&drylot,y} = 1, with 'liquid systems' and 'solid storage&drylot' animal waste management systems as distinguished by Mosier et al. (1998a) (Table 2.3).

⁵ UK Ministry of Agriculture, Fisheries and Food.

Table 2.3

N₂O emission factors for animal waste management systems (EF3_m) and fractions of total N excretion in animal houses excreted in different waste management systems (AWMSS_m)

| Animal waste management systems (<i>m</i>) | EF3 _m ^a | AWMSS _m | | | | | | | |
|--|-------------------------------|------------------------------|-------|----------------------|--------|----------------------------|--------|----------------------------|--------|
| | | Cattle and pigs ^b | | Poultry ^c | | Sheep & goats ^c | | Other animals ^c | |
| | | Liquid | Solid | W-Eur. | E-Eur. | W-Eur. | E-Eur. | W-Eur. | E-Eur. |
| Anaerobic lagoons | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Liquid systems | 1 | 1 | 0 | 0.13 | 0.28 | 0 | 0 | 0 | 0 |
| Daily spread | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dolid storage and drylot | 20 | 0 | 1 | 0.01 | 0 | 0.15 | 0 | 0 | 0 |
| Other systems | 5 | 0 | 0 | 0.86 | 0.72 | 0.85 | 1 | 1 | 1 |

^a Taken from Mosier et al. (1998a), g N₂O-N kg⁻¹ N excreted.

^b Based on subdivision in the RAINS model (see Section 2.2.3).

^c Recalculated from values presented by Mosier et al. (1998a).

Indirect emissions from nitrogen used in agriculture

Nitrogen used in agriculture may also indirectly cause emissions of N₂O. Mosier et al. (1998a) include three types of indirect N₂O emissions: (i) N₂O formation in soils and aquatic systems induced by N deposition, (ii) N₂O formation in aquatic systems induced by N leaching and runoff and (iii) N₂O formation from human consumption followed by municipal sewage treatment. Total indirect emissions are the sum of these (Appendix 2.A, Eq. (A.7)).

Following Mosier et al. (1998a), N₂O emissions after deposition of NH₃ and NO_x were accredited to the country where the NH₃ and NO_x emissions occur (although the actual N₂O formation takes place at the location of the deposition, which is not necessarily in the same country) and calculated by Eq. (A.8) in Appendix 2.A.

Mosier et al. (1998a) assume that 1% of the atmospheric N deposited is converted into N₂O (EF4). In order to assess the N deposition that is the result from agricultural activities, emissions of NH₃ and NO_x from agriculture need to be estimated. The volatilisation rate of NO_x from fertiliser application was taken from Skiba et al. (1997) (see Section 2.2.3) and emissions of NH₃ from livestock and other sources were estimated by the RAINS model.

A part of the N applied to agricultural soils as fertiliser is lost through leaching and runoff, which results in N₂O emissions (Appendix 2.A, Eq. (A.9)). Following Mosier et al. (1998a), 30% of the N applied to agricultural fields is lost through leaching and runoff (FRACLEACH), of which 2.5% (EF5) is converted to N₂O in aquatic systems. Estimates of N excretion and synthetic fertiliser use were taken from the RAINS model.

RAINS does not include information needed to calculate emissions from municipal sewage treatment (N2O(S)). These inputs include data on per capita protein consumption and human population, which were obtained from FAO (1999).

N₂O emissions from production of synthetic fertilisers

Another source of N₂O emissions related to agricultural activities is the industrial production of nitric acid (HNO₃), which is mainly produced as an intermediate in the production of nitrate fertilisers (Oonk and Kroeze, 1998). These emissions are not considered agricultural in the IPCC Guidelines, but industrial. We estimated these missions using information from the RAINS model on total production of N fertilisers in each country (Appendix 2.A, Eq. (A.10)). For each country we estimated the fraction of nitrate fertilisers (mainly ammonium nitrate) in total nitrogen fertiliser production (FRACNITR) on

the basis of FAO data for 1990 (FAO, 1999) (e.g. for the Netherlands this value is 0.3). The total amount of nitrate used in the production of N fertilisers is calculated by multiplying the total N fertiliser production (FERTP) by the fraction of nitrate fertilisers in total nitrogen fertilisers produced (FRACNITR) and by the fraction of nitrate in total N of nitrate fertiliser (50% for ammonium nitrate). The resulting amount of nitrate is multiplied by the emission factor for N₂O emissions from nitric acid production (EF7) to estimate the associated N₂O emissions.

N₂O emission rates from nitric acid production depend upon technology and operating conditions (IPCC, 1997). No information on these conditions is available for each country in Europe. Therefore, a uniform N₂O emission factor of 0.027 kg N₂O-N kg⁻¹ HNO₃-N produced was used. This is the value found by Reimer et al. (1992) for a plant not equipped with non-selective catalytic reduction technology (which is representative for plants in Europe) and presented in the IPCC Guidelines for industrial emissions (IPCC, 1997).

2.3 Impact of NH₃ abatement on the emissions of N₂O and CH₄

The RAINS model includes seven categories of options for reducing NH₃ emissions, viz. (i) low nitrogen feed, (ii) air purification in animal houses, (iii) adaptation of animal housing systems, (iv) covered storage of manure, (v) low NH₃ application of manure, (vi) urea substitution and (vii) stripping and absorption techniques in fertiliser production processes. The following subsections successively give a short description of these control options and their effect on NH₃, based on Klaassen (1991b) and Klimont (2002). Furthermore, the potential effect of applying these control options on emissions of CH₄ and N₂O is discussed.

The impact of control options on emissions is presented as a relative change in uncontrolled emissions. Uncontrolled emissions of NH₃ were estimated using the RAINS model. For CH₄ and N₂O, uncontrolled emissions were estimated using the method described in the previous section. As an example, the uncontrolled emissions for the agricultural sector in the Netherlands are presented in Table 2.4. A more extensive analysis of estimated emissions in all European countries is given in Brink et al. (2001b).

As an example, Table 2.5 presents relative changes in uncontrolled emissions of NH₃, CH₄ and N₂O from the various sources in the Dutch agricultural sector as a result of the application of NH₃ control options. Since the emission factors and the reduction efficiencies of the control options may vary between the countries, the effects on CH₄ and N₂O emissions may also be different for the various countries (Brink et al., 2001b).

According to Eq. (A.8) in Appendix 2.A, lower NH₃ emissions will result in less indirect N₂O formation induced by atmospheric deposition of NH₃. The relative reduction in these N₂O emissions is equal to the reduction of NH₃-N relative to the sum of the (uncontrolled) emissions of NH₃-N and NO_x-N from agriculture. This applies to all control options that reduce NH₃ emissions and is therefore not mentioned in the description of the other control options below.

2.3.1 Low nitrogen feed

A lower N content of fodder will reduce N excretion by animals and consequently NH₃ emissions. This can be achieved by (i) reductions in the level of N applied to grassland or substitution of grass by silage (dairy cows), (ii) a better tuning of compound feed to the nutrient needs of the animals (pigs and poultry), (iii) changes in the composition of the raw materials (pigs and poultry), (iv) supplementing

Table 2.4
 NH₃, CH₄ and N₂O emissions from the Dutch agricultural sector in 2010 (1000 ton yr⁻¹)^{a,b}

| | Sources of NH ₃ | | | | Emissions of CH ₄ | | | Emissions of N ₂ O | | | | | |
|---|----------------------------|----------------|--------------------|------------------|------------------------------|----------------------|-------------------|-------------------------------|-----------------------|-------------------|--------------------|------------|-------------|
| | Animal housing | Manure storage | Manure application | Meadow (grazing) | Total | Enteric fermentation | Manure management | Total | Direct soil emissions | Animal production | Indirect emissions | Other | Total |
| | | | | | | | | | | | N deposition | N leaching | |
| Dairy cattle (liquid) | 16.0 | 1.0 | 27.9 | 7.6 | 52.5 | 132.3 | 39.6 | 171.9 | 1.1 | 3.0 | 0.7 | 2.2 | 6.9 |
| Dairy cattle (solid) | 0.8 | 0.1 | 1.5 | 0.4 | 2.8 | 7.0 | 0.2 | 7.2 | 0.1 | 0.3 | 0.0 | 0.1 | 0.5 |
| Other cattle (liquid) | 9.6 | 0.6 | 17.3 | 5.0 | 32.5 | 131.1 | 30.6 | 161.7 | 1.2 | 1.8 | 0.4 | 1.6 | 5.0 |
| Other cattle (solid) | 2.4 | 0.2 | 4.3 | 1.3 | 8.1 | 32.8 | 0.8 | 33.5 | 0.3 | 1.1 | 0.1 | 0.4 | 1.9 |
| Pigs (liquid) | 22.5 | 2.2 | 27.8 | 0.0 | 52.4 | 14.7 | 53.8 | 68.5 | 1.2 | 0.2 | 0.7 | 1.2 | 3.3 |
| Pigs (solid) | 1.2 | 0.1 | 1.5 | 0.0 | 2.8 | 0.8 | 0.3 | 1.1 | 0.1 | 0.2 | 0.0 | 0.1 | 0.3 |
| Laying hens | 1.7 | 0.5 | 4.7 | 0.0 | 7.0 | 0.0 | 2.0 | 2.0 | 0.2 | 0.1 | 0.1 | 0.2 | 0.6 |
| Other poultry | 4.2 | 1.2 | 6.7 | 0.0 | 12.2 | 0.0 | 4.2 | 4.2 | 0.4 | 0.3 | 0.2 | 0.4 | 1.2 |
| Sheep and goats | 0.5 | 0.0 | 0.9 | 1.1 | 2.5 | 10.7 | 0.3 | 11.0 | 0.0 | 0.8 | 0.0 | 0.3 | 1.2 |
| Horses | 0.4 | 0.0 | 0.4 | 0.5 | 1.2 | 1.8 | 0.1 | 1.9 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 |
| Fertiliser use | | | | | 8.4 | | | | 5.5 | 0.0 | 0.1 | 3.4 | 9.1 |
| Fertiliser production | | | | | 5.7 | | | | | 0.0 | 0.1 | | 12.8 |
| Other sources of NH ₃ ^c | | | | | 3.2 | | | | | | | | 12.9 |
| Rice cultivation | | | | | | | | 0 | | | | | |
| Biological N ₂ fixation | | | | | | | | | 0.1 | | | | 0.1 |
| Crop residue | | | | | | | | | 0.9 | | | | 0.9 |
| Human sewage | | | | | | | | | | | | | 1.0 |
| Total | 59.4 | 5.8 | 92.9 | 15.8 | 191.2 | 331.2 | 131.8 | 463.0 | 11.1 | 7.7 | 2.5 | 9.9 | 13.8 |

^a Emissions are taken from the RAINS model (NH₃) or calculated according to the method described in Section 2.2 (N₂O and CH₄), assuming no emission control; information on agricultural activities is taken from the RAINS databases; projections for agricultural activity levels in 2010 as described in Antmann et al. (1998). Estimates for other European countries and a discussion of the results are given in Brink et al. (2001b).

^b Blank cells indicate that the categories are not a source of the associated emissions.

^c These include NH₃ emissions from chemical industry (other than fertiliser production processes) and waste treatment and disposal.

Table 2.5
Effect of NH₃ abatement on NH₃, CH₄ and N₂O emissions in Dutch agriculture (% change in uncontrolled emissions)^{a,b}
 NH₃ control options

| | Sources of NH ₃ ^c | | | | | Sources of CH ₄ ^{c,d} | | | | | Sources of N ₂ O ^c | | |
|---|---|----------------|--------------------|------------------|-----------------------|---|-----------------------|-------------------|--------------------|--------------|--|-----|-----|
| | Animal housing | Manure storage | Manure application | Meadow (grazing) | Synthetic fertilisers | Manure management | Direct soil emissions | Animal production | Indirect emissions | N deposition | N leaching | | |
| | | | | | | | | | | | | | |
| Low nitrogen feed | Dairy cattle | -15 | -15 | -15 | -15 | 0 | -15 | -15 | -15 | -15 | -15 | -15 | -15 |
| | Pigs and laying hens | -20 | -20 | -20 | 0 | 0 | -20 | -20 | -20 | -20 | -20 | -20 | -20 |
| | Other poultry | -10 | -10 | -10 | 0 | 0 | -10 | -10 | -10 | -10 | -10 | -10 | -10 |
| Air purification | Pigs (liquid) | -80 | 0 | 0 | 0 | 0 | 0 | 143 | -34 | -34 | 0 | 0 | 0 |
| | Pigs (solid) | -80 | 0 | 0 | 0 | 0 | 0 | 7 | -34 | -34 | 0 | 0 | 0 |
| | Laying hens | -80 | 0 | 0 | 0 | 0 | 0 | 15 | -20 | -20 | 0 | 0 | 0 |
| | Other poultry | -80 | 0 | 0 | 0 | 0 | 0 | 18 | -28 | -28 | 0 | 0 | 0 |
| Housing adaptation | Dairy cattle (liquid) | -50 | -50 | 0 | 0 | 0 | 12 | 0 | -16 | -16 | 4 | 4 | 4 |
| | Other cattle (liquid) | -40 | -40 | 0 | 0 | 0 | 6 | 0 | -13 | -13 | 2 | 2 | 2 |
| | Pigs (liquid) | -35 | -70 | 0 | 0 | -10* | 13 | 900* | -18 | -18 | 7 | 7 | 7 |
| | Laying hens | -70 | -70 | 0 | 0 | -90* | 14 | 900* | -23 | -23 | 8 | 8 | 8 |
| | Other poultry | -60 | -80 | 0 | 0 | -90* | 13 | 900* | -29 | -29 | 9 | 9 | 9 |
| Covered storage of manure | Cattle (liquid) | 0 | -70 | 0 | 0 | 10* | 1 | -10* | -1 | -1 | 0 | 0 | 0 |
| high efficiency | Pigs (liquid) | 0 | -70 | 0 | 0 | 10* | 2 | -10* | -3 | -3 | 1 | 1 | 1 |
| | Poultry | 0 | -70 | 0 | 0 | 10* | 3 | -10* | -5 | -5 | 2 | 2 | 2 |
| low efficiency | Cattle (liquid) | 0 | -40 | 0 | 0 | 10* | 1 | -10* | -1 | -1 | 0 | 0 | 0 |
| Low NH ₃ application of manure – | Cattle, pigs (liquid) | 0 | 0 | -60 | 0 | 0 | 100* | 0 | -32 | -32 | 7 | 7 | 7 |
| high efficiency | Cattle, pigs (solid) | 0 | 0 | -40 | 0 | 0 | 100* | 0 | -21 | -21 | 5 | 5 | 5 |
| | Laying hens | 0 | 0 | -40 | 0 | 0 | 100* | 0 | -27 | -27 | 10 | 10 | 10 |
| | Poultry | 0 | 0 | -40 | 0 | 0 | 100* | 0 | -22 | -22 | 7 | 7 | 7 |
| | Sheep and goats | 0 | 0 | -40 | 0 | 0 | 100* | 0 | -15 | -15 | 1 | 1 | 1 |
| low efficiency | Cattle, pigs (liquid) | 0 | 0 | -25 | 0 | 0 | 60* | 0 | -13 | -13 | 3 | 3 | 3 |
| | Cattle, pigs (solid) | 0 | 0 | -20 | 0 | 0 | 60* | 0 | -11 | -11 | 2 | 2 | 2 |
| | Poultry | 0 | 0 | -20 | 0 | 0 | 60* | 0 | -11 | -11 | 3 | 3 | 3 |
| | Sheep and goats | 0 | 0 | -20 | 0 | 0 | 60* | 0 | -7 | -7 | 1 | 1 | 1 |
| Urea substitution | Fertiliser use (urea) | | | | | | -87 | 0 | 0 | 0 | -85 | 0 | 0 |
| Options in fertiliser plants | Fertiliser production | | | | | | -50 | 0 | 0 | 0 | -50 | 0 | 0 |

^a The effects of NH₃ abatement techniques on CH₄ and N₂O emissions may vary between countries. Values indicated with a * are the same for all European countries.
^b For an analysis of the effect in different European countries, see Brink et al. (2001b).
^c For example, a value of -15% for NH₃ from dairy cattle during animal housing for low N feed indicates a decrease in unabated NH₃ emissions from this source during housing by 15% due to application of this control option. Some techniques can be applied in combination, with the total effect a multiplication of the fraction of emissions remaining after application of the individual techniques.
^d Effects on NH₃ emissions are taken from RAINS, effects on agricultural emissions of N₂O and CH₄ are estimated in conformity with the description in Section 2.3. There is no assumed effect of NH₃ abatement techniques on CH₄ emissions from enteric fermentation.

diets with synthetic amino acids (pigs and poultry) and (v) replacement of grass and grass silage by maize (dairy cows) (Klaassen, 1991b; Wijnands and Amadei, 1991). Changes in the diet are restricted, since the productivity of the animals should not decrease. RAINS assumes that this control option may reduce NH_3 emissions by 10-20%.

Emissions of CH_4 do not directly depend on the N content of the feed, but on several factors concerning the animal feed (notably daily feed intake and digestibility rate, (IPCC, 1997)). These factors may be affected by changes in the N content of the feed, which, in turn, may result in different levels of CH_4 emissions from enteric fermentation and from manure management. Since it is not clear to what extent and in what direction reductions in N content of the fodder will affect CH_4 emissions, we tentatively assumed no effect on CH_4 .

As described in Section 2.2.3, N_2O emissions are largely dependent on the amount of N excreted by animals. A lower N content of the fodder reduces the N excretion per animal and, as a consequence, N_2O emissions from livestock (assuming a constant livestock population). While emissions of NH_3 only depend on the mineral N in the manure, N_2O emissions also depend on the organic N in the manure. Low N feed will reduce mainly mineral N while organic N in the manure is less affected. Therefore, the reduction rate for N_2O emissions may differ from the rate for NH_3 . The qualitative effect on N_2O , however, is not well known for the animal types included in our analysis. We therefore simply assume that low N feed has the same potential effect on N_2O as on NH_3 , reducing emissions by 10-20% depending on animal type. We realise that this may potentially overestimate the reduction in N_2O emissions.

2.3.2 Cleaning the air from animal houses (air purification)

Another measure to reduce NH_3 emissions from livestock housing is treatment of the ventilated air by applying various techniques such as bio-filtration, bio-scrubbing and chemical scrubbers (Klaassen, 1991b). These techniques can only be applied in animal houses equipped with mechanical ventilation, which is often the case for poultry and pigs. In bio-filters and air scrubbers, NH_3 in the air is absorbed in the process water, converted into nitrite and then into nitrate (Scholtens and Demmers, 1991). Applying these measures can reduce NH_3 emissions from housing by 80-90% (Klaassen, 1991b).

The ventilated air from animal houses is cleaned using nitrifying bacteria to oxidise ammonium to nitrate. This nitrification process may lead to N_2O emissions, either directly or through consecutive denitrification. No information is available on the amount of N_2O produced during the purification of the ventilated air. Nevertheless, it is likely that N_2O formation here is similar to that resulting from nitrification and denitrification in soils. We therefore tentatively assumed that 1% of the total amount of $\text{NH}_3\text{-N}$ removed in this process will be converted to N_2O (which may be a conservative estimate). It is not clear what is the fate of the nitrate formed during the cleaning of the air from animal houses. Although this is also a potential source of N_2O emissions, it was not taken into account in this study.

We assumed no effect of these control techniques on bacterial processes underlying the production and consumption of CH_4 in animal production.

2.3.3 Livestock housing adaptations

For several animal categories design modifications of animal houses are possible to prevent or reduce the emissions of NH_3 (Klaassen, 1991b; Monteny and Erisman, 1998; UNECE, 1999b; Klimont, 2002). This is achieved if either the surface area of the slurry or manure exposed to the air is reduced or the waste is frequently removed (e.g. flushed with water or diluted formaldehyde) and placed in

covered storage. The RAINS model includes different control options for the various animal categories. NH₃ emissions from cattle housing can be reduced through regular washing or scraping the floor, frequent removal of the manure to a closed storage system and modification of floor design. This may reduce NH₃ emissions from animal housing typically by 35-50%. Monteny and Erisman (1998) give an extensive review of options for dairy cattle buildings and conclude that, in the Netherlands, an NH₃ emission reduction of 50% seems technically feasible applying available techniques, although there are control options that potentially can reduce emissions from housing by up to 80%. For pig housing a 30-40% reduction of NH₃ emissions can be obtained by combining good floor design (partly slatted floor, metal or plastic coated slats, inclined or convex solid part of the floor) with flushing systems. Even higher reduction efficiencies can be achieved when flushing systems with clarified aerated slurry or manure cooling systems are used (UNECE, 1999b). NH₃ emissions from housing systems for laying hens can be reduced by drying of manure, either through the application of a manure belt with forced drying or by drying the manure in a tunnel. For other poultry, NH₃ emissions from housing systems can be reduced by regularly removing the manure using a scraper or continuously blowing heated air under a floating slatted and littered floor to dry the litter. For both categories, NH₃ emissions from housing systems can be reduced by 60-80% (Klaassen, 1991b).

It is important to note that for all measures listed above it is assumed that the manure will be moved to a closed storage that is constructed along with the modifications or construction of new animal houses. This, in effect, will bring reductions of NH₃ emissions during storage. Also, preventing loss of ammonia from housing and storage will result in a higher N concentration in the remaining manure than without these measures applied. Hence the emissions of NH₃ during application of manure will increase if no preventive measures are taken (Klaassen, 1994; Monteny and Erisman, 1998).

The effect of housing measures on CH₄ from manure management differs per animal category. For dairy cows, washing the floors with water will not affect CH₄ emissions. However, if acid is used, emissions will decrease because of a change in pH. Considering the risks involved with the use of acid, it is more likely that water will be used. For pigs the effect on CH₄ from manure management depends on the efficiency of separating the manure into a liquid and a solid fraction. If this separation process is carried efficiently, there will be no change in the emissions of CH₄ since all manure will be in the solid fraction, which remains under anaerobic conditions. However, if the separation is not carried efficiently, a part of the manure will be in the liquid part that will be aerated. In this case CH₄ emissions will decrease. No information is available on the quality of the separation process. However, since urine, faeces and flushing liquid are mixed before being separated into a liquid and a solid fraction, it will be very difficult to achieve a perfect separation. Therefore, CH₄ emissions from manure management were roughly estimated to decrease by 10% (Table 2.5).

Housing adaptations for poultry mainly implies drying of manure. During drying, the manure tends to decompose aerobically and little or no CH₄ is produced (IPCC, 1997). Therefore, emissions of CH₄ were assumed to decrease by 90% (Table 2.5).

Similarly to CH₄, the effect of housing adaptations on N₂O emissions from animal waste management systems is also different for the various animal types. For dairy cows, there is no change in N₂O emissions since the system remains anaerobic. The effect on N₂O emissions from pig housing depends on the efficiency of the separation of manure into a liquid and a solid fraction. N₂O emissions from manure in aerobic systems appear to be 20 times higher than from anaerobic systems (Mosier et al., 1998a). Therefore, emissions from the manure that remains in the liquid fraction and will be aerated may be up to 20 times higher than without the aeration process. If the solid fraction is stored, it may

start to compost. This may also produce more N_2O than if the slurry is not separated. The adaptations to the poultry housing may also largely affect the N_2O emissions, since they imply aeration and heating of the manure. For both pigs and poultry, we assumed that the modifications of housing systems will cause N_2O emissions from waste management systems to increase by a factor of 10 (Table 2.5). This value is deduced from the IPCC emission factors (Mosier et al., 1998a).

The total amount of N applied to soils will increase if NH_3 emissions from housing are reduced since the amount of N contained in the manure that is applied to soils will increase. Hence, direct N_2O emissions from agricultural soils and indirect N_2O emissions induced by N leaching and runoff will increase. Estimated increases in N_2O emissions are respectively 1.25% (i.e. EF1 in Eq. (A.1) in Appendix 2.A) and 0.75% (i.e. $FRACLEACH \cdot EF5$ in Eq. (A.9) in Appendix 2.A) of the total amount of NH_3 -N emissions from housing avoided.

2.3.4 Covered outdoor storage of manure

Covering storage of manure reduces NH_3 losses from storage. The RAINS model distinguishes between covers with a high NH_3 removal efficiency, including tension caps, concrete, corrugated iron and polyester, and covers with a low efficiency, including floating foils and polystyrene (Klimont, 2002). NH_3 emissions from storage are reduced accordingly by 70% or 40%. It is important to note that this option is applicable to liquid manure (slurry) storage only.

CH_4 emissions from manure storage depend on manure type and conditions in the storage. If introducing a cover on the manure storage results in a change in conditions from aerobic to anaerobic, CH_4 emissions may increase (IPCC, 1997). The practice of storing manure varies across Europe, in particular between Western and Eastern European countries (Safley et al., 1992). However, sufficiently detailed information on the country-specific conditions was not found. This study assumed an increase of 10% in CH_4 emissions from manure management after introducing covers on manure storage (Table 2.5).

As for CH_4 , the effect on N_2O emissions also depends on manure storage conditions. Contrary to CH_4 , though, the possibly change in conditions in storage from aerobic to anaerobic will lead to a decrease of N_2O emissions. Consequently, we tentatively assumed a decrease of 10% in N_2O emissions from animal waste management systems in each country (Table 2.5).

As discussed earlier (Section 2.3.3), the reduction of NH_3 emissions at one stage results in increase of N contained in manure that is later applied to soils and hence an increase in N_2O emissions after application.

2.3.5 Low NH_3 application of manure

Several techniques are available that reduce the amount of NH_3 emissions during and after application of manure to arable land or grassland. The RAINS model distinguishes between techniques with a high NH_3 removal efficiency, including immediate incorporation and deep and shallow injection of the manure, and techniques with a low efficiency, including slit injection, trailing shoe, slurry dilution, band spreading and sprinkling (Klimont, 2002). All techniques involve placement of manure in the soils as opposed to spreading it over the surface. The NH_3 reduction efficiency is different for solid and liquid manure, i.e. 20 and 25 percent for low efficiency techniques and 40 and 60 percent for high efficiency techniques, respectively.

Changes in the way the manure is applied to agricultural soils are not likely to affect emissions of CH_4 .

The effect of low NH₃ manure application on N₂O emissions is unclear. Without doubt, these techniques increase the availability of N in agricultural soils, which in turn may affect N₂O production. In a way, low NH₃ application of manure resembles urine patches, which are known to have high N₂O emission rates per kg of N added (De Klein, 1994). Although the overall effect on N₂O formation is not well understood, Kroeze (1994b) assumed for the Netherlands that after surface application of manure 0.2-1.25% of manure-N is lost as N₂O, while manure injection may result in losses of 1.25-2.5%. Velthof and Oenema (1997) used an emission factor for N₂O that is 67% higher for slurry applied with a technique that minimises NH₃ emissions than the emission factor for surface applied slurry. The present study assumed that 1.25% of the N applied to soils by surface application is lost as N₂O (Section 2.2.3). Recognising that manure injection may resemble the impact of manure produced by grazing animals, for which Mosier et al. (1998a) use an emission factor of 2%, we tentatively assumed that low efficiency manure injection techniques may increase N₂O emissions from agricultural soils by 60% and high efficiency techniques by 100% (Table 2.5). We realise that these effects are uncertain and subject to scientific debate.

When NH₃ emissions during application of manure are reduced, more N will be subject to leaching and the related N₂O emissions will increase (Section 2.3.3).

2.3.6 Urea substitution

The proportion of N lost as NH₃ is higher for urea than for other N fertilisers (ECETOC, 1994). Substituting urea with, for example, ammonium nitrate would result in reduction of NH₃ emissions by about 80 to 90 percent, depending inter alia on climate and soil characteristics.

There are indications that N₂O emissions are relatively high for fertilisers based on organic N or anhydrous NH₃, and relatively low for fertilisers based on urea, ammonium or nitrate (of which urea seems to give rise to the lowest N₂O emissions). However, Bouwman (1996) argued that statistical analysis of the experimental data available does not allow for deriving fertiliser type specific emission factors for N₂O that are world-wide applicable. This was the major reason why in the IPCC methodology emissions are calculated as 1.25% of the N input to soils, regardless the type of fertiliser used. Therefore, this study also assumed no effect of urea substitution on N₂O emissions from agricultural soils.

Substituting urea with ammonium nitrate does not affect emissions of CH₄, because synthetic fertiliser use is not a source of CH₄.

2.3.7 End-of-pipe options in fertiliser plants

Ammonia emissions from fertiliser plants depend on the type of fertiliser produced with majority originating from mixed fertiliser plants and nitrogenous fertiliser plants, inter alia, manufacturing NH₃ and urea (UNECE, 1999b). NH₃ from industrial sources is emitted to the atmosphere either as straight NH₃ gas or as dust or particles containing NH₄⁺ or urea originating from various stages of fertiliser manufacturing process (ECETOC, 1994). These emissions can be reduced by about 95% through introduction of such techniques as stripping, absorption, cyclones and fabric filters⁶ (UNECE, 1999b). Since the applicability of these techniques is limited, an overall reduction of 50% in NH₃ emissions from fertiliser industry was assumed for this control option (Tangena, 1985).

⁶ Scrubbers, cyclones and baghouses are often an integral part of the modern mixed fertiliser plants.

There is no effect of stripping and absorption techniques on CH₄ emissions. Although it is likely that this option will affect emissions of N₂O, it is not clear to what extent. Therefore no effect was taken into account.

2.4 Conclusions

In Europe, agriculture is an important source of NH₃, CH₄ and N₂O. This paper describes a method to quantify the impact of NH₃ abatement on emissions of CH₄ and N₂O. The NH₃ module in the RAINS model was used to estimate NH₃ emissions in Europe. Agricultural emissions of N₂O and CH₄ were estimated using information on the European agricultural sector from this model as a basis. To this end, the IPCC Guidelines for estimating N₂O and CH₄ emissions from agricultural activities were adjusted.

Several of the NH₃ abatement options included in the RAINS model are likely to have an impact on emissions of N₂O and CH₄. We found that each of the NH₃ control techniques has an effect on emissions of N₂O (Table 2.5). Reducing NH₃ emissions will decrease indirect N₂O emissions induced by deposition of NH₃. Since a lower nitrogen content of the fodder will reduce the nitrogen excretion per animal, this option will reduce both NH₃ and N₂O emissions. Covered storage of manure also reduces both NH₃ and N₂O losses. On the other hand, housing adaptations and manure injection measures may cause a considerable increase in N₂O emissions. The effect of NH₃ abatement on CH₄ is moderate. Housing adaptations may cause a reduction in CH₄ emissions from manure management, whereas in some countries covering manure storage may result in higher CH₄ emissions.

The method for estimating emissions of CH₄ and N₂O from agricultural sources, using RAINS databases, can be applied to estimate total agricultural emissions in all European countries. As an illustration, this paper presents estimated emissions (Table 2.4) and estimated effects of NH₃ abatement techniques on CH₄ and N₂O (Table 2.5) for the Netherlands. Results for all European countries are presented and discussed in part 2 of the paper (Brink et al., 2001b).

Acknowledgements

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Appendix 2.A

Equations for determining emissions of N₂O, based on Mosier et al. (1998a) (see Table 2.6 for an explanation of the symbols; more details are given in Section 2.2.3).

Direct soil emissions

$$N2ODIRECT = (FSN + FAW) EF1 + OTH \quad (A.1)$$

$$FSN = \sum_x (NFERT_x (1 - FRACGASF_x)) \quad (A.2)$$

$$FAW = \sum_y (N_y NEXS_y (1 - FRACGASM_y)) \quad (A.3)$$

$$FRACGASF_x = FRACNH3_x + FRACNOX \quad (A.4)$$

$$FRACGASM_y = FRACNH3_y + FRACNOX \quad (A.5)$$

Emissions from animal waste management systems

$$N2OANIMALS = \sum_y \left(N_y \left(NEXS_y \sum_m (AWMSS_{m,y} EF3_m) + (NEXM_y EF3_{grazing}) \right) \right) \quad (A.6)$$

Indirect emissions

$$N2OINDIRECT = N2O(G) + N2O(L) + N2O(S) \quad (A.7)$$

$$N2O(G) = \left(\sum_y NH3_y + \sum_x NH3_x + NH3_{other} + FRACNOX \left(\sum_y N_y (NEXS_y + NEXM_y) + \sum_x NFERT_x \right) \right) EF4 \quad (A.8)$$

$$N2O(L) = \left(\sum_y N_y (NEXS_y + NEXM_y) + \sum_x NFERT_x \right) FRACLEACH EF5 \quad (A.9)$$

Industrial emissions

$$N2OINDUSTRY = 0.5 EF7 FRACNITR FERTP \quad (A.10)$$

Total emissions

$$N2O = N2ODIRECT + N2OANIMALS + N2OINDIRECT + N2OINDUSTRY \quad (A.11)$$

Table 2.6

Explanation of parameters used in calculating emissions of N₂O as described in Section 2.2.3

| Parameters | Description | Reference |
|---|---|--|
| AWMSS _{m_y} | Fraction of N excreted during animal housing by animal type <i>y</i> (NEXS _{<i>y</i>}) that is excreted in animal waste management system <i>m</i> (anaerobic lagoons, liquid systems, daily spread, solid storage and drylot, other systems) | Calculated on the basis of Mosier et al. (1998a) |
| EF1 | Emission factor for direct soil emissions (kg N ₂ O-N kg ⁻¹ N input) | Mosier et al. (1998a) |
| EF3 _m | N ₂ O emission factor for animal waste management system <i>m</i> (kg N ₂ O-N kg ⁻¹ N excreted, Table 2.3) | Mosier et al. (1998a) |
| EF4 | Emission factor for atmospheric deposition (kg N ₂ O-N kg ⁻¹ NH ₃ -N and NO _x -N emitted) | Mosier et al. (1998a) |
| EF5 | N ₂ O emission factor for leaching and runoff (kg N ₂ O-N kg ⁻¹ N leaching/runoff) | Mosier et al. (1998a) |
| EF7 | Emission factor for N ₂ O emissions from production of nitric acid (kg N ₂ O-N kg ⁻¹ HNO ₃ -N) | IPCC Guidelines (IPCC, 1997) |
| FAW ^a | Total N remaining in soils after application of animal waste (kg N yr ⁻¹) | Calculated (Eq. (A.3)) |
| FERTP ^a | Total fertiliser production (kg N yr ⁻¹) | RAINS |
| FRACGASF _x ^a | Fraction of NFERT _x volatilised as NH ₃ and NO _x (kg NH ₃ -N and NO _x -N kg ⁻¹ N applied) | Calculated (Eq. (A.4)) |
| FRACGASM _y ^a | Fraction of NEXS _{<i>y</i>} that volatilises as NH ₃ and NO _x (kg NH ₃ -N and NO _x -N kg ⁻¹ N excreted) | Calculated (Eq. (A.5)) |
| FRACLEACH | Fraction of N input to soils that is lost through leaching and runoff (kg N kg ⁻¹ N applied) | Mosier et al. (1998a) |
| FRACNH _{3y} ^a | Fraction of NEXS _{<i>y</i>} that volatilises as NH ₃ (kg NH ₃ -N kg ⁻¹ N excreted) | RAINS |
| FRACNH _{3x} ^a | NH ₃ volatilisation rate for NFERT _x (kg NH ₃ -N kg ⁻¹ N) | RAINS |
| FRACNITR ^a | Fraction of nitrate fertiliser production in total fertiliser production (kg N kg ⁻¹ N) | FAO (1999) |
| FRACNOX ^a | NO _x volatilisation rate for N applied to soils (kg NO _x -N kg ⁻¹ N excreted) | Skiba et al. (1997) |
| FSN ^a | Total N remaining in the soil after synthetic fertiliser application (kg N yr ⁻¹) | Calculated (Eq. (A.2)) |
| N _y ^a | Number of animals of type <i>y</i> | RAINS |
| N ₂ O(G) ^a | N ₂ O produced after atmospheric deposition of NO _x and NH ₃ emitted (kg N ₂ O-N yr ⁻¹) | Calculated (Eq. (A.8)) |
| N ₂ OINDUSTRY ^a | N ₂ O emissions from fertiliser production (kg N ₂ O-N kg ⁻¹ fertiliser N produced) | Calculated (Eq. (A.10)) |
| N ₂ O(L) ^a | N ₂ O produced from N leaching and runoff (kg N ₂ O-N yr ⁻¹) | Calculated (Eq. (A.9)) |
| N ₂ O(S) ^a | N ₂ O produced from human sewage (kg N ₂ O-N yr ⁻¹) | Estimated using data from FAO (1999) |
| N ₂ OANIMALS ^a | N ₂ O emissions from animal production and pastures (kg N ₂ O-N yr ⁻¹) | Calculated (Eq. (A.6)) |
| N ₂ ODIRECT ^a | Direct N ₂ O emissions from agricultural soils (kg N ₂ O-N yr ⁻¹) | Calculated (Eq. (A.1)) |
| NEXM _y ^a | N excretion per animal of type <i>y</i> in the meadow (kg N head ⁻¹ yr ⁻¹) | RAINS |
| NEXS _y ^a | N excretion per animal of type <i>y</i> during housing (kg N head ⁻¹ yr ⁻¹) | RAINS |
| NFERT _x ^a | Synthetic fertiliser use of type <i>x</i> (kg N yr ⁻¹ ; <i>x</i> = urea, other N fertilisers) | RAINS |
| NH _{3y} , NH _{3x} , NH _{3other} ^a | Emissions of NH ₃ -N (kg NH ₃ -N yr ⁻¹) from animal category <i>y</i> , fertiliser type <i>x</i> and other sources respectively | RAINS |
| OTH ^a | Direct N ₂ O emissions from soils due to biological N fixation, crop residues and cultivated histosols (kg N ₂ O-N yr ⁻¹) | Estimated using data from FAO (1999) |

^a These parameters have country-specific values

3

Ammonia abatement and its impact on emissions of nitrous oxide and methane - application for Europe

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Abstract

Agricultural emissions of NH₃, N₂O and CH₄ come, to a large extent, from common sources. It has been demonstrated that controlling NH₃ emissions through application of technical measures might have an impact on emissions of N₂O and CH₄. This paper presents estimates of NH₃, N₂O and CH₄ emissions from European agriculture for 1990 and four scenarios for the year 2010. The first scenario assumes no specific NH₃ abatement, but emissions of all three gases decline between 1990 and 2010 as a result of projected reductions in animal numbers and fertiliser consumption in Europe. The other three scenarios assume different levels of NH₃ abatement in Europe, including the maximum feasible reduction case. They are compared with respect to their effect on emissions of N₂O and CH₄. The results indicate that in Europe, abating agricultural emissions of NH₃ may cause releases of N₂O from this sector up to 15% higher than in the case of no NH₃ control. There may be substantial differences in the observed effects between various countries depending on the degree and type of NH₃ control options applied. The effect of NH₃ abatement on CH₄ emissions was found to be negligible.

Keywords: Emission inventory; Agriculture; Acidification; Global warming; Environmental policy interrelations

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3.1 Introduction

The agricultural sector is an important source of emissions of ammonia (NH_3), which contribute to the acidification and eutrophication of soils and waters. In Europe in 1990, about 80% of total NH_3 emissions came from livestock farming, about 16% from the use and about 2% from the production of synthetic nitrogen fertilisers (Klaassen, 1994). Moreover, agricultural activities also significantly contribute to emissions of the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). In 1990, agriculture was responsible for about 7% of total greenhouse gas emissions in Europe, of which about 75% was emitted as CH_4 and about 25% as N_2O (Olivier et al., 1996).

According to the Kyoto Protocol, many European countries are committed to reduce emissions of greenhouse gases (UNFCCC, 1997). Several studies indicate that considerable greenhouse gas emission reductions can be obtained in the agricultural sector in the near-term at limited costs (Blok and De Jager, 1994; Hendriks et al., 1998; McCarl and Schneider, 2000). Moreover, many European countries agreed to reduce emissions of pollutants that contribute to acidification, eutrophication and are precursors of tropospheric ozone, including NH_3 (UNECE, 1999a).

Environmental policies are usually designed to solve one particular environmental problem, often not taking into account possible side effects. These side effects, however, may considerably affect the cost-effectiveness of environmental policy measures (see e.g. Martin, 1989; Grennfelt et al., 1994; Amann et al., 1998). In Europe, as a first step toward an integrated approach to solve environmental issues, the Gothenburg protocol was signed in 1999, under the Convention on the Long-range Transboundary Air Pollution (UNECE, 1999a). This protocol aims at a simultaneous abatement of acidification, eutrophication and tropospheric ozone. However, up to now interrelations between acidification and global warming policies have not been taken into account to a large extent in policy-making and science.

This paper presents an analysis of potential impacts of NH_3 abatement strategies on emissions of N_2O and CH_4 from agriculture in European countries. NH_3 emissions and control strategies were determined using the RAINS model¹. Agricultural N_2O and CH_4 emissions were estimated by applying a method described in detail in part 1* of this paper (Brink et al., 2001a) and using information from the NH_3 -RAINS module as input. Estimated emissions of NH_3 , N_2O and CH_4 for 1990 were compared to existing inventories. Furthermore, several NH_3 abatement scenarios for 2010 were analysed with respect to their impact on emissions of considered greenhouse gases.

3.2 Method for estimating emissions

In this study, NH_3 emissions in Europe were estimated using the NH_3 module in the RAINS model², which includes NH_3 emissions from livestock, nitrogen fertiliser use, chemical industry, waste

* 'Part 1' refers to Chapter 2 of this thesis.

¹ Regional Air Pollution Information and Simulation model, developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for integrated assessment of alternative strategies to reduce air pollution in Europe (Alcamo et al., 1990; Amann et al., 1998).

² This study uses the same version of the model that has been used in the preparation and analysis of scenarios for the EU acidification and ozone strategy (Amann et al., 1998) as well as for the discussion of reduction targets for the Gothenburg protocol (UNECE, 1999a).

Table 3.1

Direction of effects of NH₃ control options on emissions of NH₃, CH₄ and N₂O^{a,b}

| NH ₃ control options ^d | Sources of NH ₃ | | | Sources of CH ₄ ^c | | Sources of N ₂ O | | |
|--|----------------------------|----------------|--------------------|---|-------------------|-----------------------------|-------------------|--|
| | Animal housing | Manure storage | Manure application | Meadow (grazing) | Manure management | Direct soil emissions | Animal production | Indirect emissions N deposition N leaching |
| Low nitrogen feed | – | – | – | – | 0 | – | – | – |
| Air purification | – | 0 | 0 | 0 | 0 | 0 | + | – |
| Animal housing adaptations | – | – | 0 | 0 | – | + | + | – |
| Covered storage of manure | 0 | – | 0 | 0 | + | + | – | – |
| Injection of manure | 0 | 0 | – | 0 | 0 | + | 0 | – |
| Urea substitution | – ^e | | | | 0 | 0 | 0 | – |
| Stripping/absorption | – ^f | | | | 0 | 0 | 0 | – |

^a Effects on NH₃ taken from RAINS; effects on N₂O and CH₄ according to estimates by Brink et al. (2001a).^b '+', '–' and '0' indicate an increase, decrease and no change in emissions after application of control option.^c There are no effects of NH₃ abatement on CH₄ emissions from enteric fermentation and rice cultivation.^d Control options are described in Klaassen (1994), see also Brink et al. (2001a).^e Effect on NH₃ emissions from urea fertiliser use.^f Effect on NH₃ emissions from fertiliser plants.

treatment and disposal and other anthropogenic sources. For livestock categories, the model distinguishes emissions during animal housing, manure storage, manure application and grazing (Klimont, 2002).

The information on the European agricultural sector included in the RAINS model databases was used to estimate emissions of N₂O and CH₄ from agricultural activities in Europe. The method is based on the 'Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories' (IPCC, 1997) for CH₄ and for N₂O on the method described by Mosier et al. (1998a). These methods were adapted, where necessary, in such a way that they can be applied to the information on agricultural activities in the RAINS model (Brink et al., 2001a). Sources of CH₄ emissions included are enteric fermentation, manure management and rice cultivation. N₂O emissions included are (i) direct emissions from agricultural soils, (ii) direct emissions in animal production, (iii) indirect emissions from nitrogen used in agriculture and (iv) N₂O emissions from synthetic nitrogen fertiliser production.

RAINS includes several techniques for reducing NH₃ emissions, viz. dietary changes (low nitrogen feed), air purification, animal housing adaptations, covering outside storage of manure, injection of manure during application, substitution of urea with ammonium nitrate and stripping and absorption techniques in fertiliser industry (Klimont, 2002). Besides a reduction in NH₃ emissions, these techniques may result in a change in emissions of N₂O and CH₄. This change may be either an increase or a decrease in emissions. For each of these techniques, we estimated the effect on emissions of N₂O and CH₄ (Table 3.1; details are given in Section 3 of the first part of this paper* (Brink et al., 2001a)).

3.3 Projections for 2010 and abatement strategies

The development of the animal stock and the consumption of nitrogen fertilisers are important determinants of future NH₃, N₂O and CH₄ emissions from agriculture. The RAINS model includes a set of forecasts of European agricultural activities up to 2010. In this paper, emissions in 2010 were estimated using the 'baseline' projection described in Amann et al. (1998). For this projection, livestock

* This refers to Section 2.3 in this thesis.

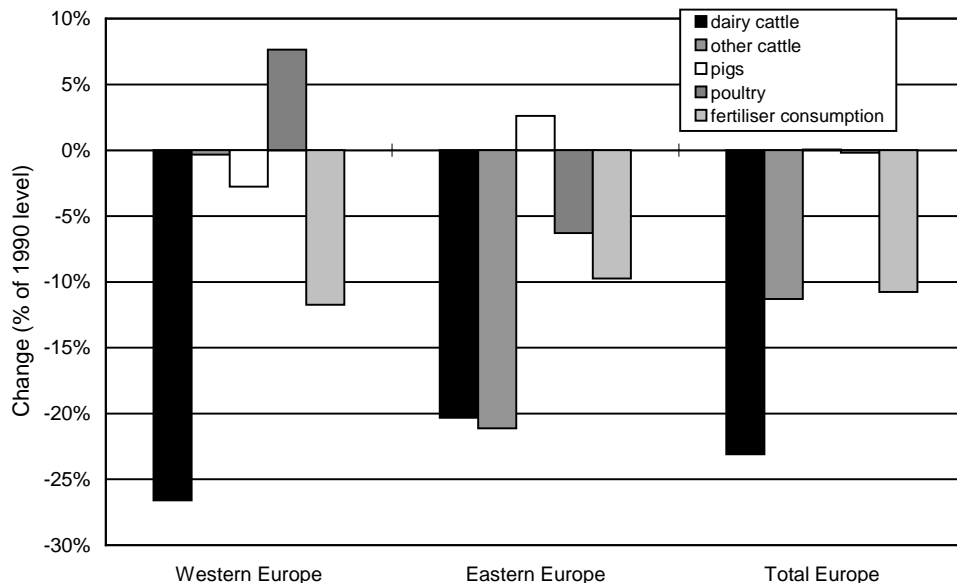


Fig. 3.1 Projected changes in animal numbers for main livestock categories and fertiliser consumption in Europe between 1990 and 2010

Table 3.2

Projections of livestock and nitrogen fertiliser use in Europe^a

| | Western Europe | | Eastern Europe | | Total Europe | |
|------------------------|----------------|--------|----------------|--------|--------------|--------|
| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
| Dairy cattle | 31.6 | 23.2 | 40.5 | 32.3 | 72.2 | 55.5 |
| Other cattle | 62.4 | 62.2 | 69.6 | 54.9 | 132.0 | 117.1 |
| Pigs | 111.3 | 108.2 | 122.9 | 126.1 | 234.2 | 234.3 |
| Poultry | 989.8 | 1065.5 | 1266.7 | 1187.0 | 2256.5 | 2252.5 |
| Fertiliser consumption | 10.9 | 9.6 | 10.0 | 9.0 | 20.9 | 18.7 |

^a According to the RAINS 'baseline projection', Amann et al. (1998) (10^6 animals and 10^6 tons N year⁻¹)

forecasts for the EU countries were based on the studies with the European Community Agricultural Model (ECAM) (Folmer et al., 1995). For other countries, studies performed for the Commission of the European Communities (DG-VI) and national information were used. Forecasts for fertiliser use were based on studies by the European Fertilizer Manufacturers Association (EFMA, 1996a, b). The forecasts were reviewed by national experts during the work on the preparation of the Gothenburg protocol³. Projected changes in agricultural activities from 1990 to 2010 are different between Western and Eastern Europe (Fig. 3.1, Table 3.2). Whereas dairy cattle and fertiliser use is assumed to decrease considerably in both Western and Eastern Europe, the population of pigs and poultry either increases or decreases, depending on the region. A large decrease in the population of non-dairy ('other') cattle is expected for Eastern Europe.

Emissions in 2010 were estimated for four scenarios, viz. no control (NOC), Gothenburg Protocol commitments (GOT), intermediate environmental impact targets (ENV) and maximum feasible

³ For a more detailed description of the forecasts and relevant references, see Amann et al. (1998 p. 60-61) and data presented on the web: <http://www.iiasa.ac.at/rains/databases.html>.

reduction (MFR). These scenarios are based on the same projection for agricultural activities, but have different underlying assumptions about the NH₃ abatement strategies (i.e. the set of NH₃ abatement options that are applied) in each country. Consequently, differences between scenario results were only caused by different assumptions about NH₃ control options implemented in 2010.

The hypothetical NOC scenario assumes no NH₃ abatement techniques implemented in any European country in 2010. Changes in emissions of NH₃ as well as of CH₄ and N₂O in 2010 with respect to 1990 that were observed are only the result of the projected changes in animal numbers and fertiliser consumption (Table 3.2).

The other three scenarios assume reductions in NH₃ emissions by the implementation of various abatement techniques, which may also have an impact on emissions of N₂O and CH₄. The GOT scenario is the result of recent negotiations and reflects commitments for NH₃ emission control in the year 2010 that are contained in the Protocol to Abate Acidification, Eutrophication and Ground-level ozone (UNECE, 1999a). Since most countries only have an emission ceiling for NH₃ and no specific legislation targeting this pollutant, we assumed that the reductions in each country are achieved in a cost-effective way (i.e. by applying those control options that yield the required emission reduction at least cost according to the RAINS model).

The ENV is an optimised scenario resulting in a cost-effective allocation of reductions in emissions of SO₂, NO_x, VOC and NH₃ in order to meet intermediate targets for reducing simultaneously acidification, eutrophication and exposure to ground-level ozone in Europe. It takes into account the different cost of controlling air pollution in European countries, differences in sensitivity of ecosystems and atmospheric transport of air pollutants. It is based on the 'medium ambition level' (J1) scenario presented in Amann et al. (1999b). In comparison with the GOT scenario, achieving the environmental targets specified in J1 requires further reductions in emissions and consequently more stringent controls of NH₃ losses from agriculture (see Amann et al., 1999b).

The MFR scenario reflects the full application of the most efficient abatement options included in the RAINS model to all sources of NH₃ emissions. This scenario illustrates the maximum reduction in NH₃ emissions, irrespective of the costs but considering the applicability⁴ of the control options in each country.

3.4 Emissions of NH₃, N₂O and CH₄ from agriculture in Europe

Emissions of NH₃, N₂O and CH₄ were estimated for the four scenarios described above using the method presented in Brink et al. (2001a) and briefly summarised in Section 3.2 of this paper. Fig. 3.2 presents total estimated emissions of NH₃, N₂O, and CH₄ from agriculture in Europe for 1990 and 2010. It is assumed that there is no NH₃ abatement in 1990. Emission estimates for 2010 are given for the NOC, GOT, ENV and MFR scenarios.

A substantial reduction in total emissions from European agriculture was estimated between 1990 and 2010 without NH₃ abatement (NOC). NH₃, N₂O and CH₄ emissions decrease by 11%, 12% and 15% respectively. This is the result of projected decreases in animal numbers and synthetic fertiliser use. Considerable differences were observed between countries as a result of differences between developments in agricultural activities (Table 3.3)

⁴ The potential for application of certain control options may be limited by, e.g., type of soil or typical housing.

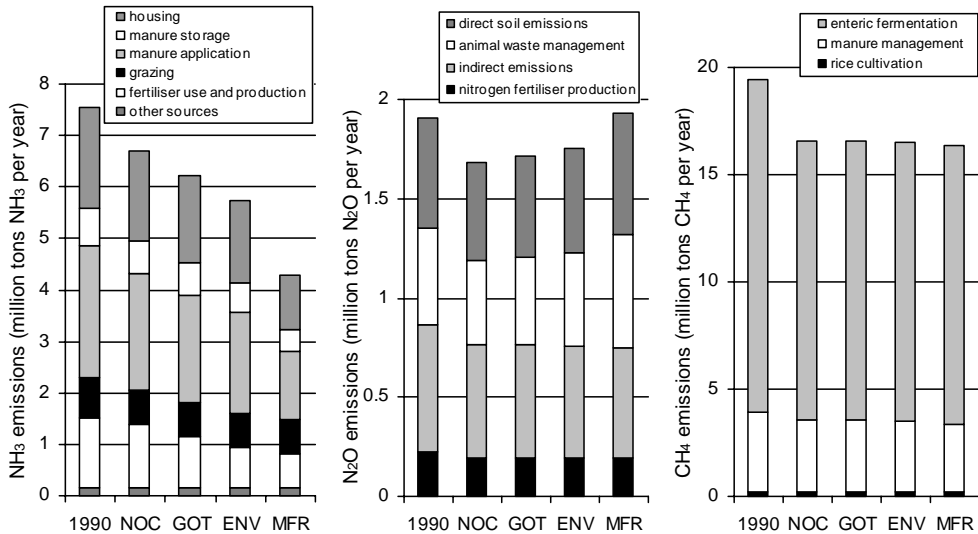


Fig. 3.2 Emissions of NH₃, N₂O and CH₄ from European agriculture in 1990 and 2010 for a scenario without emission control (NOC) and three scenarios assuming NH₃ abatement (GOT, ENV and MFR).

The three scenarios assuming NH₃ abatement (GOT, ENV and MFR) show a further decrease in NH₃ emissions. However, the results indicate that, for Europe as a whole, NH₃ control may not bring simultaneous reductions in agricultural emissions of CH₄ and N₂O. In fact, N₂O emissions are higher in the scenarios with NH₃ abatement than in the scenario without NH₃ abatement. CH₄ emissions, on the other hand, are hardly affected by NH₃ control. The largest effects were observed in the MFR scenario, where agricultural N₂O and CH₄ emissions are respectively 15% higher and 1.5% lower than in the NOC scenario (Table 3.3).

There are large uncertainties in estimating emissions from agriculture (see e.g. Van Aardenne et al. (2000) for an analysis of uncertainties in estimating N₂O emissions from agriculture). Moreover, there are uncertainties in estimating the impact of NH₃ control options on CH₄ and N₂O. Estimates presented here are considered the best, given the current state of scientific knowledge.

3.5 Discussion

3.5.1 Comparison with other inventories

The estimates of CH₄ and N₂O emissions from agricultural activities for the year 1990 were compared to some other inventories, including the Emission Database for Global Atmospheric Research (EDGAR 2.0) and second National Communications (NC2) (Fig. 3.3). The EDGAR 2.0 database is a global database including emission inventories for many compounds on a national and grid (1° longitude × 1° latitude) basis (Olivier et al., 1996). The National Communications (NCs) are reports that countries that are party to the UN Framework Convention on Climate Change have submitted to the secretariat of the climate convention (UNFCCC, 1998; Van Amstel et al., 1999). Countries can use the IPCC Guidelines for estimating their NC emissions, but can also include country-specific estimates.

Table 3.3

Country-specific emissions of NH₃, N₂O and CH₄ from European agriculture in no control scenario (NOC) (1000 tons yr⁻¹)

| | NH ₃ | | | N ₂ O | | | CH ₄ | | |
|-----------------------|-----------------|--------|-------------------------|------------------|--------|-------------------------|-----------------|---------|-------------------------|
| | 1990 | 2010 | Change (%) ^a | 1990 | 2010 | Change (%) ^a | 1990 | 2010 | Change (%) ^a |
| Albania | 32.0 | 34.9 | 9 | 8.7 | 8.8 | 1 | 91.5 | 107.7 | 18 |
| Austria | 77.3 | 66.9 | -13 | 18.9 | 15.8 | -16 | 225.7 | 188.0 | -17 |
| Belarus | 218.9 | 163.0 | -26 | 52.7 | 41.9 | -20 | 561.7 | 365.2 | -35 |
| Belgium | 97.2 | 95.8 | -1 | 25.3 | 22.9 | -9 | 276.0 | 243.0 | -12 |
| Bosnia Herzegovina | 30.8 | 23.0 | -25 | 6.3 | 4.7 | -25 | 88.3 | 67.4 | -24 |
| Bulgaria | 140.6 | 125.6 | -11 | 39.4 | 37.9 | -4 | 218.5 | 138.8 | -36 |
| Croatia | 39.9 | 37.1 | -7 | 11.6 | 13.3 | 15 | 82.8 | 61.3 | -26 |
| Czech Republic | 106.6 | 108.0 | 1 | 28.1 | 27.6 | -2 | 280.3 | 270.6 | -3 |
| Denmark | 76.9 | 71.7 | -7 | 29.8 | 24.5 | -18 | 226.5 | 198.7 | -12 |
| Estonia | 28.9 | 28.7 | -1 | 6.6 | 7.3 | 11 | 67.5 | 51.7 | -23 |
| Finland | 40.3 | 31.1 | -23 | 17.3 | 14.7 | -15 | 109.6 | 77.3 | -29 |
| France | 807.1 | 777.4 | -4 | 197.9 | 179.9 | -9 | 1850.7 | 1614.0 | -13 |
| Germany | 756.8 | 571.5 | -24 | 166.5 | 129.8 | -22 | 1744.2 | 1327.4 | -24 |
| Greece | 79.7 | 74.0 | -7 | 33.1 | 27.0 | -19 | 212.5 | 210.0 | -1 |
| Hungary | 119.9 | 136.8 | 14 | 30.5 | 42.8 | 40 | 179.8 | 183.6 | 2 |
| Ireland | 127.2 | 130.0 | 2 | 40.0 | 39.0 | -2 | 558.1 | 555.5 | 0 |
| Italy | 462.4 | 431.8 | -7 | 84.7 | 81.3 | -4 | 1025.5 | 913.2 | -11 |
| Latvia | 43.0 | 34.9 | -19 | 9.9 | 10.3 | 5 | 120.8 | 67.0 | -45 |
| Lithuania | 80.0 | 81.3 | 2 | 19.7 | 20.9 | 6 | 197.0 | 184.3 | -6 |
| Luxembourg | 7.0 | 8.5 | 21 | 1.3 | 1.4 | 8 | 16.3 | 24.4 | 49 |
| Netherlands | 232.7 | 191.2 | -18 | 61.7 | 52.6 | -15 | 531.1 | 463.0 | -13 |
| Norway | 23.1 | 21.4 | -8 | 13.6 | 12.4 | -9 | 104.6 | 94.3 | -10 |
| Poland | 504.8 | 541.2 | 7 | 88.8 | 96.0 | 8 | 808.4 | 969.5 | 20 |
| Portugal | 71.0 | 61.9 | -13 | 17.3 | 16.6 | -4 | 231.9 | 221.5 | -4 |
| Republic of Macedonia | 16.9 | 15.7 | -7 | 3.7 | 3.4 | -8 | 44.8 | 42.3 | -6 |
| Republic of Moldova | 46.7 | 47.7 | 2 | 10.3 | 12.9 | 25 | 107.4 | 94.7 | -12 |
| Romania | 291.8 | 303.5 | 4 | 75.7 | 81.0 | 7 | 672.6 | 726.0 | 8 |
| Russia | 1282.1 | 893.9 | -30 | 334.9 | 227.7 | -32 | 3776.1 | 2577.4 | -32 |
| Slovak Republic | 59.8 | 46.9 | -22 | 15.3 | 12.6 | -18 | 132.7 | 82.7 | -38 |
| Slovenia | 23.0 | 20.5 | -11 | 5.5 | 5.3 | -4 | 45.9 | 34.4 | -25 |
| Spain | 352.4 | 382.7 | 9 | 95.6 | 93.6 | -2 | 1045.3 | 1126.4 | 8 |
| Sweden | 61.1 | 61.1 | 0 | 16.6 | 16.6 | 0 | 149.7 | 150.4 | 0 |
| Switzerland | 72.2 | 66.1 | -9 | 9.3 | 7.5 | -19 | 171.8 | 156.7 | -9 |
| Ukraine | 729.3 | 649.0 | -11 | 182.8 | 159.8 | -13 | 2065.3 | 1734.4 | -16 |
| United Kingdom | 329.0 | 297.5 | -10 | 130.2 | 114.1 | -12 | 1209.5 | 1062.0 | -12 |
| Yugoslavia | 89.5 | 82.4 | -8 | 20.3 | 19.1 | -6 | 216.9 | 199.1 | -8 |
| Total | 7553.3 | 6714.6 | -11 | 1909.7 | 1683.1 | -12 | 19447.3 | 16584.0 | -15 |

^a The percentage change indicates the change in emissions with respect to 1990 emission levels.

For N₂O the estimates were also compared to those by Kroeze and Mosier (2000), who applied the IPCC method as described by Mosier et al. (1998a) using FAO data (FAO, 1999) as input but excluding emissions from cultivated histosols. Fig. 3.3 shows that the estimates in the present study are in general agreement with Kroeze and Mosier (2000). The differences between the two data sets are for most countries <15%, and caused by differences in input data mainly. The EDGAR 2.0 and NC2 estimates are in most cases considerably lower than our estimates. This is caused most probably by missing sources in EDGAR 2.0 and NC2 inventories, in particular emissions from animal waste management systems and indirect emissions. Kroeze and Mosier (2000) discuss these differences in some more detail.

Table 3.4

Country-specific emissions of NH₃, N₂O and CH₄ from agriculture in the GOT scenario (1000 tons yr⁻¹; percentage change relative to NOC scenario)

| | NH ₃ | | N ₂ O | | CH ₄ | |
|-----------------------|-----------------|-------------------------|------------------|-------------------------|-----------------|-------------------------|
| | 2010 | Change (%) ^a | 2010 | Change (%) ^a | 2010 | Change (%) ^a |
| Albania | 34.9 | 0 | 8.8 | 0 | 107.7 | 0 |
| Austria | 66.0 | -1 | 15.9 | 1 | 187.9 | 0 |
| Belarus | 158.0 | -3 | 41.9 | 0 | 365.3 | 0 |
| Belgium | 74.0 | -23 | 26.2 | 15 | 240.2 | -1 |
| Bosnia Herzegovina | 23.0 | 0 | 4.7 | 0 | 67.4 | 0 |
| Bulgaria | 108.0 | -14 | 37.9 | 0 | 138.8 | 0 |
| Croatia | 30.0 | -19 | 13.2 | -1 | 61.4 | 0 |
| Czech Republic | 101.0 | -6 | 28.9 | 5 | 269.3 | 0 |
| Denmark | 69.0 | -4 | 24.8 | 1 | 198.3 | 0 |
| Estonia | 28.7 | 0 | 7.3 | 0 | 51.7 | 0 |
| Finland | 31.0 | 0 | 14.7 | 0 | 77.3 | 0 |
| France | 777.4 | 0 | 179.9 | 0 | 1614.0 | 0 |
| Germany | 550.0 | -4 | 129.5 | 0 | 1327.7 | 0 |
| Greece | 73.0 | -1 | 27.0 | 0 | 210.1 | 0 |
| Hungary | 90.0 | -34 | 45.3 | 6 | 179.2 | -2 |
| Ireland | 116.0 | -11 | 40.7 | 4 | 554.6 | 0 |
| Italy | 419.0 | -3 | 83.2 | 2 | 909.9 | 0 |
| Latvia | 34.9 | 0 | 10.3 | 0 | 67.0 | 0 |
| Lithuania | 81.3 | 0 | 20.9 | 0 | 184.3 | 0 |
| Luxembourg | 7.0 | -18 | 1.6 | 10 | 24.5 | 0 |
| Netherlands | 128.0 | -33 | 56.8 | 8 | 457.4 | -1 |
| Norway | 21.4 | 0 | 12.4 | 0 | 94.3 | 0 |
| Poland | 468.0 | -14 | 102.9 | 7 | 963.3 | -1 |
| Portugal | 61.9 | 0 | 16.6 | 0 | 221.5 | 0 |
| Republic of Macedonia | 15.7 | 0 | 3.4 | 0 | 42.3 | 0 |
| Republic of Moldova | 42.0 | -12 | 12.8 | -1 | 94.8 | 0 |
| Romania | 210.0 | -31 | 91.1 | 12 | 712.0 | -2 |
| Russia | 893.9 | 0 | 227.7 | 0 | 2577.4 | 0 |
| Slovak Republic | 39.0 | -17 | 13.1 | 4 | 82.0 | -1 |
| Slovenia | 20.0 | -3 | 5.2 | 0 | 34.5 | 0 |
| Spain | 353.0 | -8 | 93.2 | 0 | 1126.4 | 0 |
| Sweden | 57.0 | -7 | 16.9 | 2 | 151.1 | 0 |
| Switzerland | 63.0 | -5 | 7.8 | 4 | 156.3 | 0 |
| Ukraine | 592.0 | -9 | 160.4 | 0 | 1734.5 | 0 |
| United Kingdom | 297.0 | 0 | 114.1 | 0 | 1062.0 | 0 |
| Yugoslavia | 82.4 | 0 | 19.1 | 0 | 199.1 | 0 |
| Total | 6216.6 | -7 | 1716.3 | 2 | 16545.4 | 0 |

^a Percentages reflect the changes in emissions relative to the no control scenario (NOC) emission levels.

The methods and the input data used in this study to estimate CH₄ emissions differ from EDGAR 2.0 and NC2 inventories. For most countries, the difference between our estimates and those from EDGAR 2.0 and NC2 are <30%. There is no systematic pattern in these differences, i.e. some of the EDGAR 2.0 and NC2 estimates are higher and some are lower than our estimates. Overall, however, the agreement between the data sets is better than for N₂O.

3.5.2 Differences between countries

In all three NH₃ control scenarios total agricultural N₂O emissions in Europe are higher than without NH₃ abatement options applied (NOC). However, considerable differences were observed between the total effect on N₂O emissions in the individual countries (Tables 3.4-3.6). These may be the result of

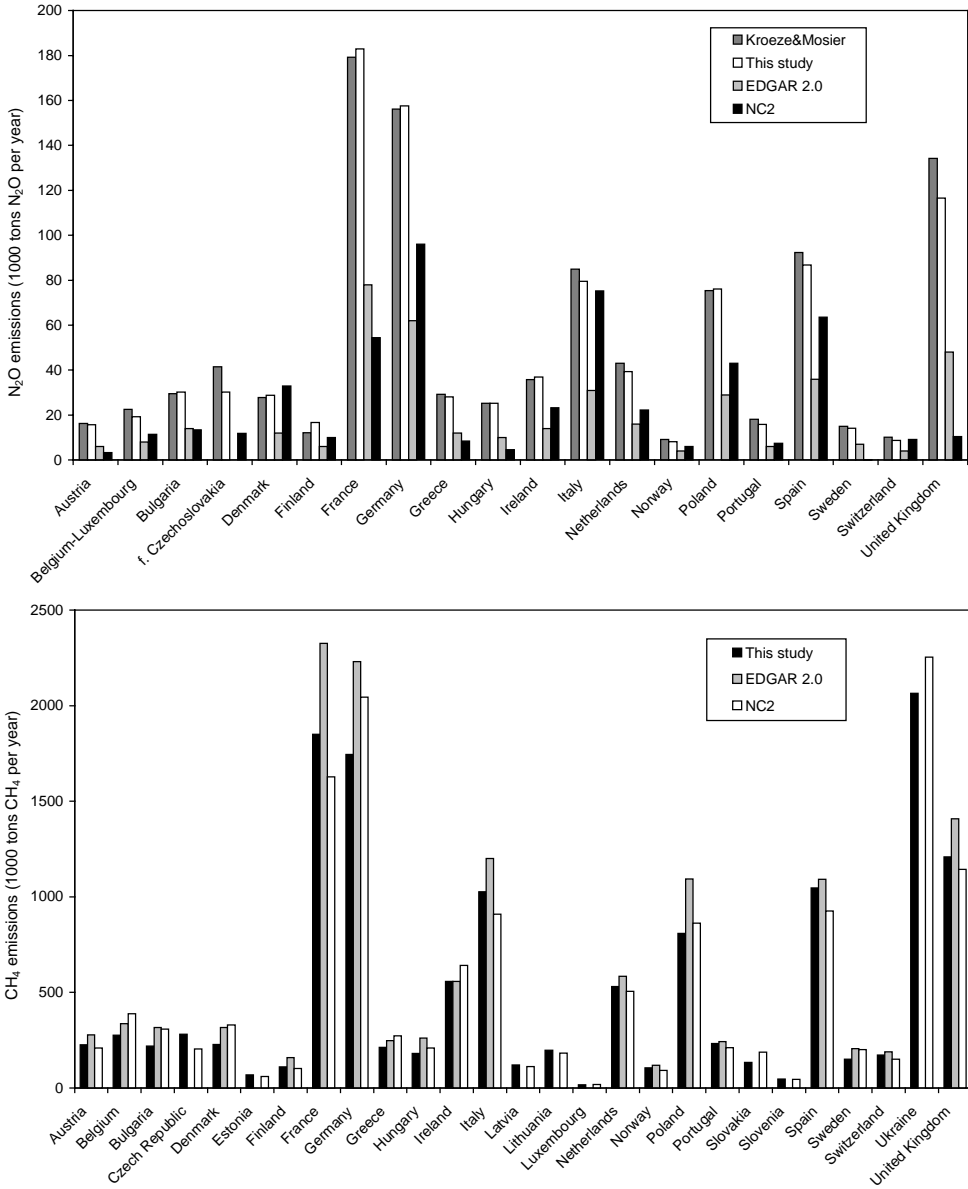


Fig. 3.3 Agricultural 1990 emissions of N₂O (top graph) and CH₄ (bottom graph) for a selection of European countries as estimated in this study, and as reported in EDGAR 2.0 (Olivier et al., 1996) and their second National Communications (NC2; estimates as available late 1998 from UNFCCC, 1998). For N₂O also estimates from Kroeze and Mosier (2000) were included.

differences in the level of NH₃ reductions as well as differences in the abatement strategies in the various countries. In countries where no or limited NH₃ reductions were achieved in the GOT and ENV scenarios (for example Austria and Greece; Tables 3.4 and 3.5), N₂O and CH₄ emissions were hardly affected. On the other hand, considerable increases in N₂O emissions (up to 19%) were

Table 3.5

Country-specific emissions of NH₃, N₂O and CH₄ from agriculture in the ENV scenario (1000 tons yr⁻¹; percentage change relative to NOC scenario)

| | NH ₃ | | N ₂ O | | CH ₄ | |
|-----------------------|-----------------|-------------------------|------------------|-------------------------|-----------------|-------------------------|
| | 2010 | Change (%) ^a | 2010 | Change (%) ^a | 2010 | Change (%) ^a |
| Albania | 31.7 | -9 | 8.7 | -1 | 107.8 | 0 |
| Austria | 66.1 | -1 | 15.9 | 0 | 188.0 | 0 |
| Belarus | 140.4 | -14 | 41.9 | 0 | 365.2 | 0 |
| Belgium | 60.4 | -37 | 27.1 | 18 | 236.8 | -3 |
| Bosnia Herzegovina | 21.9 | -5 | 4.8 | 3 | 67.2 | 0 |
| Bulgaria | 105.1 | -16 | 38.7 | 2 | 137.4 | -1 |
| Croatia | 29.2 | -21 | 13.2 | 0 | 61.3 | 0 |
| Czech Republic | 101.5 | -6 | 28.9 | 5 | 268.8 | -1 |
| Denmark | 69.2 | -3 | 24.7 | 1 | 198.5 | 0 |
| Estonia | 28.7 | 0 | 7.3 | 0 | 51.7 | 0 |
| Finland | 31.1 | 0 | 14.7 | 0 | 77.3 | 0 |
| France | 642.5 | -17 | 193.9 | 8 | 1604.3 | -1 |
| Germany | 412.8 | -28 | 142.9 | 10 | 1324.7 | 0 |
| Greece | 72.8 | -2 | 27.0 | 0 | 210.1 | 0 |
| Hungary | 76.8 | -44 | 46.2 | 8 | 177.1 | -4 |
| Ireland | 115.6 | -11 | 40.7 | 4 | 554.6 | 0 |
| Italy | 355.6 | -18 | 84.0 | 3 | 906.2 | -1 |
| Latvia | 34.9 | 0 | 10.3 | 0 | 67.0 | 0 |
| Lithuania | 71.5 | -12 | 20.8 | -1 | 184.4 | 0 |
| Luxembourg | 6.7 | -21 | 1.6 | 10 | 24.6 | 1 |
| Netherlands | 104.5 | -45 | 58.2 | 11 | 456.8 | -1 |
| Norway | 20.9 | -2 | 12.6 | 2 | 94.1 | 0 |
| Poland | 467.7 | -14 | 103.0 | 7 | 963.3 | -1 |
| Portugal | 61.9 | 0 | 16.6 | 0 | 221.5 | 0 |
| Republic of Macedonia | 14.8 | -6 | 3.6 | 4 | 42.3 | 0 |
| Republic of Moldova | 41.2 | -14 | 12.8 | -1 | 94.8 | 0 |
| Romania | 227.2 | -25 | 88.7 | 9 | 715.9 | -1 |
| Russia | 893.6 | 0 | 227.7 | 0 | 2577.4 | 0 |
| Slovak Republic | 39.1 | -17 | 13.1 | 4 | 82.0 | -1 |
| Slovenia | 16.2 | -21 | 5.2 | 0 | 34.5 | 0 |
| Spain | 353.0 | -8 | 93.2 | 0 | 1126.4 | 0 |
| Sweden | 48.0 | -21 | 17.3 | 4 | 150.9 | 0 |
| Switzerland | 62.9 | -5 | 7.8 | 4 | 156.3 | 0 |
| Ukraine | 587.6 | -9 | 160.9 | 1 | 1734.4 | 0 |
| United Kingdom | 264.3 | -11 | 116.4 | 2 | 1060.7 | 0 |
| Yugoslavia | 64.5 | -22 | 20.4 | 7 | 197.6 | -1 |
| Total | 5741.7 | -14 | 1750.7 | 4 | 16521.8 | 0 |

^a Percentages reflect the changes in emissions relative to the no control scenario (NOC) emission levels.

observed in several countries with substantial NH₃ emission reduction rates in the GOT and ENV scenarios (such as Belgium, Germany, Hungary, Luxembourg, the Netherlands and Romania).

However, in some countries, such as Bulgaria, Croatia and the Republic of Moldova, similar NH₃ reduction rates were obtained almost without an effect on N₂O emissions (Tables 3.4 and 3.5). This is mainly because in the latter countries substantial reductions in NH₃ emissions could be realised by substituting urea fertiliser with other N fertilisers, which was assumed to have no effect on direct N₂O emissions, while other countries mainly relied on manure injection techniques and animal housing adaptations. In the MFR scenario, in each country agricultural N₂O emissions are higher than in the NOC scenario, although there are differences between countries (Table 3.6). The increase in N₂O emissions is mainly the result of manure injection techniques and stable adaptations, which are among

Table 3.6

Country-specific emissions of NH₃, N₂O and CH₄ from agriculture in the MFR scenario (1000 tons yr⁻¹; percentage change relative to NOC scenario)

| | NH ₃ | | N ₂ O | | CH ₄ | |
|-----------------------|-----------------|-------------------------|------------------|-------------------------|-----------------|-------------------------|
| | 2010 | Change (%) ^a | 2010 | Change (%) ^a | 2010 | Change (%) ^a |
| Albania | 24.5 | -30 | 9.6 | 10 | 106.9 | -1 |
| Austria | 47.1 | -30 | 18.4 | 16 | 186.5 | -1 |
| Belarus | 101.6 | -38 | 46.6 | 11 | 362.0 | -1 |
| Belgium | 52.8 | -45 | 28.6 | 25 | 236.7 | -3 |
| Bosnia Herzegovina | 16.9 | -27 | 5.6 | 18 | 66.7 | -1 |
| Bulgaria | 84.4 | -33 | 41.0 | 8 | 134.6 | -3 |
| Croatia | 21.2 | -43 | 14.1 | 6 | 60.4 | -1 |
| Czech Republic | 69.8 | -35 | 32.7 | 18 | 265.3 | -2 |
| Denmark | 39.2 | -45 | 29.5 | 20 | 192.7 | -3 |
| Estonia | 15.7 | -45 | 8.2 | 12 | 50.9 | -2 |
| Finland | 22.5 | -28 | 15.3 | 4 | 76.6 | -1 |
| France | 518.6 | -33 | 211.8 | 18 | 1595.1 | -1 |
| Germany | 349.1 | -39 | 150.4 | 16 | 1318.5 | -1 |
| Greece | 58.0 | -22 | 30.1 | 12 | 204.6 | -3 |
| Hungary | 69.6 | -49 | 47.3 | 11 | 177.1 | -4 |
| Ireland | 110.5 | -15 | 41.0 | 5 | 555.4 | 0 |
| Italy | 269.2 | -38 | 96.5 | 19 | 886.6 | -3 |
| Latvia | 18.7 | -46 | 11.3 | 9 | 66.0 | -1 |
| Lithuania | 48.7 | -40 | 23.4 | 12 | 182.5 | -1 |
| Luxembourg | 6.7 | -22 | 1.6 | 12 | 24.5 | 1 |
| Netherlands | 99.4 | -48 | 60.9 | 16 | 452.0 | -2 |
| Norway | 16.8 | -21 | 13.1 | 5 | 94.1 | 0 |
| Poland | 361.9 | -33 | 104.5 | 9 | 961.1 | -1 |
| Portugal | 39.9 | -36 | 19.7 | 18 | 214.7 | -3 |
| Republic of Macedonia | 10.9 | -30 | 4.8 | 39 | 40.8 | -4 |
| Republic of Moldova | 28.3 | -41 | 14.6 | 14 | 93.1 | -2 |
| Romania | 199.5 | -34 | 93.4 | 15 | 712.1 | -2 |
| Russia | 561.0 | -37 | 263.5 | 16 | 2549.0 | -1 |
| Slovak Republic | 29.6 | -37 | 14.3 | 14 | 80.3 | -3 |
| Slovenia | 11.3 | -45 | 6.1 | 16 | 33.4 | -3 |
| Spain | 212.6 | -44 | 108.2 | 16 | 1085.4 | -4 |
| Sweden | 43.7 | -28 | 17.8 | 7 | 150.9 | 0 |
| Switzerland | 53.6 | -19 | 8.2 | 10 | 156.0 | 0 |
| Ukraine | 397.9 | -39 | 186.6 | 17 | 1712.5 | -1 |
| United Kingdom | 214.2 | -28 | 126.2 | 11 | 1052.1 | -1 |
| Yugoslavia | 53.0 | -36 | 21.8 | 14 | 196.7 | -1 |
| Total | 4278.5 | -36 | 1926.6 | 14 | 16333.7 | -2 |

^a Percentages reflect the changes in emissions relative to the no control scenario (NOC) emission levels.

the most efficient NH₃ control options and therefore widely applied in this scenario.

Differences between countries were also observed for the effect of NH₃ control on CH₄ emissions. In all countries the effects are limited, ranging from -2% to 0% (GOT) and -4% to +1% (ENV and MFR).

3.5.3 Impact of individual NH₃ control options on N₂O and CH₄

The effects of NH₃ control on N₂O and CH₄ emissions as presented in the tables 3.4-3.6 are the net effects of all NH₃ control options implemented in a country. Some NH₃ control options tend to increase while others tend to decrease N₂O and/or CH₄ emissions (see Brink et al. (2001a) and Table 3.1). The impact of individual techniques on N₂O and CH₄ was analysed by calculating emissions excluding the

Table 3.7

Effects of individual NH₃ control options on agricultural N₂O emissions in three scenarios for the year 2010 (1000 tons N₂O yr⁻¹; percentage change in emissions)^{a,b,c}

| | | No options ^d | Low N feed (%) ^e | Housing adaptations (%) ^f | Manure injection (%) ^g | Housing adaptations + manure injection (%) ^h | All options (%) ⁱ |
|----------------|-----|-------------------------|-----------------------------|--------------------------------------|-----------------------------------|---|------------------------------|
| Belgium | GOT | 22.9 | -1 | 8 | 9 | 16 | 15 |
| | ENV | 22.9 | -2 | 13 | 9 | 23 | 19 |
| | MFR | 22.9 | -2 | 13 | 9 | 23 | 25 |
| Germany | GOT | 129.8 | 0 | 0 | 0 | 0 | 0 |
| | ENV | 129.8 | -1 | 4 | 8 | 11 | 10 |
| | MFR | 129.8 | -1 | 5 | 10 | 15 | 16 |
| Hungary | GOT | 42.8 | -1 | 5 | 3 | 8 | 6 |
| | ENV | 42.8 | -2 | 7 | 5 | 12 | 8 |
| | MFR | 42.8 | -2 | 7 | 5 | 12 | 11 |
| Netherlands | GOT | 52.6 | -3 | 6 | 7 | 14 | 8 |
| | ENV | 52.6 | -3 | 8 | 8 | 16 | 11 |
| | MFR | 52.6 | -3 | 10 | 8 | 18 | 16 |
| Romania | GOT | 81.0 | -1 | 8 | 7 | 15 | 13 |
| | ENV | 81.0 | -1 | 6 | 5 | 12 | 10 |
| | MFR | 81.0 | -1 | 8 | 7 | 15 | 16 |
| Europe (total) | GOT | 1683.1 | 0 | 1 | 1 | 3 | 2 |
| | ENV | 1683.1 | 0 | 3 | 2 | 5 | 4 |
| | MFR | 1683.1 | -1 | 7 | 7 | 14 | 15 |

^a NH₃ abatement strategies in the GOT, ENV and MFR scenarios were not changed. Agricultural N₂O emissions in the scenarios were estimated including only the effect of the control option(s) indicated in the first row.

^b Percentages reflect the effect of the NH₃ control option concerned on N₂O emissions relative to the 'no options' emission level (assuming no effect of NH₃ control on N₂O).

^c The effect of air purification and covering manure storage on N₂O emissions was very small and therefore not included (largest effect observed in individual European countries is +0.2% (air purification) and -0.3% (covering manure storage)).

^d N₂O emissions assuming no effects of NH₃ control on N₂O (equal to emissions in NOC scenario, Table 3.3).

^e N₂O emissions including only the effect of low nitrogen feed on N₂O emissions.

^f N₂O emissions including only the effect of livestock housing adaptations on N₂O.

^g N₂O emissions including only the effect of manure injection techniques on N₂O.

^h N₂O emissions including only the effect of manure injection techniques and animal house adaptations on N₂O.

ⁱ N₂O emissions including the effects of all NH₃ control options on N₂O (i.e. as presented in tables 3.4-3.6).

effects of all other control options (results for a selection of countries are presented in Tables 3.7 and 3.8).

It appears that in particular manure injection techniques and livestock housing adaptations have a large impact on N₂O emissions. These options were mainly responsible for the observed increase in N₂O emissions (Table 3.7). This can be explained by the fact that (i) the estimated impact of these techniques on N₂O emissions is a considerable increase in emissions (Brink et al., 2001a) and (ii) these techniques belong to the most effective reduction measures for NH₃ and therefore are required if a significant reduction of NH₃ emissions is asked for⁵.

The effects of other control options on total N₂O emissions are much smaller. Reducing the N content of the feed results in lower N₂O emissions. The net effect on N₂O emissions observed for covering manure storage and air purification was very small (the effect in individual countries was in a

⁵ Without implementation of manure injection, some countries would not be able to reduce their NH₃ emissions sufficiently to meet the Gothenburg Protocol target levels.

Table 3.8

Effects of individual NH₃ control options on agricultural CH₄ emissions in three scenarios for the year 2010 (1000 tons CH₄ yr⁻¹; percentage change in emissions)^{a,b}

| | | No options ^c | Covered manure storage (%) ^d | Animal housing adaptations (%) ^e | All options (%) ^f |
|----------------|-----|-------------------------|---|---|------------------------------|
| Belgium | GOT | 243.0 | 0 | -1 | -1 |
| | ENV | 243.0 | 0 | -3 | -3 |
| | MFR | 243.0 | 0 | -3 | -3 |
| Germany | GOT | 1327.4 | 0 | 0 | 0 |
| | ENV | 1327.4 | 1 | -1 | 0 |
| | MFR | 1327.4 | 0 | -1 | -1 |
| Hungary | GOT | 183.6 | 0 | -2 | -2 |
| | ENV | 183.6 | 0 | -4 | -4 |
| | MFR | 183.6 | 0 | -4 | -4 |
| Netherlands | GOT | 463.0 | 0 | -1 | -1 |
| | ENV | 463.0 | 0 | -2 | -1 |
| | MFR | 463.0 | 0 | -2 | -2 |
| Romania | GOT | 726.0 | 0 | -2 | -2 |
| | ENV | 726.0 | 0 | -1 | -1 |
| | MFR | 726.0 | 0 | -2 | -2 |
| Europe (total) | GOT | 16584.0 | 0 | 0 | 0 |
| | ENV | 16584.0 | 0 | -1 | 0 |
| | MFR | 16584.0 | 0 | -2 | -2 |

^a NH₃ abatement strategies in the GOT, ENV and MFR scenarios were not changed. Agricultural CH₄ emissions in the scenarios were estimated including only the effect of the control option(s) indicated in the first row.

^b Percentages reflect the effect of the NH₃ control option concerned on CH₄ emissions relative to the 'no options' emission level (assuming no effect of NH₃ control on CH₄).

^c CH₄ emissions assuming no effects of NH₃ control on CH₄ (equal to emissions in NOC scenario, Table 3.3).

^d CH₄ emissions including only the effect of covering manure storage on CH₄.

^e CH₄ emissions including only the effect of livestock housing adaptations on CH₄.

^f CH₄ emissions including the effects of all NH₃ control options on CH₄ (as presented in Tables 3.4-3.6).

range of -0.3% to +0.1% and 0.0%–0.2%, respectively).

The decrease in CH₄ emissions due to NH₃ control was caused by animal housing adaptations. Reductions by up to 4% were observed in individual countries (Table 3.8). Covering manure storage caused only a small increase in CH₄ emissions (<1% in each country).

3.6 Conclusions

This paper presents estimates for emissions of ammonia (NH₃), nitrous oxide (N₂O) and methane (CH₄) from the agricultural sector in European countries in 1990 and 2010 using information on the European agricultural sector in the RAINS databases. Emissions of N₂O and CH₄ were estimated according to the method described by Brink et al. (2001a).

Emissions of N₂O and CH₄ estimated in this study for 1990 were compared to estimates from other inventories. N₂O emissions estimated in this study are comparable to estimates by Kroeze and Mosier (2000). The differences found between this study and the EDGAR 2.0 and NCs inventories can be explained by the use of different emission factors and activity levels.

As a result of projected changes in agricultural activity levels, total agricultural emissions in Europe of NH₃ as well as N₂O and CH₄ decrease between 1990 and 2010 by 11%, 12% and 15% respectively.

For 2010, emissions were estimated for three scenarios that require further reductions of NH_3 emissions. The effect of these NH_3 abatement strategies on emissions of N_2O and CH_4 in European countries was estimated using the results presented in part 1 of this paper (Brink et al., 2001a), which shows that several NH_3 control options may have an impact on emissions of N_2O and CH_4 . Particularly N_2O emissions tend to be affected by NH_3 control. The estimated net effect of NH_3 abatement in the three scenarios is that N_2O emissions from European agriculture are up to 15% higher than in the case of no NH_3 control. Application of manure injection techniques and adaptations to animal houses were mainly responsible for this. Other control options have a much smaller effect on N_2O emissions. Besides the reduction in N_2O emissions following the decline in N deposition (resulting from lower NH_3 emissions in the considered scenarios), reducing the N content of the animal feed is the only control option that considerably reduced the emissions of N_2O . For CH_4 , only a modest decrease in emissions was found as a result of NH_3 abatement strategies in Europe.

The results of this study indicate that it is necessary to take into account possible unintentional effects of abatement measures in agriculture. However, the existence of these adverse side effects is not necessarily limited to agriculture, but may also occur in other economic sectors (for instance, catalysts applied to reduce nitrogen oxides emissions from cars and trucks tend to increase N_2O emissions (Kroeze, 1994a)). Considering the difficulties many European countries face to meet their targets for greenhouse gas emission reductions in the coming decade, increases in greenhouse gas emissions will further increase the costs of environmental policies. We are convinced that substantial cost savings can be obtained by taking these side effects into account in designing environmental policies.

4

Cost-effectiveness of interrelated emission reduction strategies in agriculture – model structure

This chapter is based on:

Corjan Brink, Ekko van Ierland, Leen Hordijk, Carolien Kroeze. Cost-effectiveness of interrelated emission reduction strategies in agriculture. Submitted and revised for publication in *European Review of Agricultural Economics*

Abstract

Environmental policies usually focus on one pollutant or environmental issue, but may have substantial impacts on other emissions and environmental problems. Neglecting these impacts will result in sub-optimal policies. We present a model for identifying cost-effective strategies to simultaneously reduce emissions of several pollutants from several sources, allowing for interrelations between sources and abatement options. The model is used to analyse interrelations in reducing ammonia, nitrous oxide and methane emissions from European agriculture.

Keywords: Environmental policy interrelations; Cost-effective abatement; Acidification; Global warming; European agriculture

4.1 Introduction

For many industrialised countries, international environmental agreements resulted in commitments to reduce atmospheric emissions of several pollutants. Examples are the 'Gothenburg Protocol', aiming at the control of acidification, eutrophication and ground-level ozone concentrations in Europe (UNECE, 1999a) and the 'Kyoto Protocol', aiming at reductions in greenhouse gas emissions in industrialised countries all over the world (UNFCCC, 1997). Important interrelations exist between different environmental issues (cf. Grennfelt et al., 1994). First, one pollutant may have an impact on several environmental problems. Second, emissions of pollutants may originate from the same human activities (e.g. fossil fuel consumption). Third, technical measures to reduce emissions of one pollutant may also affect emissions of other pollutants, either beneficially or adversely. Finally, environmental effects may influence each other.

Our study presents a model for cost-effectiveness analysis of emission reduction strategies, specifically designed to include these interrelations. For simultaneously imposed limits on emissions of several pollutants, the model determines which abatement measures have to be applied to meet these limits at least cost. We used the model in a case study to analyse interrelations between emission reduction strategies for ammonia (NH₃), nitrous oxide (N₂O) and methane (CH₄) in the agricultural sector in Europe. The results of the analyses will be presented in Chapter 5.

4.2 Background

In the past decades, environmental policies evolved from a uniform reduction percentage for single pollutants to an effect-based approach, taking into account several pollutants and several pollution effects. Several studies deal with the linkages between local and regional air pollution problems (Grennfelt et al., 1994; Van Ierland and Schmieman, 1999). The 'multi-pollutant multi-effect' Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, signed in Gothenburg in 1999 (UNECE, 1999a), was the first protocol to include several pollutants and several environmental effects in Europe. The RAINS model¹ was used to analyse cost-effective strategies for the reduction of these environmental effects (Amann et al., 1998).

Global warming will be another important issue in environmental policy-making in Europe in the coming years. Policies with respect to global warming mainly focus on carbon dioxide (CO₂), but also take into account other greenhouse gases. Interactions between policies to reduce greenhouse gas emissions and policies for other environmental issues (like acidification and tropospheric ozone) are, however, often neglected.

An increasing number of studies pay attention to interactions between abatement of greenhouse gases and air pollutants². These can be subdivided in three groups (Davis et al., 2000): (1) literature that primarily looks at reductions in emissions of greenhouse gases and recognises there may be effects on emissions of air pollutants (e.g. Ekins, 1996; McCarl and Schneider, 2000); (2) literature that primarily looks at reductions in emissions of air pollutants and recognises there may be effects on

¹ Regional Air Pollution Information and Simulation model, developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for the integrated assessment of alternative strategies to reduce air pollution in Europe (Alcamo et al., 1990; Amann et al., 1998).

² In this paper, the term 'air pollutant' is restricted to pollutants contributing to transboundary air pollution problems such as high concentrations of ground-level ozone, acidification, and eutrophication. Greenhouse gases are not included in this term.

greenhouse gas emissions (Brink et al., 2001a, b); (3) literature that looks at the combination of reductions in emissions of greenhouse gases and air pollutants from an integrated perspective (Aaheim et al., 1999; Mayerhofer et al., 2001). The present study can be categorised in the third group.

Examples of interactions mentioned in the literature can be categorised according to the four interrelations described in Section 4.1. First, emissions may have an effect on global temperature as well as on other environmental problems, for instance (a) sulphur dioxide (SO₂) emissions result in acid deposition and also increased concentrations of sulphate aerosols, which may mask global warming by scattering solar radiation and modifying clouds and their properties (Posch et al., 1996); or (b) nitrogen oxides (NO_x) emissions contribute to the formation of tropospheric ozone, which has a negative impact on human health and crop production and also contributes to global warming (Kyrö et al., 1996). Second, greenhouse gases and air pollutants are to a large extent emitted by the same sources, for instance (a) fossil fuel use results in emissions of the greenhouse gas CO₂ and the air pollutants SO₂ and NO_x (Ayres and Walter, 1991; Boyd et al., 1995; Syri et al., 2001); or (b) agriculture is a source of the greenhouse gases N₂O and CH₄ and the acidifying compound NH₃ (Brink et al., 2001b). Third, technical measures to reduce emissions of air pollutants may have an impact on emissions of greenhouse gases and the other way around, for instance (a) 3-way catalytic converters in cars reduce emissions of NO_x, but result in an increase in emissions of N₂O (Michaels, 1998); (b) scrubbers installed in power plants to reduce SO₂ emissions may increase CO₂ emissions through increased coal use (Martin, 1989); or (c) several measures to reduce NH₃ emissions in agriculture have an effect on N₂O and CH₄ emissions (Brink et al., 2001a). Finally, global warming and air pollution may have an effect on each other, for instance (a) changes in temperature and precipitation affect the rate of acidification, the distribution of air pollutants through the atmosphere, and the sensitivity of ecosystems for acidification and eutrophication (Martin, 1989; Mayerhofer et al., 2001); or (b) ground-level ozone production may increase with rising temperatures (Maarouf and Smith, 1997).

To our knowledge, only a few studies deal with efficiency of joint abatement strategies for greenhouse gases and air pollutants considering interrelations mentioned before. Within the AIR-CLIM project (Van Harmelen et al., 2001), cost-effective abatement of SO₂ and NO_x emissions was analysed considering reductions in SO₂ and NO_x as a result of CO₂ abatement strategies. Aunan et al. (1998) and Aaheim et al. (1999) include several effects of energy saving measures by estimating their economic value. Our study presents a model for analysing joint abatement strategies for air pollutants and greenhouse gases that include those control options that reduce contributing emissions simultaneously and cost-effectively, explicitly considering interrelations in emission reduction strategies.

4.3 Theoretical model

In this section we present a static optimisation model to determine cost-effective policies for several environmental targets simultaneously, considering interrelations between these policies. The emissions of pollutants are the result of economic activities, which are exogenous to the model. Emissions can be reduced by several abatement options, for which costs and effects on emissions are known. In order to reflect the individual abatement options, the model is formulated as a linear program using piece-wise linear functions that represent non-linear functions for abatement cost. The linear approach to calculate emissions, costs and effects of abatement makes it possible to include a large number of sources, pollutants and abatement options while maintaining the most important non-linear characteristics of the model, such as the increasing and convex abatement cost functions. To keep the analysis as concise as

possible, we have chosen for a static formulation of the model. Moreover, in order to focus specifically on the topic of the interrelations, the level of economic activities causing emissions of pollutants has been kept exogenous to the model and not affected by the level of total abatement cost. This could easily be modified in further applications of the model.

For a good understanding, we will first describe a model for only one pollutant (i.e. ignoring interactions between abatement of different pollutants). Subsequently, the model is extended to include several pollutants and interactions between abatement of these pollutants.

4.3.1 Single pollutant, no interactions

The model minimises total cost of abatement that can be implemented at the various sources to achieve a given constraint on the emission level of the pollutant. The model is described by Eqs. (4.1) to (4.6):

$$\min \sum_{k \in K} C_k(v_k) \text{ with } v_k \text{ a vector with elements } a_{k,n}, n \in N \quad (4.1)$$

subject to

$$C_k(v_k) = \sum_{n \in N} a_{k,n} \cdot \gamma_{k,n} \cdot \bar{X}_k \quad \forall k \in K \quad (4.2)$$

$$e_k = \varepsilon_k \cdot \bar{X}_k \cdot \left(1 - \sum_{n \in N} a_{k,n} \cdot \rho_{k,n} \right) \quad \forall k \in K \quad (4.3)$$

$$\sum_{k \in K} e_k \leq \bar{E} \quad (4.4)$$

$$\sum_{n \in N} a_{k,n} \leq 1 \quad \forall k \in K \quad (4.5)$$

$$a_{k,n} \geq 0 \quad \forall k \in K, n \in N \quad (4.6)$$

Eq. (4.1) is the objective function, which minimises the sum of the annual abatement costs C_k over the sources $k \in K$. The decision variables in the model are the application rates $a_{k,n}$ for abatement options $n \in N$ at source k (with N the set of abatement options available). For each source k , application rates $a_{k,n}$ for all $n \in N$ are included in the vector v_k . Furthermore, abatement costs at source k depend on the (exogenous) activity level \bar{X}_k and the per unit cost of abatement options, $\gamma_{k,n}$ for all $n \in N$ (Eq. (4.2)). Annual emissions from source k , e_k , depend on activity level \bar{X}_k , emission factor ε_k , application rate $a_{k,n}$ and effectiveness $\rho_{k,n}$ of the abatement options applied (Eq. (4.3)). Total emissions are constrained in Eq. (4.4). The application rate $a_{k,n}$ is constrained in Eqs. (4.5) and (4.6).

The set K of emission sources in the model may consist of various types of economic activities. The distinction between sources is based on differences in the effect on emissions. The level of economic activity per year at source k is exogenous to the model and indicated by \bar{X}_k .³ A linear relation was assumed between economic activities and unabated emissions at each source, represented by emission factor ε_k .

Total annual emissions may not exceed level \bar{E} (Eq. (4.4)). To meet this restriction, emissions from each source can be reduced by several abatement options included in set N^4 . Application rate $a_{k,n}$

³ This could be modified by estimating a relationship between economic activity levels and abatement costs, for example the cost-elasticity of production for each source.

⁴ Emissions can not be reduced by changes in production level or mix of inputs, because activity levels in each sector are exogenous. So far, it was also assumed that activity level \bar{X}_i does not change as a result of applying abatement options.

indicates the fraction of economic activity at source k to which abatement option n is applied (Appendix 4.A) and ranges from zero (no application) to one (full application).

The model includes a set of abatement options (N), which includes both single abatement technologies and possible combinations of these technologies. Combinations of abatement technologies are included in set N as a new abatement option to avoid non-convexities and as a consequence multiple local optima (Appendix 4.A). It is possible to apply several abatement options at the same time to different fractions of an economic activity (Eq. (4.5))⁵.

The effect of abatement option n on emissions from source k is represented by $\rho_{k,n}$, which indicates the emission reduction as fraction of unabated emissions. The total reduction in emissions by abatement options n is $\varepsilon_k \cdot \bar{X}_k \cdot a_{k,n} \cdot \rho_{k,n}$.

The cost of an abatement option is linearly related to the economic activity level⁶ and the application rate. Cost per unit of activity at full application, $\gamma_{k,n}$, may differ between sources. Total cost of abatement at source k is the sum of the cost for the various abatement options (Eq. (4.2)). Overall abatement costs are the sum of costs at the various sources (Eq. (4.1)). Only direct costs of applying abatement techniques (annual investment, operating and maintenance cost) are included. Secondary impacts on the economy as a whole, for example as a result of price changes, were not considered.

Linear approximations of essentially non-linear abatement cost curves can be constructed to compare abatement costs at various sources⁷. These cost curves indicate for emission reduction levels ranging from zero up to the technically feasible limit least cost abatement strategies by ranking abatement options according to their increasing marginal cost. To determine marginal cost of abatement options, the cost of abatement option n per unit of emissions abated ($\xi_{k,n}$) is calculated:

$$\xi_{k,n} = \frac{\gamma_{k,n}}{\varepsilon_k \rho_{k,n}} \quad (4.7)$$

Next, for each source k abatement options are sorted according to the increasing removal efficiency $\rho_{k,n}$. Options that have a lower efficiency ($\rho_{k,n}$) and higher costs per ton reduced ($\xi_{k,n}$) are excluded from the analysis because they will not be applied in a cost-effective solution. For the remaining options, marginal reduction costs are determined (the position of abatement options in the ordered set for source k is indicated by $d(k)$, see Tables 4.1 and 4.2):

$$\mu_{k,d(k)} = \frac{\xi_{k,d(k)} \rho_{k,d(k)} - \xi_{k,d(k)-1} \rho_{k,d(k)-1}}{\rho_{k,d(k)} - \rho_{k,d(k)-1}} \quad (4.8)$$

where $\mu_{k,d(k)}$ is the marginal cost of abatement option at position $d(k)$, i.e. the cost of reducing an additional unit of emissions by abatement option at position $d(k)$ instead of the option at position $d(k) - 1$ (the next less effective option at the source)⁸. Abatement options that have a higher marginal cost and a lower efficiency are eliminated, after which marginal costs are determined once more. The remaining options are sorted according to increasing marginal cost of abatement, resulting in abatement cost curves for the various sources (Table 4.1). These abatement cost curves are piecewise linear. Each

⁵ If, for example, at source k two abatement options are applied at rates $a_{k,1} = 0.6$ and $a_{k,2} = 0.4$, this means that option 1 is applied to 60% and option 2 to the remaining 40% of activities within source k .

⁶ This means that economies of scale are disregarded.

⁷ The methodology described here to construct the abatement cost curves was taken from the RAINS model (Klimont et al., 2000).

⁸ For $d(k) = 1$, $\mu_{k,d(k)} = \xi_{k,d(k)}$.

Table 4.1
Construction of abatement cost curve for emissions from source k

| Abatement option ^a | Marginal cost | Remaining emissions | Total cost |
|-------------------------------|---------------------------|--|--------------------------|
| No control | 0 | $\bar{X}_k \varepsilon_k$ | 0 |
| $d(k) = 1$ | $\mu_{k,1} (= \xi_{k,1})$ | $\bar{X}_k \varepsilon_k (1 - \rho_{k,1})$ | $\gamma_{k,1} \bar{X}_k$ |
| $d(k) = 2$ | $\mu_{k,2}$ | $\bar{X}_k \varepsilon_k (1 - \rho_{k,2})$ | $\gamma_{k,2} \bar{X}_k$ |
| ... | ... | ... | ... |
| $d(k) = D$ | $\mu_{k,D}$ | $\bar{X}_k \varepsilon_k (1 - \rho_{k,D})$ | $\gamma_{k,D} \bar{X}_k$ |

^a The position of abatement options in the ordered set for source k is indicated by $d(k)$.

Table 4.2
Construction of abatement cost curve for whole economy

| Source k^a | Abatement option ^b | Marginal cost | Remaining emissions ^c | Total cost ^c |
|--------------|-------------------------------|---------------------------|---|---|
| | no control | 0 | $e(0) = \sum_{k \in K} (\bar{X}_k \cdot \varepsilon_k)$ | 0 |
| $k = 2$ | $d(2) = 1$ | $\mu_{2,1} (= \xi_{2,1})$ | $e(1) = e(0) - r_{2,1}$ | $c(1) = \mu_{2,1} \cdot r_{2,1}$ |
| $k = 1$ | $d(1) = 1$ | $\mu_{1,1} (= \xi_{1,1})$ | $e(2) = e(1) - r_{1,1}$ | $c(2) = c(1) + \mu_{1,1} \cdot r_{1,1}$ |
| $k = 1$ | $d(1) = 2$ | $\mu_{1,2}$ | $e(3) = e(2) - r_{1,2}$ | $c(3) = c(2) + \mu_{1,2} \cdot r_{1,2}$ |
| $k = 2$ | $d(2) = 2$ | $\mu_{2,2}$ | $e(4) = e(3) - r_{2,2}$ | $c(4) = c(3) + \mu_{2,2} \cdot r_{2,2}$ |
| $k = 2$ | $d(2) = 3$ | $\mu_{2,3}$ | $e(5) = e(4) - r_{2,3}$ | $c(5) = c(4) + \mu_{2,3} \cdot r_{2,3}$ |
| ... | ... | ... | ... | ... |

^a The position of abatement options at various sources in the cost curve depends on their marginal cost. The order applied in this table is used as an example.

^b The position of abatement options in the ordered set for source k is indicated by $d(k)$.

^c Variables $e(i)$ and $c(i)$ respectively indicate the emission level and total abatement cost at stage i . Each stage indicates application of an abatement option at one of the sources with higher marginal abatement cost. For example, at stage 3 option 2 is applied at source 1 instead of option 1, which yields an additional emission reduction of $r_{1,2}$ at higher marginal cost ($\mu_{1,2} > \mu_{1,1}$).

linear segment corresponds with application of a particular abatement option. The kinks in the curve indicate increases in marginal abatement cost, which occur when an additional abatement option is required to achieve the associated emission reduction (see Table 4.1: abatement option at position $d(k)$ is fully applied and higher reductions can only be obtained by applying abatement option at position $d(k) + 1$ instead, which is more effective, but has a higher marginal cost⁹).

To construct the abatement cost curve for the economy as a whole, cost curves of individual sources are integrated into one cost curve by ranking abatement options that can be applied at the various sources according to their marginal abatement cost (Table 4.2). For each option the emission reduction is calculated:

$$r_{k,d(k)} = \bar{X}_k \cdot \varepsilon_k \cdot (\rho_{k,d(k)} - \rho_{k,d(k)-1}) \quad (4.9)$$

where $r_{k,d(k)}$ is the additional amount of emissions reduced after implementation of the abatement option at position $d(k)$ instead of the abatement option at position $d(k) - 1$.¹⁰ Fig. 4.1 shows, as an example, curves for total and marginal cost of reducing ammonia emissions in the United Kingdom in 2010, reflecting increasing marginal cost of emission reduction. An emission reduction up to 20

⁹ For a gradually increasing emission reduction, there is a smooth transition from option at position $d(k)$ to option position $d(k) + 1$. The application rate for abatement option at position $d(k) + 1$, $a_{k,d(k)+1}$, increases from zero to one, while at the same time $a_{k,d(k)}$ decreases from one to zero, under the restriction that $a_{k,d(k)} + a_{k,d(k)+1} = 1$.

¹⁰ For $d(k) = 1$, $r_{k,d(k)} = \bar{X}_k \cdot \varepsilon_k \cdot \rho_{k,d(k)}$.

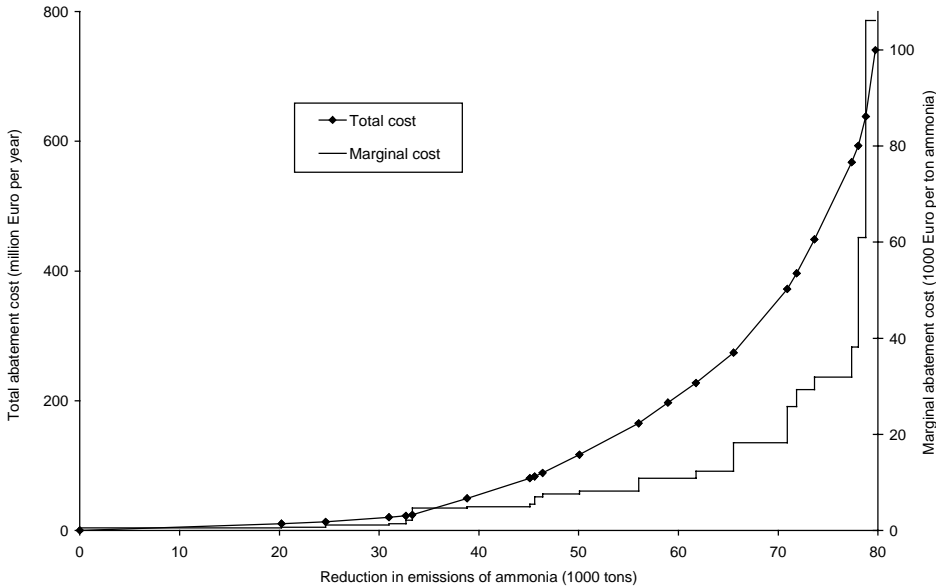


Fig. 4.1 Total abatement cost curve and marginal abatement cost curve for abatement of ammonia in the UK in 2010 as included in the RAINS model (Amann et al., 1998).

kilotons can be obtained at a constant marginal cost of EUR 500 per ton. For further reductions the marginal cost changes as a result of changes in the abatement options applied. Total cost of reducing ammonia emissions by 80 kilotons is EUR 740 million per year. From the curve we can also derive that 70 kilotons ammonia can be reduced at a marginal cost less than EUR 20,000 per ton. The marginal cost of further reductions in emissions quickly increases to more than EUR 100,000 per ton for an emission reduction of about 80 kilotons per year.

4.3.2 Several pollutants

The model described above allows for determining cost-effective abatement strategies for a single pollutant, based on the assumption that this is the only pollutant for which an emission reduction target exists. The model is extended to include several pollutants p in a set P . For each source, emission factors are distinguished for the various pollutants ($\epsilon_{k,p}$). Targets can be specified for emissions of all $p \in P$ (\bar{E}_p).

For multiple emission constraints, overall cost-effectiveness can be obtained by determining cost-effective abatement strategies for each pollutant separately only if an abatement option for one pollutant does not affect emissions of others for which reduction targets exist and if application of an abatement technology for one pollutant does not affect the applicability of abatement technologies for others. An abatement option for one pollutant, however, may affect emissions of other pollutants and application of an abatement option for one pollutant may exclude abatement options for others. Consequently, cost-effective strategies for simultaneous emission reductions of several pollutants can only be determined in an integrated analysis.

In the model abatement options are no longer attributed to a single specific pollutant. An abatement option now may have impacts on various pollutants simultaneously, either reducing or increasing

emissions, and reducing emissions of at least one pollutant. When the application of an abatement technique excludes the application of another, the combination of these techniques is not included as an abatement option in set N . The parameter $\rho_{k,n,p}$ represents the effect of abatement option $n \in N$ on emissions of pollutant $p \in P$ at source k . For $0 < \rho_{k,n,p} \leq 1$, emissions of p decrease (by no more than 100%), for $\rho_{k,n,p} = 0$ there is no effect on emissions of p , and for $\rho_{k,n,p} < 0$ emissions of p increase (possibly more than 100%¹¹).

With several pollutants included in the model, Eqs. (4.10) and (4.11) replace Eqs. (4.3) and (4.4) (other equations remain unchanged):

$$e_{k,p} = \varepsilon_{k,p} \cdot \bar{X}_k \cdot \left(1 - \sum_{n \in N} a_{k,n} \cdot \rho_{k,n,p} \right) \quad (4.10)$$

$$\sum_{k \in K} e_{k,p} \leq \bar{E}_p \quad \forall p \in P \quad (4.11)$$

To determine cost-effective strategies to reduce several pollutants *simultaneously*, the marginal cost approach as described in Section 4.3.1 can only be applied if emissions of all pollutants can be added up (e.g. using weighting factors for individual pollutants). This implies that a trade-off is allowed between abatement of various pollutants (i.e. increasing emissions of one pollutant can be compensated by emission reductions of another). This is possible if all pollutants contribute to the same environmental problem, e.g. using CO₂ equivalents for greenhouse gases. In that case, abatement cost curves can be constructed that represent the cost associated with various levels of greenhouse gas abatement in terms of CO₂ equivalents. However, we would like to emphasise that if *several* environmental problems are considered *simultaneously*, cost-effective abatement strategies to achieve emission targets for all pollutants can no longer be determined by ranking abatement options according to their marginal cost, because these marginal costs will depend on the emission targets of the various pollutants. In such an integrated analysis it is no longer possible to determine a conventional, two-dimensional cost curve, because the various abatement measures have widely divergent impacts on emissions of the various pollutants. With restrictions on several pollutants, marginal costs for one pollutant also depend on restrictions on emissions of other pollutants. Therefore, to define a set of technical abatement measures that yield the required reductions in emissions of various pollutants at least cost, a bottom-up analysis is required, including specific abatement techniques. This provides detailed information about (1) techniques that can contribute to emission reductions of the specified pollutants in the year for which the analysis is performed, (2) the emission reduction potential for the pollutant the abatement technique is primarily aimed at, (3) effects on other pollutants and (4) associated costs.

The impact of different values for the effects of abatement options on the optimal solution can be investigated analytically for a formulation of the problem with two pollutants (p_1, p_2) and two abatement options (n_1, n_2). To avoid needless complexity of the analysis, the model is simplified by assuming only one source k with activity level $\bar{X}_k = 1$ and emission factor $\varepsilon_k = 1$. The emission constraint (Eq. (4.11)) was rewritten to $\sum_{n \in N} a_n \rho_{n,p} \geq R_p$, with $R_p = 1 - \bar{E}_p$. This gives the following

formulation of the model:

¹¹ For example, adaptations to animal housing to reduce NH₃ emissions may result in an increase in N₂O emissions of 900% at some sources (Table 4.5).

$$\begin{aligned} &\text{Minimise} && a_{n1}\gamma_{n1} + a_{n2}\gamma_{n2} \\ &\text{subject to} && a_{n1}\rho_{n1,p1} + a_{n2}\rho_{n2,p1} \geq R_{p1} \\ &&& a_{n1}\rho_{n1,p2} + a_{n2}\rho_{n2,p2} \geq R_{p2} \end{aligned}$$

Furthermore, it is assumed that both abatement options are applied ($a_{n1} > 0$ and $a_{n2} > 0$) and that abatement option n_1 is the first choice for reducing pollutant p_1 and option n_2 for pollutant p_2 (i.e. $\rho_{n1,p1} > 0$; $\rho_{n2,p2} > 0$; $\rho_{n1,p1} > \rho_{n2,p1}$; and $\rho_{n2,p2} > \rho_{n1,p2}$). Table 4.3 presents the optimal application rates a_n^* for different cases. It turns out that, in general, $a_{n1}^* = \frac{R_{p1} - \rho_{n2,p1}a_{n2}^*}{\rho_{n1,p1}}$ and $a_{n2}^* = \frac{R_{p2} - \rho_{n1,p2}a_{n1}^*}{\rho_{n2,p2}}$. If only

one of the two abatement options, say n_1 , has a side effect, this changes the application rate of the other abatement option, n_2 , because, depending on the side effect, less or more of this abatement option is required to meet the reduction target for p_2 (Table 4.3). If both abatement options have a side effect, the optimal application rates for both abatement options are mutually dependent. The expressions in Table 4.3 for this case indicate that the optimal application rate corrected for the side effect of the other abatement option is multiplied by an additional effect because of the abatement option's own side effect. The net effect of both side effects on the optimal application rate of abatement options n_1 and n_2 depends on $\left(\frac{\rho_{n2,p1}R_{p2}}{R_{p1}} - \frac{\rho_{n1,p2}\rho_{n2,p1}}{\rho_{n1,p1}}\right)$ and $\left(\frac{\rho_{n1,p2}R_{p1}}{R_{p2}} - \frac{\rho_{n1,p2}\rho_{n2,p1}}{\rho_{n2,p2}}\right)$ respectively.

For a larger number of abatement options and pollutants, cost-effective abatement strategies are determined by numerically solving the optimisation problem (i.e. minimisation of the total abatement cost) for specific emission constraints, considering the effect of abatement options on all pollutants included in the analysis. A set of abatement options that is cost-effective for one set of emission constraints may be not cost-effective for another set of constraints, depending on the cost and effects of the options, including side effects.

Table 4.3

Analytical investigation of optimal application rates of abatement options n (a_n^*) with two pollutants (p_1, p_2) and two abatement options (n_1, n_2) for different values of side effects ($\rho_{n1,p2}, \rho_{n2,p1}$)^a

| | $\rho_{n1,p2} = 0$ $\rho_{n2,p1} = 0$ | $\rho_{n1,p2} \neq 0, \rho_{n2,p1} = 0$ | $\rho_{n1,p2} = 0, \rho_{n2,p1} \neq 0$ | $\rho_{n1,p2} \neq 0, \rho_{n2,p1} \neq 0$ |
|------------|--|---|---|---|
| a_{n1}^* | $\frac{R_{p1}}{\rho_{n1,p1}}$ | $\frac{R_{p1}}{\rho_{n1,p1}}$ | $\frac{R_{p1}}{\rho_{n1,p1}} - \frac{\rho_{n2,p1} R_{p2}}{\rho_{n1,p1} \rho_{n2,p2}}$ | $\left(\frac{R_{p1}}{\rho_{n1,p1}} - \frac{\rho_{n2,p1} R_{p2}}{\rho_{n1,p1} \rho_{n2,p2}}\right) \left(\frac{\rho_{n1,p1} \rho_{n2,p2}}{\rho_{n1,p1} \rho_{n2,p2} - \rho_{n1,p2} \rho_{n2,p1}}\right)$ |
| a_{n2}^* | $\frac{R_{p2}}{\rho_{n2,p2}}$ | $\frac{R_{p2}}{\rho_{n2,p2}} - \frac{\rho_{n1,p2} R_{p1}}{\rho_{n2,p2} \rho_{n1,p1}}$ | $\frac{R_{p2}}{\rho_{n2,p2}}$ | $\left(\frac{R_{p2}}{\rho_{n2,p2}} - \frac{\rho_{n1,p2} R_{p1}}{\rho_{n2,p2} \rho_{n1,p1}}\right) \left(\frac{\rho_{n1,p1} \rho_{n2,p2}}{\rho_{n1,p1} \rho_{n2,p2} - \rho_{n1,p2} \rho_{n2,p1}}\right)$ |

^a $\rho_{11} > 0, \rho_{22} > 0, a_{n1}^* > 0$ and $a_{n2}^* > 0$.

4.4 Application to the agricultural sector in Europe

4.4.1 Model description

In Chapter 5, the model will be used in a numerical analysis to study cost-effectiveness of strategies to reduce emissions of ammonia (NH₃), nitrous oxide (N₂O) and methane (CH₄) from European agriculture, considering interactions between abatement of these gases. Emissions of these pollutants (included in set P) are to a large extent associated with the same agricultural activities. The model distinguishes 36 countries and in each country 14 categories of activities: 11 livestock categories,

synthetic fertiliser use (2 types) and nitrogen fertiliser production, resulting in more than 500 emission sources (set *K*). Activity levels were taken from databases in the RAINS model¹², which includes data for 1990, 1995 and projections up to 2010 (Amann et al., 1998). Emission factors for NH₃ were taken from the RAINS model. Emission factors for N₂O and CH₄ were determined according to the method described by Brink et al. (2001a).

Abatement options in the model (set *N*) include technical measures for reducing NH₃, N₂O and CH₄ and possible combinations of up to six of these techniques, which results in about 750 abatement options in total¹³. Information on technical measures to reduce NH₃ was taken from the RAINS model (Brink et al., 2001a; Klimont, 2002). For technical measures particularly aiming at reducing emissions of N₂O and CH₄ from agriculture, information was taken from Hendriks et al. (1998) and Bates (1998a; 1998b; 2001). Details about these abatement options, their costs and effects on emissions are given in Appendix 4.B. Tables 4.4-4.6 give an overview of abatement techniques included.

For the empirical application, the model was implemented in the GAMS programming language (General Algebraic Modelling System), which has been developed for the solution of large mathematical optimisation models (Brooke et al., 1998). Appendix I gives the specifications of the model in the GAMS language.

4.4.2 Discussion

The model presented in this chapter is designed as a tool to identify cost-effective abatement strategies under different sets of constraints on emissions and hence explore the implications of interrelations between abatement of various pollutants for cost-effective emission control. The model is empirically applied to European agriculture. The results are presented in Chapter 5. Obviously, the model results are an abstraction from reality in several ways because of several assumptions that have been made in the formulation of the model. Nevertheless, the model can be used to improve our understanding of interrelations between abatement measures for several pollutants emitted by European agriculture and their implications for cost-effective abatement strategies. This section will discuss the implications of several assumptions and limitations in the model for the interpretation of results presented in Chapter 5.

We have chosen for a comparative static formulation of the model, which implies that transition dynamics can not be considered. However, technological progress was considered in estimates for the cost and effects of each abatement option in 2010 as presented in Tables 4.4-4.6. Moreover, for each abatement option we included a maximum application rate for 2010 based on information in various studies on abatement techniques for NH₃, N₂O and CH₄ in European agriculture (in particular Bates, 2001; Klimont, 2002). A set of forecasts of agricultural activities in Europe in 2010 was taken from Amann et al. (1998).

The level of economic activities causing emissions of pollutants is exogenous in the model and not affected by the level of total abatement cost. In fact, this can be interpreted as if all abatement costs will be fully subsidised such that production costs (and hence supply and demand) will not change as a result of abatement. It is possible to allow the demand for the various products to be endogenously

¹² The agricultural sector was included in the RAINS model to estimate NH₃ emissions and analyse cost-effectiveness of NH₃ abatement (Klaassen, 1994).

¹³ Although abatement options are not attributed to a specific pollutant, they are presented in the literature as options to reduce emissions of a specific pollutant. Following these studies, abatement options are presented here as options for a specific pollutant to indicate their primary purpose.

Table 4.4
Costs and effects of measures primarily aimed at reducing NH₃ emissions (% change in emissions from source to which applied)^{a,b}

| | Cost (EUR ₁₉₉₀ per animal per year) ^{c,d} | Emissions of NH ₃ ^c | | | | Emissions of CH ₄ | | | Emissions of N ₂ O | | | |
|--|---|---|--------------------|----------------------------|-------------|------------------------------|--------------------------|-----------------------|-------------------------------|-----------------------------|-------------------------|-------------------------|
| | | Animal housing (%) | 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 | 0.1 – 46 | -20 to -5 | -20 to -5 | -20 to -5 | -20 | 0 | 0 | 0 | -20 to -5 | -20 to -5 | -20 to -5 | -20 to -5 |
| Remove NH ₃ from the air in animal housing | 1.3 – 85 | -80 to -21 | 0 | 0 | 0 | 0 | 0 | 0 | 2 to 295 | -54 to -7 | 0 | 0 |
| Adaptations to animal houses to reduce NH ₃ | 0.2 – 206 | -80 to -2 | -80 to -4 | 0 | 0 | 0 | 0 | -90 to -1 | >0 to 99 | 45 to 900 | -68 to -1 | >0 to 36 |
| Covered outdoor storage of manure | >0 – 105 | 0 | -70 to -20 | 0 | 0 | 0 | 0 | 1 to 10 | >0 to 19 | -10 to -1 | -27 to <0 | >0 to 10 |
| Low NH ₃ application of manure | >0 – 71 | 0 | 0 | -60 to -4 | 0 | 0 | 0 | 0 | 6 to 100 | 0 | -32 to -1 | >0 to 13 |
| Substitute urea fertilisers 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 fertiliser plants | 3 – 77 | 0 | 0 | 0 | 0 | -50 | 0 | 0 | 0 | 0 | -50 | 0 |

^a This table is based on Brink et al. (2001a).

^b The ranges in the table reflect differences in costs and effects between sources the measures can be applied to. The cost, effect and applicability of an abatement option may vary between different types of activities and between countries because of different characteristics of agriculture in different countries.

^c Information on costs and effects on NH₃ emissions was taken from the RAINS model (Amann et al., 1998; Klimont, 2002).

^d For abatement technologies that are applicable to fertiliser use and production, costs are given in EUR₁₉₉₀ per ton nitrogen per year.

Table 4.5
Costs and effects of measures primarily aimed at reducing N₂O emissions (% change in emissions from source to which applied)^{a,b}

| | Cost (EUR ₁₉₉₀ per animal per year) ^c | Emissions of N ₂ O | | | Emissions of CH ₄ | | | Emissions of NH ₃ | | | | |
|--|---|-------------------------------|-----------------------------|--------------------------------------|------------------------------|---------------------------|--------------------------|------------------------------|--------------------|--------------------|----------------------------|-----------------|
| | | Direct soil emissions (%) | Animal waste management (%) | Nitrogen deposition ^d (%) | Leaching and runoff (%) | Fertiliser production (%) | Enteric fermentation (%) | Manure management (%) | Animal housing (%) | Manure storage (%) | Fertiliser application (%) | Grazing (%) |
| Catalytic conversion of nitric acid production | 0.4 – 4.2 | 0 | 0 | 0 | 0 | -24 | 0 | 0 | 0 | 0 | 0 | 0 |
| Substituting inorganic with organic N fertiliser | 918 – 941 | -15 | 0 | -15 to -11 | -15 | 0 | 0 | 0 | 0 | 0 | 0 | -15 |
| Restrictions on timing of fertiliser application | >0 – 1.8 | 0 | 20 | >0 to 10 | -15 | 0 | 0 | 20 | 0 | 0 | 20 | 1 |
| Fertiliser efficiency improvements | 8 | -5 ^e | 0 | -5 to -4 | -5 ^e | 0 | 0 | 0 | 0 | 0 | 0 | -5 ^e |
| Adjusting groundwater levels for grassland | 0.2 – 0.6 | -10 | 0 | 0 | 0 | 0 | 0 ^f | 0 | 0 | 0 | 0 | 0 |
| Restrictions on grazing | >0 – 68 | 1 to 111 | -46 to -2 | -15 to +41 | 0 | 0 | 0 | 1 to 74 | 1 to 74 | 1 to 74 | 1 to 74 | 1 to 74 –50 |

^a A description of the control options and the assumptions underlying these figures is given in Appendix 4.B.

^b The ranges in the table reflect differences in costs and effects between sources the measures can be applied to. The cost, effect and applicability of an abatement option may vary between different types of activities and between countries because of different characteristics of agriculture in different countries.

^c For abatement technologies that are applicable to fertiliser use and production in EUR₁₉₉₀ per ton nitrogen per year.

^d The effect on N₂O emissions induced by nitrogen deposition is related to the overall effect on NH₃ emissions.

^e A 5% reduction in N₂O and NH₃ emissions from synthetic fertiliser application.

^f This option may result in higher CH₄ emissions from agricultural soils (Velthof et al., 1998), but this source of CH₄ was not included in this study.

Table 4.6
Costs and effects of measures primarily aimed at reducing CH₄ emissions (% change in emissions from source to which applied)^{a,b}

| | Cost (EUR ₁₉₉₀ per animal per year) | Emissions of CH ₄ | | | Emissions of N ₂ O | | | Emissions of NH ₃ | | | |
|--|---|--------------------------------|-----------------------------|---------------------------------|-----------------------------------|-------------------------------|-------------------------------|------------------------------|--------------------------|----------------------------------|----------------|
| | | Enteric fermentation (%) | Manure management (%) | Direct soil emissions (%) | Animal waste management (%) | Nitrogen deposition (%) | Leaching and runoff (%) | Animal housing (%) | Manure storage (%) | Fertiliser application (%) | Grazing (%) |
| Propionate precursors | 25 – 60 | -12 to -1 | -5 to <0 | -5 to <0 | -5 to <0 | -5 to <0 | -5 to <0 | -5 to <0 | -5 to <0 | -5 to <0 | -5 to <0 |
| Probiotics | 15 – 35 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 | -2 to <0 |
| Daily spread of manure | 8 – 75 | 0 | -23 | 20 | 0 | -5 to +1 ^c | 20 | 0 | -13 | 3 | 0 |
| Anaerobic digestion of manure – centralised plant | 3 – 26 | 0 | -12 to -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| – small scale plant | 11 – 155 | 0 | -29 to <0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

^a A description of the control options and the assumptions underlying these figures is given in Appendix 4.B.

^b The ranges in the table reflect differences in costs and effects between sources the measures can be applied to. The cost, effect and applicability of an abatement option may vary between different types of activities and between countries because of different characteristics of agriculture in different countries.

^c The change in N₂O emissions induced by nitrogen deposition is related to the change in NH₃ emissions.

affected by their production costs by introducing a price elasticity for each demand category. For instance, Loulou and Lavigne (1996) and Wietschel et al. (1997) both describe a partial equilibrium approach to include the price reactions of energy demand into bottom-up models of energy-environment systems, that might also be applicable to our model. However, this is beyond the scope of this thesis, because the focus is on technical abatement measures for different pollutants and how they interact.

In the model, the unit cost of abatement techniques is assumed to be constant. Unit cost may, however, decrease with increasing application rates, as a result of, for instance, economies of scale in the production of the technology and learning effects. These effects may occur at sector, national and international level, depending on the characteristics of the sector and the technology. As a result, an abatement technology that initially was less cost-effective than other techniques at a certain source may become more cost-effective because the unit cost decreases when this technology is applied at another source. This effect is self-enforcing, because the unit cost decreases for each additional source where the technology is implemented. Thus, including these effects will reduce total abatement cost, whereas the abatement options applied as well as the allocation of abatement over the various sources will also change. No information, however, was available to make a realistic estimate of these effects for the technical abatement measures that were included in the application of the model for European agriculture. Therefore, these effects were not considered in this thesis.

Uncertainties are not considered in the empirical application of the model because they are beyond the scope of this thesis. Uncertainties in estimating emissions from agriculture (in particular N_2O) are, however, large (Van Aardenne et al., 2000; Van Aardenne, 2002). Moreover, there are uncertainties associated with the model structure, parameters and input data (Suutari et al., 2001; Van Aardenne, 2002). There are also important uncertainties in estimating side effects of abatement options. Brink et al. (2001a) indicate that particularly the effect of low NH_3 application of manure on N_2O emissions is uncertain and subject to scientific debate. Quantitative information about side effects of abatement options for NH_3 , N_2O and CH_4 from agriculture and associated uncertainties is, however, hardly available. The estimated side effects used in this thesis and presented in Tables 4.4-4.6 are considered the best given the current state of scientific knowledge.

4.5 Conclusions

In this chapter, we have described the structure of the model developed to study interrelations between policies for various environmental problems. Interrelations may exist when (i) one pollutant contributes to several environmental problems, (ii) one source emits several pollutants contributing to different environmental problems, (iii) abatement of one pollutant also affects other emissions (either beneficially or adversely) and (iv) one environmental problem influences other environmental effects. These interrelations may largely affect cost-effectiveness of abatement strategies, but are usually neglected in designing environmental policies.

We presented a static optimisation model to analyse cost-effectiveness of environmental policies with respect to various environmental problems taking into account interrelations between these policies. A large number of technical measures to reduce emissions can be considered, taking into account their cost and effect on emissions of pollutants included. The model applies a stepwise linear approach to calculate emissions, emission reductions and abatement costs and minimises total cost to meet specified emission constraints.

Moreover, we presented input data for an empirical application of the model to the agricultural sector in Europe, which is an important source of NH_3 (contributing to acidification and eutrophication), and the greenhouse gases N_2O and CH_4 . We include data on agricultural activities in 36 European countries in 1990 and 2010. Moreover, several technical measures to reduce NH_3 , N_2O and CH_4 emissions from agriculture are considered. For each measure, we include its cost and estimates of its effect on emissions of all three gases. Chapter 5 will present the results of the empirical analysis.

Quantitative information about side effects of abatement options for NH_3 , N_2O and CH_4 from agriculture is hardly available. Moreover, there are many uncertainties in estimating the effects of control measures on emissions. Therefore, more research is required on the effects of abatement options, in particular on possible side effects.

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Appendix 4.A

Determination of parameters for combinations of abatement techniques

The model includes a set N of abatement options, which includes single abatement techniques and possible combinations of these techniques. Set Y is the set of single abatement techniques, which is a subset of set N . Possible combinations of techniques are included as separate options with their own parameters for cost and effect, calculated on the basis of parameters of single techniques in the combination. This appendix describes how parameters for combinations are determined.

Although it is not made explicit in the model, in fact each source k is considered to consist of a number of firms in which similar economic activities take place. The sum of the activity levels in the individual firms gives the activity level for the source:

$$\sum_{f_k \in F_k} \bar{x}_{f_k} = \bar{X}_k$$

with F_k the set of firms f_k that together form source k and \bar{x}_{f_k} the activity level at firm f_k . The application rate $a_{k,n}$ represents the fraction of economic activity at source k to which abatement option n is applied. At firm level abatement options are either fully applied or not applied, i.e. $b_{f_k,n} \in \{0,1\}$, with $b_{f_k,n}$ the application of abatement option n at firm f_k . The application rate at source level is

$$a_{k,n} = \frac{\sum_{f_k \in F_k} b_{f_k,n} \cdot \bar{x}_{f_k}}{\bar{X}_k}$$

At firm level, several single abatement techniques $y \in Y$ can be applied together. The joint effect on emissions of these techniques is not the sum of the effects of single techniques. When two techniques are applied together, the second technology only affects the emissions that remain after the first technique has been applied. Consequently, the joint impact will be lower than the sum of the effects of individual techniques. In fact, the additional effect of the second technique on emissions is equal to the removal efficiency of this technique (ρ_2) multiplied by the fraction of emissions remaining after application of the first technique ($1 - \rho_1$). Hence, the total impact of the combination of the two techniques is $\rho_1 + \rho_2 - \rho_1\rho_2$. In general, the relative reduction of a combination of techniques is

$$\rho_{k,n} = 1 - \prod_{y \in S(n)} (1 - \rho_{k,y}) \quad \forall n \in N$$

$S(n) \subseteq Y$ is the set of single abatement techniques included in abatement option n and $\rho_{k,y}$ is the effect on emissions of the single technology y . The effect on emissions is independent of the order of introduction of the different techniques. The cost per unit of activity of a combination of techniques is equal to the sum of the cost of the single techniques applied:

$$\gamma_{k,n} = \sum_{y \in S(n)} \gamma_{k,y} \quad \forall n \in N$$

with $\gamma_{k,y}$ the unit cost of single technology y . Once the parameters $\rho_{k,n}$ and $\gamma_{k,n}$ are determined for all possible combinations, they can be treated as single techniques for which the application rate at each source, $a_{k,n}$ is determined.

Please note that it would also have been possible to include combinations of techniques directly in the model, but this would result in non-linearities and even non-convexities. Consequently, optimisation would result in local optima and it would be difficult to find the optimal solution. By treating combinations as separate options this is avoided and the model remains linear.

Appendix 4.B

Abatement measures for N₂O and CH₄ emissions from agriculture and estimated side effects on NH₃, N₂O and CH₄ emissions

This appendix elaborates on abatement measures for emissions of nitrous oxide (N₂O) and methane (CH₄) from agriculture that were considered in the analyses presented in Chapters 5 and 6 of this thesis. This appendix is meant to lay down the assumptions and choices we have made. These were based on information that is available in the literature and this appendix includes references to the studies concerned.

Several options to reduce N₂O and CH₄ emissions from agriculture have been mentioned in the literature. In this thesis we included a selection of these options, based on the availability of information on costs and effects, and on the estimated applicability of the options in Europe in 2010. Information on the selected measures for reducing N₂O and CH₄ emissions was largely based on several studies commissioned by the European Commission, viz. Bates (1998a; 1998b; 2001), Hendriks et al. (1998) and Hendriks and Bode (2000). These studies are based on experiences in individual countries, in particular the United Kingdom, the Netherlands and Denmark.

Usually, information on the effect of an abatement technology is limited to the effect on emissions it is primarily aimed at. Information on possible side effects is hardly available in the literature. In our analyses, however, we aim to include effects of each abatement technology on emissions of all three pollutants considered in the analyses in this thesis (i.e. NH₃, N₂O and CH₄). Therefore, we estimated to the best of our ability the direction (increasing or decreasing emissions) and the magnitude of effects. To this end we used information on the underlying processes involved. Wherever appropriate, the potential effects on emissions were quantified using the IPCC method for estimating national greenhouse gas emissions (IPCC, 1997; Mosier et al., 1998a; see also Chapter 2). Further research is, however, required to improve these estimates. We do not include side effects on emissions of other air pollutants such as nitrogen oxides (NO_x) or carbon dioxide (CO₂).

The purpose of this appendix is to justify assumptions that have been made on information used in the analyses in this thesis. In the following, we first describe the measures, and their effect on emissions for which they were meant. Next, the associated costs are presented in EUR₁₉₉₀¹⁴. Only direct resource costs and benefits were taken into account. Macroeconomic and social costs and benefits of abatement were not included. Third, the side-effects on other emissions are described. Effects on emissions are presented as a percentage change in emissions from the sources (e.g. animal categories) to which the control option is applied, relative to unabated emissions from these sources. The effects on emissions refer to the specific sub-sources of emissions (e.g. manure storage, manure application and grazing). For each of the technical measures included, we estimated the impact on emissions of other pollutants.

For most emission control measures, the studies that were available assume equal costs and effects in various countries within the EU. No information was available on costs, effects and applicability of these measures in countries outside the EU. Therefore, we assumed that abatement measures that are

¹⁴ 1 ECU is considered to be equal to 1 Euro. Costs are converted to EUR₁₉₉₀ using the Industrial Producer Price Index for total industry in EU15 (Eurostat, 1997).

available for EU countries can also be applied in other European countries. Moreover, we assumed that costs and effects of these measures are the same in EU and non-EU countries. The applicability of measures in non-EU countries was estimated based on information for EU countries.

As noted earlier in this thesis, emission factors for estimating N₂O and CH₄ emissions from agriculture are relatively uncertain (for a discussion of uncertainties in emission inventories, see Van Aardenne, 2002). Moreover, there are uncertainties in estimates of the costs and impacts on emissions of a number of control options. This means that the cost-effectiveness estimates presented in this appendix also have a relatively high degree of uncertainty. This should be noted when interpreting the results.

Tables 4.5 and 4.6 give an overview of the abatement options for N₂O and CH₄ included in the analyses presented in this thesis and ranges of costs and effects, reflecting the differences between sources the options can be applied to. These ranges were calculated on the basis of the assumptions described in this appendix.

Measures to reduce N₂O emissions

Catalytic conversion of N₂O in nitric acid production

N₂O emissions from industrial nitric acid production processes can be reduced very effectively (up to 80%) by catalytic decomposition converting N₂O to N₂ and H₂O (Oonk and Kroeze, 1998; Hendriks and Bode, 2000). Catalytic converters for nitric acid production are not yet commercially available, but they are demonstrated in a few plants in Europe. Based on Bates (1998b), we assume that they will be available in 2010 and can be applied to 30% of total N₂O emissions from nitric acid production in each country at most.

Because these catalytic converters are not yet commercially available, no detailed information is available on their costs (Hendriks and Bode, 2000). Estimates on the basis of preliminary data arrive at an annual cost of EUR 140–400 per ton N₂O abated (Hendriks et al., 1998; Hendriks and Bode, 2000). Based on these estimates, we used annual costs of EUR₁₉₉₀ 250 per ton N₂O abated.

Because nitric acid production is not a source of NH₃ and CH₄, it is unlikely that catalytic reduction of N₂O in the production process affects emissions of NH₃ and CH₄.

Substituting inorganic with organic nitrogen fertiliser

The total amount of nitrogen in arable and grassland systems can be reduced by replacing inorganic nitrogen with manure that is otherwise disposed of as a waste product (Bates, 1998b; Hendriks et al., 1998). This can be effectuated by imposing restrictions on the application of inorganic nitrogen. The resulting decrease in nitrogen input to agricultural systems will result in lower N₂O emissions. A limit on inorganic fertiliser application on cereals and grassland to 50 kg per hectare may result in an estimated reduction of synthetic fertiliser use and associated N₂O emissions of 15% in each country (Bates, 1998b).

Cost savings result from reduced application of inorganic fertiliser. On the other hand, additional costs are associated with transporting, storing and processing manure. Estimates for the net costs range from EUR₁₉₉₅ 148 to 243 million per kiloton N₂O abated (Bates, 1998b; Hendriks et al., 1998). We used annual costs of EUR₁₉₉₀ 200 million per kiloton N₂O abated.

A 15% reduction in the use of inorganic fertilisers will likely reduce total NH₃ emissions associated with synthetic fertiliser use by 15%. Fertiliser application in itself is not a source of CH₄ emissions. We

therefore assume no effect of this measure on CH₄ emissions. We realise that we ignore a possible effect on CH₄ emissions from manure storage, because the manure is stored before it will be processed. This may cause an increase in CH₄ emissions, depending on storage conditions and the time the manure is stored. . Quantifying this effect, however, requires additional analyses which is beyond the scope of this project.

In Germany and the Netherlands existing policies already limit the use of nitrogen (Bates, 2001). Therefore, this option is assumed to be not applicable in these countries, whereas in other countries it is assumed fully applicable.

Restrictions on timing of fertiliser application

Restrictions on application of synthetic fertilisers and manure during autumn and winter will reduce nitrogen leaching and the associated indirect N₂O emissions (Bates, 1998b; Hendriks et al., 1998). Restrictions on timing of fertiliser application have been estimated to reduce total agricultural N₂O emissions in the EU in 2010 by up to an estimated 4.5% (Hendriks et al., 1998). In general, N₂O emissions induced by nitrogen leaching may contribute by about one third to total agricultural N₂O emissions (Kroeze et al., 1999). Based on this, we assumed that restrictions on timing of fertiliser application will reduce N₂O emissions induced by nitrogen leaching by about 15% in each country.

Costs are mainly associated with additional storage capacity for manure. They are estimated at about EUR₁₉₉₀ 6 million per kiloton N₂O abated (Bates, 1998b). For synthetic fertilisers, costs are much lower (we assumed EUR₁₉₉₀ 1 million per kiloton N₂O abated).

NH₃ emissions are highest under warm, dry, windy conditions and can be reduced by choosing the optimum time of application, i.e. cool, humid, before or during rain, not in June, July, August (UNECE, 1999c). These conditions differ from the optimum conditions for low N₂O emissions from nitrogen leaching (i.e. no application during autumn and winter). The likely increase in annual NH₃ emissions due to restrictions on timing of fertiliser application meant to reduce leaching losses are, however, not easily quantified. Here we tentatively assumed that restricting fertiliser application during autumn and winter will cause a small increase in NH₃ emissions from the application of synthetic fertiliser and manure (1%).

Restrictions on timing of fertiliser application require longer manure storage times and greater storage capacities (Bates, 1998b). As a result, emissions of NH₃, N₂O and CH₄ during manure storage may increase by an estimated 20% (Hendriks et al., 1998).

This measure only applies to application of manure from cattle, pigs and poultry and application of inorganic fertilisers. In the Netherlands, timing of fertiliser application is already bounded by regulations in order to reduce nitrate leaching. Therefore, we assumed that this measure is not applicable in the Netherlands.

Fertiliser efficiency improvements

A more efficient use of fertilisers will reduce the amount of fertiliser nitrogen applied to agricultural soils, and hence the associated emissions of N₂O as well as NH₃. Efficiency of fertilisers can be improved in various ways, such as improved maintenance of fertiliser spreaders to ensure uniform spreading, maintaining a fertiliser free zone on the edge of the fields, and optimisation of fertiliser distribution geometry (Bates, 2001).

The total package of measures to improve fertiliser efficiency may reduce total agricultural emissions of N₂O in the EU by 2.5% (Hendriks et al., 1998). According to our calculations (cf. Chapter

2), about 35% of total agricultural N₂O emissions in the EU is related to synthetic fertiliser use. Based on this, we assumed that in each European country emissions of N₂O that result from inorganic fertiliser use (i.e. direct and indirect emissions) can be reduced by 5% with fertiliser efficiency improvements.

These measures to improve fertiliser efficiency are reported to be available at no direct cost, or even yield benefits (Mosier et al., 1998b; Bates, 2001). Transaction costs and increased uncertainties in crop yield are, however, not included in the estimated negative costs presented in these studies (Bates, 2001). Risk and information barriers represent real economic cost (see also a discussion of this issue with respect to energy conservation costs in Boyd et al., 1995 p.3). Reasonable estimates for these costs do not exist. Moreover, in combination with some other measures described in this appendix, the risks for yield reduction may increase. We therefore concluded that it is likely that fertiliser efficiency improvement may in fact be associated with net costs, and tentatively estimated the overall costs at EUR₁₉₉₀ 5 million per kiloton N₂O abated, well within the range of the costs of greenhouse gas emission control¹⁵.

We assume fertiliser efficiency improvements will reduce emissions of NH₃ associated with synthetic fertiliser use as effectively as emissions of N₂O (15%). There is no side-effect on CH₄.

Adjusting groundwater levels for grassland

Adjusting groundwater levels for grassland and preventing large fluctuations in groundwater levels can reduce N₂O emissions from agricultural soils (Oenema et al., 1998; Velthof et al., 1998).

Costs and potential effects of this option are difficult to quantify at a national level. Moreover, no information is available about applicability of this measure in European countries. Because N₂O production in soils is not only governed by groundwater level, but also by a number of other environmental factors, we tentatively assumed that in each country this option could yield a moderate reduction in N₂O emissions from agricultural soils by 10% at a cost of EUR₁₉₉₀ 5 million per kiloton N₂O abated¹⁶.

As a side effect, this option may in theory promote emissions of CH₄ from agricultural soils (Velthof et al., 1998). In our analyses, agricultural soils are however not included as a source of CH₄.

Restrictions on grazing

Restrictions on grazing can reduce N₂O emissions from animal waste, because emissions are much higher for manure produced by grazing animals than for manure produced in animal housing with anaerobic storage of manure (Mosier et al., 1998a). Therefore, restrictions on grazing can reduce N₂O emissions from dairy farming systems by a shift from high N₂O emissions during grazing to lower emissions from animal housing (Velthof and Oenema, 1997; Oenema et al., 1998).

This measure implies that cattle will be inside for a longer time. Consequently, more manure is collected from animal houses, subsequently stored, and finally applied as fertiliser to agricultural fields. Therefore, restrictions on grazing may increase NH₃ and CH₄ emissions from manure management as well as N₂O and NH₃ emissions after application of manure (Velthof and Oenema, 1997). NH₃

¹⁵ EUR 5 million per kiloton N₂O is equivalent to about EUR 16 per ton CO₂-equivalents, and well within the range of abatement costs for greenhouse gas mitigation as reported by other studies (IPCC, 2001b).

¹⁶ See footnote 15.

emissions during grazing will obviously decrease, but overall NH₃ emissions are likely to increase (Oudendag and Wijnands, 1989).

Effects on emissions of NH₃, N₂O and CH₄ were estimated on the basis of the method for calculating emissions as described in Chapter 2, which is based on the IPCC emission inventory method for N₂O and CH₄ from agriculture (IPCC, 1997; Mosier et al., 1998a). Due to restrictions on grazing, part of the amount of nitrogen that was excreted during grazing (NEXM) will now be excreted in the animal houses (NEXS), i.e. $\Delta\text{NEXM} = -\Delta\text{NEXS}$ (for an explanation of these variables, see Appendix 2.A). The avoided nitrogen excretion during grazing is added to the amount of nitrogen excreted in the animal house, which results in an increase in emissions from animal housing, manure storage and manure application and a reduction in emissions during grazing. The change in emissions depends on the initial amount of nitrogen excreted in the meadow and in the animal house in each country. N₂O emissions only decrease in case manure is stored in anaerobic or liquid waste management systems.

Costs associated with additional manure storage capacities are based on information on nitrogen content of manure for different manure types and costs per ton manure stored (Bates, 1998b). For cattle and pigs, an additional kilogram of nitrogen excreted in the animal house instead of in the meadow is assumed to cost EUR₁₉₉₀ 1 and for poultry this is assumed EUR₁₉₉₀ 0.15 (Bates, 1998b).

Measures to reduce CH₄ emissions

CH₄ emissions from enteric fermentation can be reduced by improving feed conversion efficiency, increasing rumen efficiency or increasing animal productivity (Bates, 2001). Several options to improve feed conversion efficiency have been estimated to give net benefits to the farmers (Bates, 2001). We assume that these beneficial measures will be implemented in Europe in 2010 even without environmental policies and thus are accounted for in the exogenous projections of agricultural activities¹⁷. Moreover, some options reported in the literature were not included because insufficient information was available on cost and effect. CH₄ emissions from manure management can be reduced by ensuring aerobic decomposition or controlling anaerobic digestion and collect the evolved CH₄ and use it as a fuel. The options that were included in our analyses are described below.

Propionate precursors

Propionate precursors can be introduced as a feed additive for livestock receiving concentrates to reduce CH₄ production within the rumen (Bates, 2001). They can be added to feed for animals that receive concentrates (i.e. cattle). This may reduce CH₄ emissions from enteric fermentation by up to 25% (dairy cattle) and 10% (non-dairy cattle) (Bates, 2001)¹⁸.

On the basis of a 80g per day supplement at a cost of EUR₁₉₉₀ 2010, total costs are estimated to be about EUR₁₉₉₀ 60 per animal per year (Bates, 2001).

Propionate precursors increase animal productivity. In our analyses, total agricultural production of milk and meat in each country was assumed constant. Consequently, an increase in animal productivity implies a reduction in the livestock population and, as a result, a reduction in emissions of CH₄, N₂O

¹⁷ These options will result in increased animal productivity, which is one of the causes of the projected decrease in animal numbers in Europe between 1990 and 2010.

¹⁸ Supplements are given to dairy cows year-round, but non-dairy cattle can only be fed with supplements when they are housed inside, which is assumed on average to be 40% of the year (Bates, 2001).

and NH_3 associated with manure produced by animals, assuming constant emissions per animal. These emissions may decrease by up to 5% (Bates, 2001).

Propionate precursors can only be given to animals receiving supplements. This typically only applies to cattle kept in herds greater than 100 heads. Percentages of cattle in herds larger than 100 heads in each EU country are provided by Bates (1998a). Estimates of herd sizes in non-EU countries were not available. We assumed that in these countries 10% of dairy cattle and 70% of non-dairy cattle is kept in herds greater than 100 heads, which are the averages of applicability in EU countries.

Probiotics

Probiotics are microbial feed additives that improve animal productivity for milk and growth (Bates, 2001) and hence can reduce CH_4 from ruminants (Mosier et al., 1998c). They are already widely used in the EU. A productivity gain of 7.5% may be obtained (Bates, 2001). Total production of milk and meat in each country was assumed constant in our analyses. Therefore, an increase in the production per animal implies that fewer animals are needed to satisfy the demand for agricultural products. As a result, the population of dairy cattle and associated CH_4 emissions may decrease by up to 7.5% (Bates, 2001). As with propionate precursors, probiotics are less applicable to non-dairy cattle¹⁹. CH_4 emissions from non-dairy cattle may be reduced by 3% (Bates, 2001).

On the basis of a 50g per day supplement at a cost of EUR₁₉₉₀ 1900, total costs are estimated to be about EUR₁₉₉₀ 35 per animal per year (Bates, 1998a).

A decrease in animal numbers can be expected to also reduce emissions of NH_3 and N_2O from cattle. Assuming constant emissions per animal, the reduction in these emissions was assumed to be linear with the productivity increase (i.e. 7.5% and 3% for dairy and non-dairy cattle respectively).

As for propionate precursors, probiotics are applicable only to cattle receiving feed additives. Probiotics are already widely available in the EU. Therefore, we assumed the applicability to be 50% of the applicability of propionate precursors as discussed above.

Daily spread of manure

CH_4 emissions from manure mainly occur during storage. Daily spread of manure reduces storage time and may therefore reduce emissions of CH_4 from manure management considerably (Bates, 1998a). This option concerns a direct removal of manure excreted by animals kept in liquid waste management systems from the animal houses and a daily application of the manure to the fields. We also assumed that the manure is incorporated into the soil in order to minimise the NH_3 emissions associated with manure application, while in the initial situation the manure is usually spread over the surface. Daily spread of manure may reduce CH_4 emissions from animal waste management systems by an estimated 90% because of a reduction in storage time (Bates, 1998a). Meanwhile, there are several side-effects on emissions of NH_3 and N_2O , as described below.

Costs are associated with increased labour requirements. Annual costs are about EUR₁₉₉₀ 75 (dairy cattle), EUR₁₉₉₀ 37.5 (non-dairy cattle) and EUR₁₉₉₀ 7.5 (pigs) per animal per year (Bates, 1998a).

N_2O emissions are affected in several ways when manure is not stored, but added to the field on a daily basis. Firstly, emissions from animal storage will be reduced. Daily spread of manure was, however, assumed applicable to liquid waste management systems only. Because these waste management systems have very low N_2O emissions, we assumed the effect on these N_2O emissions to

¹⁹ See footnote 18.

be negligible. Secondly, direct N₂O emissions from agricultural soils may increase because the manure is incorporated into the soils instead of spread over the surface. Consistent with the estimated effect of low NH₃ application techniques on N₂O emissions in Chapter 2, we assumed an 80% increase in direct N₂O emissions from agricultural soils due to application of the manure from the relevant sources. Finally, daily spread of manure implies that the manure is applied to agricultural soils throughout the year, including those periods when the fields are out of crop, or when crops do not need nutrients. In other words, the timing of manure application is not chosen on the basis of crop needs. If and to what extent direct N₂O increase as a result of this depends on factors such as manure application techniques, crop nitrogen needs, rainfall and time of the year (Mosier et al., 1998a). It is, however, likely that in these periods nitrogen leaching will increase, resulting in increased indirect N₂O emissions. We expected a substantial increase and therefore tentatively assumed that N₂O emissions induced by nitrogen leaching that is caused by the manure from the relevant sources increase by 80%.

Emissions of NH₃ are also affected in a number of ways. Firstly, there is an effect on emissions from storage. Because the storage of manure is minimised by daily spreading, this option is likely to have a considerable, possibly similar effect on NH₃ emissions during storage. To not overestimate this effect on NH₃, however, we assumed a 50% reduction in NH₃ emissions from animal housing concerned. Secondly, daily spread of manure may result in an increase in emissions of NH₃ during the application of manure because of the sub-optimal timing of manure application (as discussed above) and an increase in the nitrogen content of the manure that is applied as a result of reduced NH₃ volatilisation during the storage of manure (cf. Monteny and Erisman, 1998). This increase in NH₃ emissions is partly offset because we assumed that the daily spread is associated with low NH₃ application techniques. We assumed a 10% increase in NH₃ emissions from application of the manure when this option is applied.

In addition to the effects on N₂O and NH₃ emissions, daily spread of manure may have some other undesirable impacts, such as a risk of nitrogen run-off causing water pollution during times of high rainfall, damage to soil structure from large numbers of vehicle movements and increased eutrophication (Bates, 1998a, 2001). The applicability of this option may be limited because of existing policies for these harmful effects (Bates and Meeks, 1999). Moreover, in some regions (particularly in Western Europe) daily spread is common practice (IPCC, 1997). Therefore, we assumed this measure to be applicable to only 25% of cattle and pigs in liquid waste management systems in each country.

Anaerobic digestion of manure

Anaerobic digestion of manure results in CH₄ emissions (biogas), which can be recovered and used for energy purposes (Hendriks et al., 1998; Mosier et al., 1998c). This may reduce CH₄ emissions from manure that would otherwise be stored as liquid slurry by 50-75% in Europe (Bates, 2001). Because of different emission factors for CH₄ from manure management in countries with a cool climate and countries with a warmer climate (see also Chapter 2), higher reduction rates can be obtained in countries with a warm climate. Following Bates (2001), we distinguish between small-scale (located on a farm) and large-centralised anaerobic digestion plants, with different costs (Bates, 2001).

Cost estimates for anaerobic digestion plants are sensitive to assumptions about sales of heat or electricity and the digestate (i.e. the rest-product of the digestion process) (Bates and Meeks, 1999). Moreover, cost data available for plants in several countries show considerable variation (Bates, 2001). Costs for small scale plants were calculated on the basis of information for a Dutch plant, which was assumed to be representative of the types of plant that might be built in other countries, resulting in

EUR₁₉₉₀ 4.4 per ton manure processed (Bates, 2001). Costs for centralised plants were calculated on the basis of information for a plant in the United Kingdom, resulting in EUR₁₉₉₀ 0.7 per ton manure processed (Bates, 1998a).

If increased digestion of manure results in increased controlled anaerobic storage conditions, NH₃ and N₂O emissions from animal waste systems may decrease. This has, however, not yet been studied (Bates, 2001). Also, the net effect of using the digested manure as a fertiliser on emissions of N₂O and NH₃ from agricultural fields is unclear.

Anaerobic digestion can only be applied to manure from animals in liquid waste systems. Small scale plants are applicable only to farms with at least 50 cattle or 500 pigs. For EU countries, percentages of farms above this size are provided by Bates (2001). For non-EU countries, no information was available on the applicability of small scale anaerobic digestion plants. For these countries we used the average of the applicability rates for EU countries provided by Bates (2001). Moreover, following Bates (2001), we assumed that the maximum applicability in 2010 is 50% of the eventual applicability rates.

Centralised plants need sufficient supply of manure and other organic material from the surrounding area (Bates, 2001). Moreover, the surrounding land must have sufficient capacity to accept the nutrients in the digestate. Within the EU, centralised plants are only a viable option in Belgium, Denmark, the Netherlands and the United Kingdom, where the maximum applicability of centralised plants is assumed to be 50% of total anaerobic digestion plants (Bates, 2001). No information was available on applicability of centralised anaerobic digestion plants in non-EU countries. Given the limited applicability in the EU, we considered this option not applicable in European countries outside the EU.

5

Cost-effectiveness of interrelated emission reduction strategies in agriculture – results

This chapter is based on:

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Corjan Brink, Ekko van Ierland, Leen Hordijk, Carolien Kroeze. Cost-effectiveness of interrelated emission reduction strategies in agriculture. Submitted and revised for publication in *European Review of Agricultural Economics*.

Corjan Brink, Ekko van Ierland, Leen Hordijk, Carolien Kroeze. Cost-effective emission abatement in agriculture in the presence of interrelations: the case of the Netherlands and Europe. Accepted pending adequate revisions for publication in *Ecological Economics*.

Abstract

The model presented in Chapter 4 is used for an empirical analysis of interrelations in reducing NH₃, N₂O and CH₄ emissions from the agricultural sector in Europe. Emissions are calculated for 1990 and 2010. We compare scenarios for 2010 with different combinations of emission constraints for NH₃, N₂O and CH₄ from agriculture in 36 European countries. Cost-effective abatement strategies are identified for these scenarios considering side effects of abatement options. We analyse the impact of considering interrelations on abatement options selected, total abatement cost and allocation of emission reductions over various emission sources.

Keywords: Ammonia; Nitrous oxide; Methane; European agriculture; Emission abatement; Interrelations; Cost-effectiveness analysis

5.1 Introduction

The model described in Chapter 4 is applied to European agriculture. In the application we calculated emissions of NH_3 , N_2O and CH_4 from agricultural sources in Europe for 1990, as a base year, and for various scenarios for 2010. The scenarios assume different emission constraints for NH_3 , N_2O and CH_4 emissions from agriculture in the various European countries. Cost-effective abatement strategies are identified for these targets considering side effects of abatement options.

The aim of this chapter is to investigate the interrelations between emission reduction strategies for NH_3 , N_2O and CH_4 from European agriculture and their economic implications, and to analyse how side effects will affect cost-effective abatement strategies. In particular attention will be paid to the amount of emissions reduced, associated abatement costs and differences between countries. Moreover, cost-effective abatement strategies will be analysed with respect to the abatement options included and the allocation of abatement over different countries and sources of emissions.

First, in Sections 5.2 and 5.3 we analyse cost curves for abatement of NH_3 , N_2O and CH_4 under different assumptions. Cost curves reflect the relation between emission reduction levels and the costs of realising these reductions. As indicated in Section 4.3, with restrictions on several pollutants and interrelations between abatement of these pollutants, marginal costs for one pollutant also depend on restrictions on emissions of other pollutants. Therefore, a conventional, two-dimensional cost curve for reducing one pollutant can be determined only for specific cases that explicitly include assumptions about restrictions on emissions of other pollutants involved. In this chapter we will identify cost curves for various cases in order to analyse how abatement cost curves for one pollutant will depend on different restrictions on pollutants that are also affected.

Cost curves represent cost-effective (i.e. minimum cost) solutions for different levels of emission reductions. Cost curves are determined by solving the objective function of the model (i.e. minimise total abatement cost) for a series of increasing restrictions on emissions. For NH_3 , restrictions are on total emissions per country, whereas for N_2O and CH_4 (which are uniformly mixed in the atmosphere) restrictions are on total emissions from agriculture in Europe. N_2O and CH_4 emissions are added up by converting them to CO_2 equivalent emissions using the IPCC's global warming potentials for a time horizon of 100 years (310 for N_2O ; 21 for CH_4 ; IPCC, 1994). Section 5.2 presents cost curves for the abatement of NH_3 and for the combined reduction of N_2O and CH_4 emissions from agriculture in the Netherlands in 2010. Section 5.3 presents cost curves for a combined reduction of total N_2O and CH_4 emissions from agriculture in Europe in 2010, with various assumptions about the country-specific NH_3 emission constraints.

Section 5.4 zooms in on specific points of cost curves for Europe and identifies cost-effective abatement strategies for emission constraints for NH_3 , N_2O , CH_4 and combinations in various scenarios for 2010. First, we analyse the potential impacts of strategies in European agriculture to control emissions of one pollutant on emissions of other pollutants. Next, we identify abatement measures that are included in cost-effective strategies to simultaneously reduce emissions of NH_3 , N_2O and CH_4 from European agriculture at different levels. We analyse the impact of considering interrelations by comparing cost-effective abatement strategies that do not consider interrelations with strategies that do consider interrelations with respect to total abatement cost, total emissions reduced and the allocation of emission reductions over countries and sources.

Emission reduction measures that are included in the analysis were described in Section 2.3 (NH_3) and in Appendix 4.B (N_2O and CH_4). These sections also present the input data for the costs and

Table 5.1

Emission reduction measures and the range of their net effects on emissions of NH₃, N₂O and CH₄ from individual sources in European agriculture (% change in emissions from source to which applied)^a

| | NH ₃ (%) | N ₂ O (%) | CH ₄ (%) |
|---|---------------------|----------------------|---------------------|
| Low nitrogen feed ^b | -20 to -5 | -20 to -5 | 0 |
| Removing NH ₃ from ventilated air in animal housing ^b | -55 to -7 | 0 | 0 |
| Modifications of animal houses to prevent or reduce NH ₃ emissions ^b | -68 to -1 | 0 to 207 | -90 to 0 |
| Covered outdoor storage of manure ^b | -27 to 0 | -3 to +3 | 0 to 10 |
| Low NH ₃ application of manure ^b | -32 to 0 | 0 to 51 | 0 |
| Substituting urea fertiliser with ammonium nitrate ^b | -93 to -80 | -9 to -2 | 0 |
| End-of-pipe techniques to reduce NH ₃ emissions from fertiliser production ^b | -50 | -50 to 0 | 0 |
| Catalytic conversion of N ₂ O in nitric acid production processes (Oonk and Kroeze, 1998) | 0 | -24 to -23 | 0 |
| Substituting inorganic with organic nitrogen fertiliser (Bates, 1998b; Hendriks et al., 1998) | -15 | -15 | 0 |
| Restrictions on the timing of fertiliser application (Bates, 2001) | 0 to 10 | -6 to +9 | 1 to 20 |
| Fertiliser efficiency improvements (Bates, 2001) | -5 | -5 | 0 |
| Adjusting groundwater levels for grasslands (Velthof et al., 1998) | 0 | -4 to -1 | 0 |
| Restrictions on grazing (Velthof and Oenema, 1997; Oenema et al., 1998) | -15 to +42 | -6 to 0 | 1 to 26 |
| Propionate precursors (Bates, 2001) | -5 to 0 | -5 to 0 | -12 to 0 |
| Probiotics (Bates, 2001) | -2 to 0 | -2 to 0 | -2 to 0 |
| Daily spread of manure (Bates, 1998a) | -5 to +1 | 9 to 18 | -21 to -4 |
| Controlled anaerobic digestion of manure using produced CH ₄ for energy purposes (Bates, 2001) | 0 | 0 | -27 to -1 |

^a Measures are described in Section 2.3 and Appendix 4.B. Estimates for primary effects were based on the studies referred to. Side effects were estimated as described in Section 2.3 and Appendix 4.B. Ranges reflect differences between source categories and countries.

^b Options to reduce NH₃ emissions included in the RAINS model (Amann et al., 1998).

effects of these measures, including estimates of side effects on emissions of NH₃, N₂O and CH₄ (see Tables 4.4-4.6 for an overview). Table 5.1 indicates the range of net effects of measures included in the model on emissions of NH₃, N₂O and CH₄ from individual sources in European agriculture that are considered in the model. These net effects were calculated on the basis of information presented in Chapters 2 and 4.

Sections 5.2 and 5.3 present abatement cost curves for a number of different cases. Table 5.2 gives an overview of the cases that will be analysed.

5.2 Abatement cost curves for the agricultural sector 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 and on the

Table 5.2

Overview of cases for which abatement cost curves are analysed in Sections 5.2 and 5.3

| | pollutant(s) primarily reduced | additional restrictions |
|--|--|--|
| <i>Section 5.2: Abatement cost curves for agriculture in the Netherlands</i> | | |
| - Case a | NH ₃ | no |
| - Case b | NH ₃ | N ₂ O and CH ₄ may not exceed their initial level |
| - Case c | sum of N ₂ O and CH ₄ (CO ₂ -eq.) | no |
| - Case d | sum of N ₂ O and CH ₄ (CO ₂ -eq.) | Gothenburg Protocol target for NH ₃ , NH ₃ abatement strategy fixed |
| - Case e | sum of N ₂ O and CH ₄ (CO ₂ -eq.) | Gothenburg Protocol target for NH ₃ , NH ₃ abatement strategy free |
| <i>Section 5.3: Abatement cost curves for European agriculture</i> | | |
| - Case f | sum of N ₂ O and CH ₄ (CO ₂ -eq.) | no |
| - Case g | sum of N ₂ O and CH ₄ (CO ₂ -eq.) | Gothenburg Protocol targets for NH ₃ , NH ₃ abatement strategies fixed |
| - Case h | sum of N ₂ O and CH ₄ (CO ₂ -eq.) | Gothenburg Protocol targets for NH ₃ , NH ₃ abatement strategies free |

ranking of abatement options according to their cost-effectiveness within one country, we performed an optimisation analysis for increasing restrictions on emissions of NH_3 , N_2O and CH_4 from agriculture in the Netherlands for 2010. The Netherlands was chosen as an illustrative example, because this country has considerable emission reduction targets for NH_3 emissions according to international agreements and even more drastic reductions contained in the national policy targets. For a sequence of increasing emission reduction targets we calculated the minimum costs required to achieve these targets and identified the associated abatement strategies, given the costs and effects of abatement options presented in Chapters 2 and 4. This resulted in abatement cost curves, representing the relation between emission reduction levels and the costs of realising these reductions.

5.2.1 Cost curves for NH_3 abatement

Cost curves for NH_3 abatement in the Netherlands were determined as well as their effect on N_2O and CH_4 emissions. First, we calculated costs of reducing NH_3 emissions *without* constraints on N_2O and CH_4 emissions (case *a*). Second, we calculated costs of reducing NH_3 emissions *with* the additional constraint that emissions of N_2O and CH_4 from agriculture may not exceed their initial levels. Starting point for the cost curves is a hypothetical scenario in 2010 in which no technical NH_3 control measures are applied.

Case a: reducing NH_3 without restrictions on N_2O and CH_4

In case *a* NH_3 abatement resulted in increasing N_2O emissions and unaffected or decreasing CH_4 emissions (Fig. 5.1). N_2O and CH_4 emissions vary for different NH_3 abatement levels, because they depend on the specific NH_3 abatement options applied. Therefore, it is interesting to analyse which abatement techniques are responsible for the changes in N_2O and CH_4 emissions at various NH_3 abatement levels. The first 50 kilotons NH_3 can be abated at lowest costs by manure application techniques with low NH_3 emissions (e.g. manure injection), which cause an increase in N_2O emissions and do not affect CH_4 emissions. The relatively small reduction in N_2O emissions associated with 22

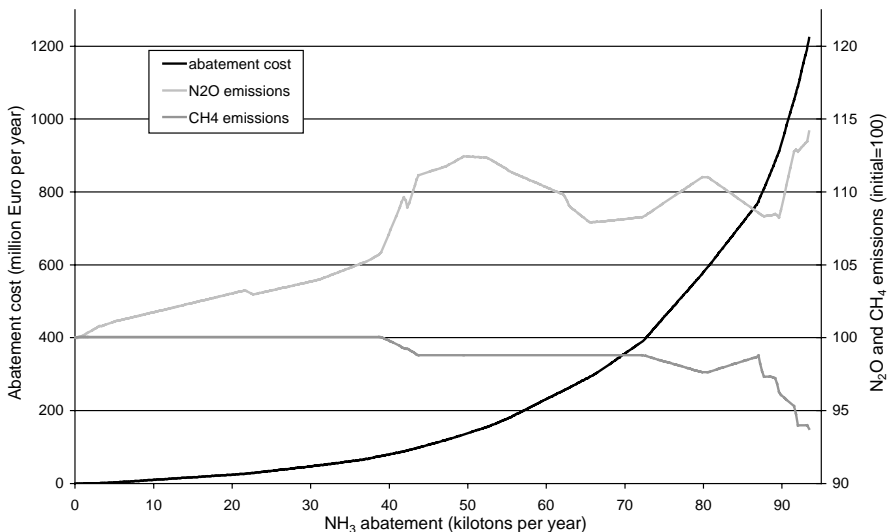


Fig. 5.1 Costs of NH_3 abatement and associated N_2O and CH_4 emissions (initial emissions = 100) in the agricultural sector in the Netherlands without a restriction on N_2O and CH_4 emissions (case *a*).

kilotons NH_3 abatement (Fig. 5.1) is caused by the introduction of low nitrogen feed for laying hens, which also has no effect on CH_4 . When reducing NH_3 emissions by 40–44 kilotons, N_2O emissions increase relatively quickly whereas CH_4 emissions decrease (Fig. 5.1) due to the introduction of adaptations to poultry housing. For NH_3 abatement of 53–66 kilotons, N_2O emissions decrease along with NH_3 emissions (Fig. 5.1) because of low nitrogen feed options. NH_3 abatement of 66–80 kilotons is obtained by adapting animal houses, causing an increase in N_2O emissions and a reduction in CH_4 emissions (Fig. 5.1). For NH_3 abatement of 80–88 kilotons, N_2O emissions decrease (Fig. 5.1) 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 NH_3 reduction potential and a smaller impact on N_2O emissions than housing adaptations. Consequently, N_2O emissions are reduced with respect to the emission level in an earlier stage of the cost curve. The decrease in CH_4 emissions at the end of the curve (Fig. 5.1) is caused by the introduction of propionate precursors and animal housing adaptations. Propionate precursors increase animal productivity and hence reduce emissions of NH_3 , N_2O and CH_4 simultaneously. Total N_2O emissions, however, increase in this stage of the cost curve (Fig. 5.1) because of the effects of animal housing adaptations and air cleaning techniques, which are also applied in this stage.

Case b: reducing NH_3 with restrictions on N_2O and CH_4

In case *b*, in addition to the NH_3 reduction targets of case *a*, both N_2O and CH_4 emissions may not exceed their initial levels. With the additional restriction in case *b*, total abatement costs are higher than in case *a* (Fig. 5.2). The difference in abatement costs between cases *a* and *b* is relatively small: < EUR 1 million per year for NH_3 abatement up to 40 kilotons, EUR 1-6 million for 40–90 kilotons NH_3 abatement, and increasing to EUR 35 million for higher NH_3 abatement levels (Fig. 5.2). Abatement costs are higher in case *b* than in case *a* because (i) N_2O abatement options with no effect on NH_3 are applied to cancel out increases in N_2O 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

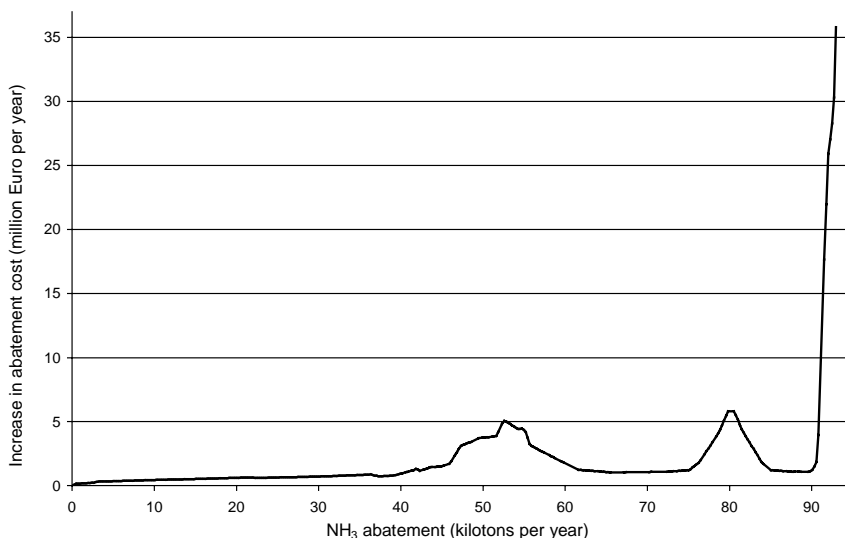


Fig. 5.2 Increase in total cost of reducing NH_3 , N_2O and CH_4 for various levels of NH_3 abatement with restricted N_2O and CH_4 emissions (case *b*) compared to total cost without a restriction on N_2O and CH_4 emissions (case *a*).

have a smaller impact on N_2O emissions. All three reasons were observed in analysing differences between case *a* and *b*, that is (i) application of catalytic reduction of N_2O in industrial production of nitric acid for fertiliser production, introduction of restrictions on timing of synthetic fertiliser application and adjusting groundwater levels for grasslands, (ii) early introduction of low nitrogen feed, cleaning air from animal houses, fertiliser efficiency improvements, end-of-pipe abatement techniques in fertiliser production and propionate precursors and (iii) covering outdoor storage of manure instead of applying animal house adaptations. These changes prevent N_2O and CH_4 emissions from exceeding their initial level at relatively low additional abatement costs.

5.2.2 Cost curves for N_2O and CH_4 abatement

Cost curves for reducing the sum of N_2O and CH_4 emissions (in CO_2 equivalents) from agriculture in the Netherlands were determined, as was their effect on NH_3 emissions. First, we calculated costs to reduce agricultural emissions of N_2O and CH_4 in the Netherlands *without* a restriction on NH_3 emissions (case *c*). Furthermore, we analysed the effect of a reduction target for NH_3 on costs to reduce agricultural emissions of N_2O and CH_4 in the Netherlands in two cases: with a predetermined abatement strategy for NH_3 (case *d*) and with a cost-effective strategy for NH_3 , N_2O and CH_4 abatement simultaneously (case *e*).

Case c: reducing N_2O and CH_4 without restrictions on NH_3

In case *c*, a reduction in N_2O emissions from agriculture in the Netherlands by up to 1500 kilotons CO_2 equivalents can be achieved very cost-effectively by catalytic reduction of N_2O in industrial production of nitric acid (Fig. 5.3). This technology reduces N_2O emissions and has no effects on NH_3 and CH_4 emissions (Fig. 5.3). For reductions of more than 1500 kilotons CO_2 equivalents, abatement options had to be applied that also affected emissions of NH_3 . For abatement levels from 1500-1700 kilotons CO_2 equivalents, NH_3 emissions are calculated to increase moderately as a result of introducing

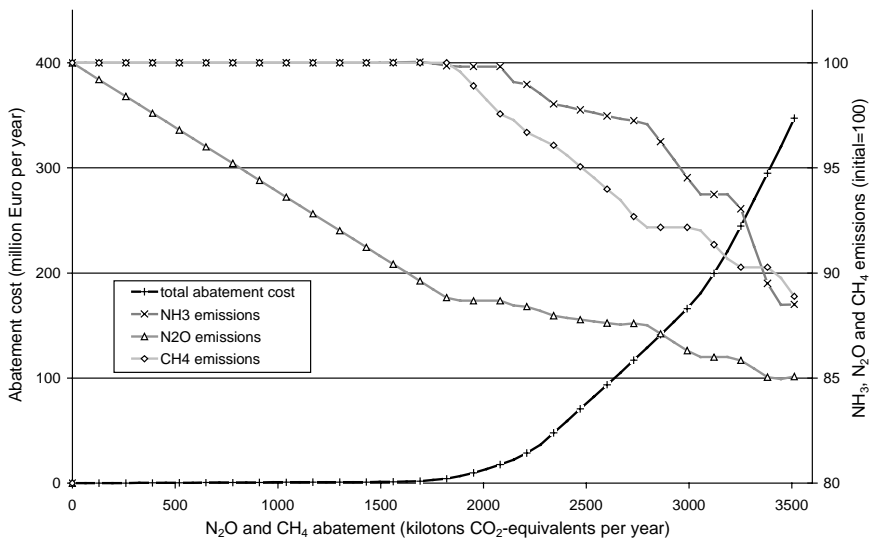


Fig. 5.3 Total cost of reducing the sum of N_2O and CH_4 emissions (CO_2 equivalents) from agriculture in the Netherlands and resulting emissions of NH_3 , N_2O and CH_4 (initial emissions = 100) without a restriction on NH_3 emissions (case *c*).

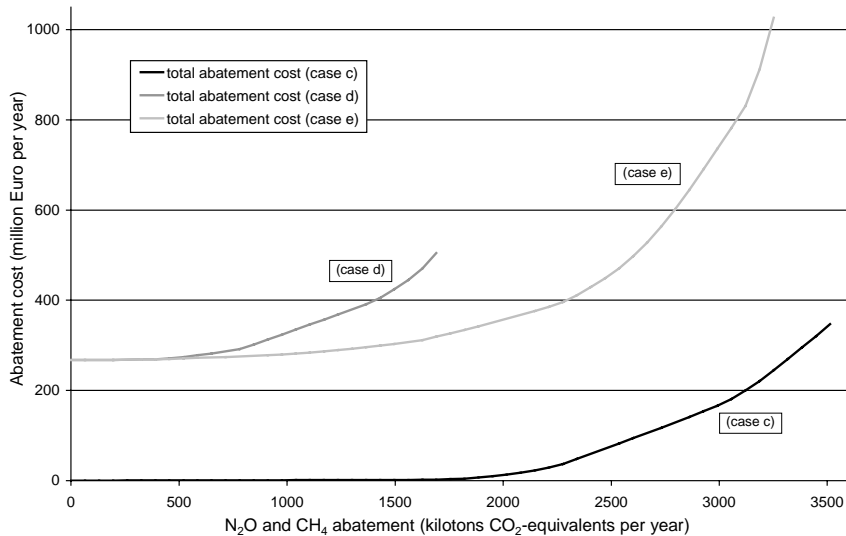


Fig. 5.4 Total cost of reducing NH_3 , N_2O and CH_4 if the sum of N_2O and CH_4 emissions (CO_2 equivalents) from agriculture in the Netherlands is reduced (i) without a restriction on NH_3 emissions (case c), (ii) with a reduction target for NH_3 emissions of 63 kilotons and a fixed NH_3 abatement strategy (case d) and (iii) with a reduction target for NH_3 emissions of 63 kilotons and the NH_3 abatement strategy free (case e).

restrictions on fertiliser timing (Fig. 5.3). Abatement levels beyond 1700 kilotons CO_2 equivalents are realised by N_2O and CH_4 control options that simultaneously reduce NH_3 emissions, resulting in a more than 10% reduction in NH_3 emissions for a reduction of N_2O and CH_4 emissions by 3500 kilotons CO_2 equivalents (Fig. 5.3).

Case d: reducing N_2O and CH_4 with a restriction on NH_3 – fixed NH_3 abatement strategy

In case d, we first determined a cost-effective abatement strategy for reducing NH_3 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, 1999a)) without restrictions on N_2O and CH_4 emissions (in the following, this NH_3 abatement strategy is referred to as the 'fixed NH_3 abatement strategy'). This NH_3 reduction level can be obtained at EUR 270 million (see Fig. 5.1). Subsequently, we analysed what additional abatement options have to be applied to cost-effectively reduce N_2O and CH_4 emissions at an increasing rate while maintaining the abatement options that are applied in the fixed NH_3 abatement strategy. The resulting cost curve starts from a cost level of about EUR 270 million (i.e. the costs for reducing NH_3 emissions by 63 kilotons, Fig. 5.1). Total and marginal costs of reducing N_2O and CH_4 emissions are higher, and the maximum level of N_2O and CH_4 abatement (about 1.7 megatons CO_2 equivalents) is lower in case d than in case c (Fig. 5.4). This is because not all abatement options that are available in case c can be applied in case d. Some measures for reducing N_2O and CH_4 emissions can not be applied together with NH_3 abatement options that are included in the fixed NH_3 abatement strategy¹. Moreover, reductions in NH_3 emissions due to abatement options for N_2O and CH_4 can not

¹ For instance, in our model we do not allow for applying low nitrogen feed together with feed additives to reduce CH_4 emissions (propionate precursors and probiotics, see Appendix 4.B) because it is not clear to what extent these measures can be applied together without affecting total production of milk and meat.

be used instead of measures reducing only NH₃ emissions that are in the fixed NH₃ abatement strategy. Thus, there is less flexibility in choosing abatement strategies to reduce N₂O and CH₄ emissions, resulting in higher abatement costs and a lower reduction potential.

Case e: reducing N₂O and CH₄ with a restriction on NH₃ – free NH₃ abatement strategy

In case *e*, we also determined cost-effective abatement strategies for N₂O and CH₄ with a reduction target for NH₃ emissions of 63 kilotons. Unlike case *d*, the NH₃ abatement strategy is not fixed in case *e*. For increasing N₂O and CH₄ reduction levels, abatement strategies were determined such that the emission reduction targets for NH₃ as well as N₂O and CH₄ were achieved at least costs. In case *e*, the abatement cost curve also starts from EUR 270 million and, like in case *d*, total and marginal abatement costs are higher and the maximum feasible reduction in N₂O and CH₄ emissions is lower than in case *c* (Fig. 5.4), because of the additional NH₃ reduction target. However, total and marginal costs of reducing N₂O and CH₄ emissions are lower, and the maximum level of N₂O and CH₄ reduction (about 3.3 megatons CO₂ equivalents) is higher in case *e* than in case *d* (Fig. 5.4). This is because changes can be made in abatement strategies with respect to the initial NH₃ abatement strategy, applying measures reducing NH₃ and N₂O or CH₄ together, instead of abatement options related only to reducing NH₃ emissions (and possibly even increasing N₂O or CH₄ emissions).

5.3 Abatement cost curves for the European agricultural sector

Cost curves for reducing agricultural emissions of N₂O and CH₄ were also analysed for Europe as a whole, including 36 countries. Again, cost curves were determined for reducing total agricultural N₂O and CH₄ emissions in Europe in three cases with different assumptions about NH₃ abatement taking place. First we calculated cost-effective abatement strategies for N₂O and CH₄ without a restriction on NH₃ emissions (case *f*). Furthermore, we analysed the effect of the commitments for NH₃ emission control in the year 2010 that are contained in the Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (the Gothenburg Protocol, UNECE, 1999a) on costs to reduce agricultural emissions of N₂O and CH₄ in Europe. We did this for two cases: with fixed abatement strategies for NH₃ in each country with a commitment to reduce its NH₃ emissions (case *g*) and with abatement strategies for NH₃, N₂O and CH₄ determined simultaneously (case *h*).

Case f: reducing N₂O and CH₄ without restrictions on NH₃

Calculations for case *f* indicate that by application of the abatement options included in the analysis and without restrictions on NH₃ emissions, emissions of N₂O and CH₄ from European agriculture can be reduced by 85 megatons CO₂ equivalents (i.e. almost 10% of initial emissions). Although NH₃ emissions are not restricted in any way, overall emissions of NH₃ in Europe decline together with N₂O and CH₄ emissions as a result of the abatement options applied. Abatement costs are relatively low for the first 35 megatons CO₂ equivalents of N₂O and CH₄ to be reduced (marginal abatement cost is less than EUR 20/ton CO₂ equivalents reduced), but quickly increase for further emission reductions (Fig. 5.5).

Case g: reducing N₂O and CH₄ with restrictions on NH₃ – fixed NH₃ abatement strategies

In case *g*, we determined first for each country a cost-effective strategy to reduce NH₃ emissions according to the emission targets as contained in the Gothenburg Protocol. Subsequently, we analysed what additional abatement options have to be applied to cost-effectively reduce N₂O and CH₄

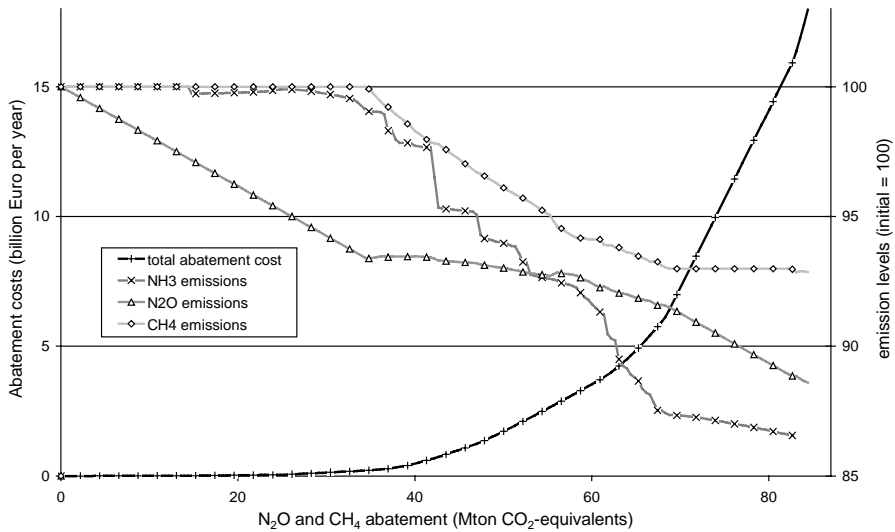


Fig. 5.5 Total cost of reducing the sum of N₂O and CH₄ emissions from agriculture in Europe (CO₂ equivalents) and resulting emissions of NH₃, N₂O and CH₄ (initial emissions = 100) without a restriction on NH₃ emissions (case *f*)

emissions at an increasing rate, while maintaining the abatement options applied in the abatement strategies for NH₃ determined first. Obviously, total abatement costs are substantially higher in case *g* than in case *f* because in addition to reducing N₂O and CH₄ emissions from agriculture, NH₃ emissions have to be reduced (Fig. 5.6). The difference in abatement costs between case *g* and *f* starts at EUR 1.6 billion and increases to EUR 8.6 billion. Moreover, the highest possible reduction of N₂O and CH₄ emissions is less in case *g* (73 megatons CO₂-eq.) than in case *f* (84 megatons CO₂ equivalents). This smaller reduction potential is because some abatement options applied in case *f* can not be applied in case *g* because they can not be combined with NH₃ abatement options that are in the fixed NH₃ abatement strategy.

Case h: reducing N₂O and CH₄ with restrictions on NH₃ – free NH₃ abatement strategies

In case *h*, for each CO₂ equivalent reduction level of N₂O and CH₄, abatement strategies were determined such that this reduction as well as the NH₃ reductions required for the Gothenburg Protocol were achieved at minimum cost. We calculated that for N₂O and CH₄ reduction levels of more than 30 megatons CO₂-eq. total abatement costs in case *h* are lower than in case *g* (with a difference of EUR 5.7 billion for a N₂O and CH₄ reduction of 73 megatons CO₂-eq.). Moreover, the highest possible reduction in N₂O and CH₄ emissions is higher in case *h* than in case *g* (83 megatons CO₂-eq.). This is because in case *h* it is possible to apply instead of NH₃ abatement options that as a side effect result in an increase in N₂O and CH₄ emissions, abatement options that have no or positive side effects. NH₃ reductions in case *g* to a large extent depend on modifications to animal houses and low NH₃ application techniques, which are both options that are estimated to cause a substantial increase in N₂O emissions (Brink et al., 2001a). In case *h* these abatement options are applied to a smaller extent, and instead more expensive options that have no side effects on N₂O and CH₄, like removing NH₃ from ventilated air, are applied.

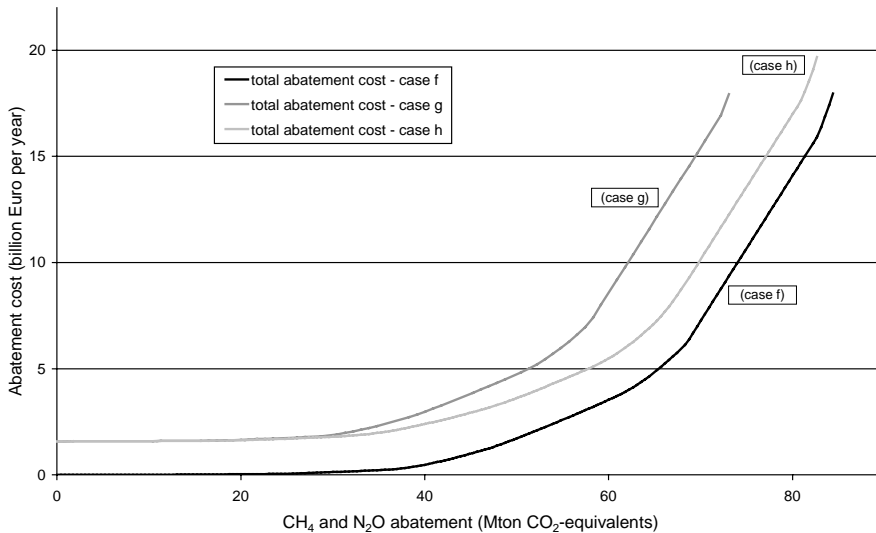


Fig. 5.6 Total cost of reducing NH_3 , N_2O and CH_4 if the sum of N_2O and CH_4 emissions (CO_2 equivalents) from agriculture in Europe are reduced (i) without a restriction on NH_3 emissions (case f), (ii) with fixed abatement strategies to meet emission targets for NH_3 contained in the Gothenburg Protocol (case g) and (iii) with simultaneously determined abatement strategies to meet the emission targets for NH_3 contained in the Gothenburg Protocol and reductions in N_2O and CH_4 emissions from agriculture in Europe (case h)

5.4 Emission reduction scenarios for the European agricultural sector

5.4.1 Scenarios

Emissions of NH_3 , N_2O and CH_4 from European agriculture were estimated for 1990 (no abatement assumed) and for various scenarios in 2010. These scenarios are all based on the same projections for agricultural activities, but differ with respect to restrictions for emissions of NH_3 , N_2O and CH_4 . In this section we present results for two sets of scenarios. As a reference scenario for both sets, we included a scenario without restrictions on emissions in 2010. The first set consists of scenarios assuming current targets for NH_3 , a reduction target for total European emissions of N_2O and CH_4 added up and combinations of these targets. These scenarios were selected to illustrate the potential cost savings that can be obtained at the European level if interrelations are considered. The second set of scenarios assumes more restrictive reduction targets for NH_3 , N_2O and CH_4 . These scenarios were selected to investigate interrelations with more drastic emission reductions, resulting in more distinct changes in emissions. Table 5.3 gives an overview of the various scenarios presented in this section.

- 1) The no control scenario (NOC) assumes that in 2010 no technical measures to reduce emissions from agriculture would be applied in any European country. This is a hypothetical scenario, because it also excludes measures that have to be taken in the future according to adopted national and international legislation for emission control. The only reductions in emissions in 2010 with respect to 1990 result from expected reductions in livestock population and fertiliser consumption in Europe between 1990 and 2010. Differences between emissions in the NOC scenario and in other scenarios can entirely be attributed to the impact of abatement options that are applied in the other scenarios.

Table 5.3

Overview of scenarios with different restrictions on emissions of NH₃, N₂O and CH₄ from European agriculture in 2010.

| Scenario | Restrictions on emissions | Additional characteristics |
|------------|---|--|
| 1 NOC | no restrictions | none |
| 2 GOT | restrictions on NH ₃ emissions in each country as contained in the Gothenburg Protocol | minimising total abatement cost in Europe |
| 3 NMR | 7.5% reduction in total CO ₂ equivalent emissions of N ₂ O and CH ₄ from European agriculture compared with NOC | minimising total abatement cost in Europe |
| 4 GOT&NMR1 | restrictions on NH ₃ emissions in each country as in GOT; reduction target for total emissions of N ₂ O and CH ₄ from European agriculture as in NMR | minimising total abatement cost in Europe |
| 5 GOT&NMR2 | restrictions on NH ₃ emissions in each country as in GOT; reduction target for total emissions of N ₂ O and CH ₄ from European agriculture as in NMR | minimising total abatement cost in Europe given the abatement strategies for NH ₃ in each country determined in GOT |
| 6 ENV | reductions in NH ₃ emissions according to the 'medium ambition level' scenario to reduce acidification and eutrophication (Amann et al., 1999b p.25) | minimising total abatement cost in Europe |
| 7 MFR | highest possible reduction in NH ₃ emissions by technical measures included in the model | maximising reduction in total NH ₃ emissions in Europe |
| 8 NOM | N ₂ O mitigation by the most effective abatement measures for this gas (12.7% reduction compared to NOC) | maximising reduction in total N ₂ O emissions from agriculture in Europe |
| 9 CHM | CH ₄ mitigation by the most effective abatement measures for this gas (9.6% reduction compared to NOC) | maximising reduction in total CH ₄ emissions from agriculture in Europe |

- 2) The Gothenburg Protocol scenario (GOT) reflects country-specific reduction targets for NH₃ for 2010 as contained in that agreement (UNECE, 1999a). It is assumed that the required NH₃ reductions are realised at minimum total abatement costs in each country.
- 3) The Nitrous oxide and Methane Reduction scenario (NMR) assumed a tentative 7.5% reduction in total N₂O and CH₄ emissions from European agriculture in 2010 compared with emission levels in the NOC scenario². Unlike NH₃ emissions, which have local and regional effects, N₂O and CH₄ emissions are uniformly mixed in the atmosphere and hence have a global effect. This implies that the location of emissions does not matter for their contribution to the greenhouse effect. Therefore, in our analysis an emission reduction target for N₂O and CH₄ is specified for Europe as a whole. Emission reductions are allocated over the various countries on the basis of cost-effectiveness.
- 4) The GOT&NMR1 scenario combines the restrictions on NH₃ emissions (GOT) and the reduction target for N₂O and CH₄ from agriculture (NMR). In this scenario, cost-effective strategies for reducing emissions of the three gases are determined simultaneously (i.e. applying abatement options that simultaneously yield the required emission reductions for NH₃, N₂O and CH₄ at least cost).
- 5) The GOT&NMR2 scenario also combines the restrictions on NH₃ emissions (GOT) and the reduction target for N₂O and CH₄ from agriculture (NMR). In this scenario, the application rates for abatement measures reducing NH₃ emissions in the GOT scenario are set fixed. Subsequently, it is determined what abatement options are required additionally to meet the reduction targets for all three gases. The GOT&NMR2 scenario indicates the effect of first establishing policies for NH₃ abatement

² As indicated earlier, N₂O and CH₄ emissions can be added up using weighting factors reflecting their relative contribution to the greenhouse effect (IPCC, 1994). In this analysis, emissions were converted to CO₂ equivalent emissions using global warming potentials for a 100-years time-horizon of 310 (N₂O) and 21 (CH₄).

without considering effects on emissions of N_2O and CH_4 , and afterwards determining optimal policies for N_2O and CH_4 from agriculture.

- 6) The environmental targets scenario (ENV) includes a control strategy for NH_3 that is based on calculations for the 'medium ambition level' scenario described by Amann et al. (1999b 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 NH_3 in each country (Amann et al., 1999b p.27). Thus, the scenario shows the effect of NH_3 reductions needed in European countries to achieve certain realistic targets for acid deposition in 2010 on agricultural emissions of N_2O and CH_4 . For each country a cost-effective abatement strategy was determined to achieve the required reduction.
- 7) The maximum feasible NH_3 reduction scenario (MFR) assumes the highest possible reduction of NH_3 emissions in Europe by technical abatement measures as included in the RAINS model (see also Table 4.4), irrespective of the costs.
- 8) The N_2O mitigation scenario (NOM) assumes the highest possible reduction of N_2O emissions from European agriculture by the measures included in this analysis (Table 4.5), resulting in a reduction by 12.7% compared with emissions in 2010 without control (NOC).
- 9) The CH_4 mitigation scenario (CHM) assumes the highest possible reduction of CH_4 emissions from European agriculture by the measures included in this analysis (Table 4.6), resulting in a reduction by 9.6% compared with emissions in 2010 without emission control (NOC).

For each of these scenarios we applied the model described in Chapter 4 to calculate emissions of NH_3 , N_2O and CH_4 for 36 European countries given the restrictions and objectives (i.e. minimising total abatement costs or maximising emission reductions). As indicated, Appendix I presents a specification of the model in the GAMS programming language.

5.4.2 Results for GOT, NMR, GOT&NMR1 and GOT&NMR2

Table 5.4 presents emissions and abatement costs estimated for 1990 and the scenarios for 2010. Due to (exogenous) changes in agricultural activity levels between 1990 and 2010, even without abatement options applied (NOC) emissions of all three gases were below their 1990 levels. NH_3 abatement only (GOT) caused an increase in N_2O emissions (1.4% compared with NOC) as a result of abatement

Table 5.4

Estimated NH_3 , N_2O and CH_4 emissions from European agriculture (million tons per year; in brackets percentage of NOC emissions), total abatement cost (billion EUR₁₉₉₀ per year) and marginal abatement cost for N_2O and CH_4 (1,000 EUR₁₉₉₀ per ton CO_2 equivalents), for 1990 and scenarios in 2010

| Scenario | NH_3 emissions (10^6 ton NH_3) | | N_2O emissions (10^6 ton N_2O) | | CH_4 emissions (10^6 ton CH_4) | | Total abatement cost (10^9 Euro) | Marginal abatement cost N_2O & CH_4 ^a (10^3 Euro/ton CO_2 -eq.) |
|----------|---|--------|---|--------|---|--------|---|---|
| 1990 | 7.6 | (112%) | 1.9 | (113%) | 19.4 | (117%) | 0 | not applicable |
| NOC | 6.7 | (100%) | 1.7 | (100%) | 16.6 | (100%) | 0 | not applicable |
| GOT | 6.2 | (93%) | 1.7 | (101%) | 16.5 | (100%) | 2 | not applicable |
| NMR | 6.0 | (89%) | 1.5 | (92%) | 15.5 | (93%) | 5 | 0.36 |
| GOT&NMR1 | 5.7 | (85%) | 1.5 | (92%) | 15.5 | (93%) | 7 | 0.43 |
| GOT&NMR2 | 5.6 | (84%) | 1.6 | (92%) | 15.4 | (93%) | 12 | 0.68 |

^a Emission reduction targets for NH_3 as contained in the Gothenburg Protocol and as a result, marginal abatement costs for NH_3 differ substantially between the various countries. Therefore, marginal abatement costs for NH_3 were not presented in the table.

Table 5.5

Calculated change in emissions of N₂O and CH₄ relative to emissions in the NOC scenario as a result of NH₃ abatement in the GOT scenario for European countries in 2010 (kilotons NH₃ or CO₂ equivalents per year; percentages represent changes relative to emissions in the NOC scenario)

| Countries ^a | Change in NH ₃ (1,000 ton NH ₃) | | Change in N ₂ O + CH ₄ ^b (1,000 ton CO ₂ -eq.) | |
|------------------------|---|--------|---|-------|
| Austria | -1 | (-1%) | 17 | (0%) |
| Belarus | -5 | (-3%) | -18 | (-0%) |
| Belgium | -22 | (-23%) | 952 | (8%) |
| Bulgaria | -18 | (-14%) | -26 | (-0%) |
| Croatia | -7 | (-19%) | -28 | (-1%) |
| Czech Republic | -7 | (-6%) | 337 | (2%) |
| Denmark | -3 | (-4%) | 63 | (1%) |
| Finland | -0 | (-0%) | -0 | (-0%) |
| Germany | -21 | (-4%) | 1 | (0%) |
| Greece | -1 | (-1%) | -2 | (-0%) |
| Hungary | -47 | (-34%) | 480 | (3%) |
| Ireland | -14 | (-11%) | 358 | (2%) |
| Italy | -13 | (-3%) | 508 | (1%) |
| Luxembourg | -2 | (-18%) | 39 | (4%) |
| Netherlands | -63 | (-33%) | 1333 | (5%) |
| Poland | -73 | (-14%) | -13 | (-0%) |
| Republic of Moldova | -6 | (-12%) | -22 | (-0%) |
| Romania | -94 | (-31%) | 2214 | (5%) |
| Slovak Republic | -8 | (-17%) | 22 | (0%) |
| Slovenia | -1 | (-3%) | -1 | (-0%) |
| Spain | -30 | (-8%) | -215 | (-0%) |
| Sweden | -4 | (-7%) | 117 | (1%) |
| Switzerland | -3 | (-5%) | 87 | (2%) |
| Ukraine | -57 | (-9%) | 154 | (0%) |
| United Kingdom | -0 | (-0%) | -2 | (-0%) |
| Europe total | -498 | (-7%) | 6354 | (1%) |

^a Countries where emissions of all three pollutants do not change in the GOT scenario with respect to the NOC scenario are not included.

^b N₂O and CH₄ from agriculture are added converting them to CO₂ equivalents using global warming potentials of 310 (N₂O) and 21 (CH₄).

options such as manure injection and animal housing adaptations (Table 4.4). CH₄ emissions were estimated to decrease a little (0.2% compared with NOC). Effects differed between countries. Increases in emissions of N₂O and CH₄ mainly occurred in countries that had to reduce their NH₃ emissions considerably, but there is no definite relationship between the level of NH₃ abatement and effects on N₂O and CH₄ emissions. Reductions in NH₃ emissions may cause a decrease (e.g. Croatia) as well as an increase (e.g. Luxembourg) in emissions of N₂O and CH₄ (Table 5.5). Differences were due to different abatement options applied in the various countries.

Abatement strategies to reduce N₂O and CH₄ emissions (NMR) caused in all countries a reduction in NH₃ emissions compared with NOC (11% reduction in total European emissions; Table 5.4). Total NH₃ emissions in Europe in NMR were also below emissions in GOT (4%), but in some countries the reduction in NH₃ emissions was not sufficient to meet the Gothenburg Protocol reduction targets.

In the latter countries the constraints on NH₃ emissions in GOT&NMR1 are binding and additional abatement is required compared with NMR. The marginal cost of N₂O and CH₄ abatement changes because of the effect of NH₃ abatement on these emissions. As a result, the cost-effective allocation of abatement over all countries changes. Marginal cost of N₂O and CH₄ abatement is the same in all

countries because the emission constraint is on the sum of these emissions over all countries. While in NMR marginal abatement cost for N₂O and CH₄ is EUR 360 per ton CO₂ equivalents, in GOT&NMR1 it is 20% higher, at EUR 430 per ton CO₂ equivalents. Total abatement costs in GOT&NMR1 were almost 50% higher than in NMR.

Although differences between total European emissions estimated for GOT&NMR2 and GOT&NMR1 were small, optimal abatement strategies (and as a consequence emission levels and abatement costs) in GOT&NMR2 differed from those in GOT&NMR1 for most countries. Marginal cost of N₂O and CH₄ abatement in the GOT&NMR2 scenario (i.e. first NH₃ emissions were reduced and subsequently N₂O and CH₄ emissions) is 60% higher than in GOT&NMR1 (i.e. NH₃, N₂O and CH₄ emissions were reduced simultaneously), viz. EUR 680 per ton. Total annual abatement costs in GOT&NMR2 are EUR 5 billion higher than in GOT&NMR1. This indicates that considerable cost savings can be obtained if policies for abatement of NH₃, N₂O and CH₄ in European agriculture are based on integrated analyses instead of determined separately from each other.

Marginal cost of N₂O and CH₄ abatement in the scenarios NMR, GOT&NMR1 and GOT&NMR2 are quite sensitive for the emission reduction target. For a less stringent reduction target for N₂O and CH₄ emissions (6.5% instead of 7.5%), the marginal cost would decrease to EUR 190 (NMR and GOT&NMR1) and EUR 384 (GOT&NMR2) per ton CO₂ equivalents. For a more stringent reduction target for N₂O and CH₄ emissions (8.5% instead of 7.5%), the marginal cost would increase to EUR 680 (NMR and GOT&NMR1) and EUR 19,850 (GOT&NMR2) per ton CO₂ equivalents.

Several studies have produced a wide range of numbers for the marginal cost of reducing greenhouse gas emissions, which is obviously very much dependent on reduction targets, timing, possibility of internationally trading emission credits and countries participating. The numbers for the marginal abatement cost found in the various scenarios in this study are high compared to those reported in other studies for the EU and the US (e.g. McCarl and Schneider, 2000; Syri et al., 2001), even for the scenario without NH₃ abatement (NMR). These studies, however, include several sectors, whereas the present analysis is limited to agriculture. Moreover, the emission reduction targets for N₂O and CH₄ from agriculture (a 6.5%–8.5% reduction compared to the uncontrolled emission level in the

Table 5.6
Application of abatement options over all sources of emissions in scenarios as a percentage of maximum application potential

| | GOT | NMR | GOT&NMR1 | GOT&NMR2 |
|---|-----|-----|----------|----------|
| Low nitrogen feed | 12% | 65% | 91% | 94% |
| Cleaning air from animal housing | 1% | – | 6% | 1% |
| Animal housing adaptations | 15% | – | 1% | 15% |
| Covered outdoor storage of manure | 12% | – | 9% | 12% |
| Low NH ₃ application manure | 9% | – | 4% | 9% |
| Substitution of urea by ammonium nitrate | 48% | 89% | 95% | 95% |
| End-of-pipe options in fertiliser plants | 12% | – | 14% | 12% |
| Catalytic conversion N ₂ O in nitric acid production | – | 78% | 78% | 78% |
| Substituting inorganic by organic N fertiliser | – | – | – | 23% |
| Restrictions on timing of fertiliser application | – | 25% | 25% | 25% |
| Fertiliser efficiency improvement | 20% | 96% | 96% | 96% |
| Groundwater level adjustments grassland | – | 98% | 98% | 98% |
| Restrictions on grazing | 0% | 0% | 0% | 9% |
| Propionate precursors | – | 98% | 98% | 97% |
| Probiotics | 1% | – | 0% | 1% |
| Daily spread of manure | – | 35% | 35% | 32% |
| Anaerobic digestion of manure | – | 32% | 57% | 64% |

Table 5.7

Estimated emissions from European agriculture (million tons NH₃, N₂O and CH₄ per year; in brackets emissions as a percentage of emissions in NOC scenario) and total abatement cost (billion EUR₁₉₉₀/year) for several scenarios in 2010^a

| Scenario | NH ₃ emissions (10 ⁶ ton NH ₃) | | N ₂ O emissions (10 ⁶ ton N ₂ O) | | CH ₄ emissions (10 ⁶ ton CH ₄) | | Total abatement cost (10 ⁹ Euro) |
|----------|---|--------|--|--------|---|--------|--|
| 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 NH₃ abatement (ENV and MFR), a scenario assuming abatement of N₂O (NOM) and a scenario assuming abatement of CH₄ (CHM).

same year) are drastic and associated with the steeper part of the abatement cost curve for these gases.

The bottom-up approach allows for an analysis of the specific abatement measures applied in the various scenarios (Table 5.6). Low nitrogen feed was applied less frequently in the GOT scenario than in the other scenarios. This technology was included as an abatement technology for NH₃, but it proved to be also very cost-effective in reducing N₂O emissions. Adaptations to animal housing, covering manure storage and low NH₃ application of manure were applied less frequently in GOT&NMR1 than in GOT, because of the increase in N₂O emissions they cause. These control options are, however, effective in reducing NH₃ emissions and were needed to meet the required reductions in emissions of this pollutant in some countries.

The results indicate that policies that do not consider interactions with other areas of environmental policies may be inefficient. The implications of the results for policies for acidification and greenhouse gas mitigation in European agriculture are elaborated in Section 5.5.

5.4.3 Results for ENV, MFR, NOM and CHM

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 5.7³. Comparing emissions in scenarios focusing on NH₃ abatement (ENV and MFR) with emissions in the NOC scenario reveals that NH₃ abatement in Europe may as a side effect increase agricultural N₂O emissions in Europe. In the MFR scenario, with the highest NH₃ abatement in each country, total N₂O emissions from European agriculture were more than 9% higher than in the NOC scenario. Agricultural emissions of CH₄ decreased by 0.4% (ENV) and 5.4% (MFR) compared with NOC emissions. Furthermore, abatement of N₂O (NOM) in European agriculture was calculated to reduce NH₃ emissions by 8%, whereas calculated CH₄ emissions are almost 4% higher than the NOC emissions. Abatement of CH₄ (CHM) was calculated to reduce NH₃ emissions by more than 6%, whereas calculated N₂O emissions are almost 6% higher than the NOC emissions.

³ 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.

5.5 Discussion and conclusions

In Europe, agriculture is 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. Emissions are associated with livestock farming, fertiliser use and fertiliser 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 a number of control options primarily aimed at NH_3 , N_2O or CH_4 the effects on emissions of all three gases.

The model presented in Chapter 4 was used to analyse interrelations between efforts to reduce emissions of NH_3 , N_2O and CH_4 from agriculture in Europe. The aim of the chapter was to investigate the extent of interrelations between emission reduction strategies for NH_3 , N_2O and CH_4 from European agriculture and to analyse how side effects will affect cost-effective abatement strategies.

First, we analysed abatement cost curves for NH_3 , N_2O and CH_4 under different assumptions to investigate how, in the presence of interrelations, cost curves for one pollutant depend on restrictions on emissions of other pollutants that are affected. Furthermore, we identified cost-effective abatement strategies for various specific emission reduction targets for NH_3 , N_2O , CH_4 and for combinations of these pollutants.

The results of an analysis of abatement cost curves for agriculture in the Netherlands indicated that, for the largest part of the NH_3 reduction potential, the cost of reducing NH_3 was not more than EUR 6 million higher in case N_2O and CH_4 emissions were not allowed to increase than in case effects on these emissions were not considered. Costs to maintain greenhouse gas emissions at their initial level were small because relatively inexpensive control options are available to reduce N_2O emissions. We also found that abatement of N_2O and CH_4 emissions from agriculture in the Netherlands was more expensive if there was also a reduction target for NH_3 emissions, in particular if the cost-effective strategy for NH_3 reduction was determined first and subsequently cost-effective strategies to reduce N_2O and CH_4 emissions were determined.

Calculations for Europe as a whole indicate that reductions in emissions of N_2O and CH_4 from agriculture together with the reductions in NH_3 emissions as agreed in the Gothenburg Protocol can be obtained at much lower costs when interrelations with N_2O and CH_4 mitigation are considered than when NH_3 abatement strategies are determined first and subsequently N_2O and CH_4 emissions are reduced. When the agricultural sector has to reduce both emissions of greenhouse gases (N_2O and CH_4) and NH_3 , control options that are cost-effective in reducing NH_3 emissions, but cause an increase in N_2O emissions, such as livestock housing adaptations and manure injection techniques, become less attractive. Instead, abatement options without adverse side effects or with beneficial side effects will be applied. Interrelations not only exist in agriculture, but also in other sectors. Considering these interrelations may reduce total costs of environmental policies substantially.

Calculations with the model to identify cost-effective abatement strategies for country-specific reduction targets for NH_3 emissions from European agriculture in 2010 show that cost-effective abatement of NH_3 according to the Gothenburg protocol may cause an increase in emissions of N_2O by about 7 megatons CO_2 equivalents (a 1.4% increase compared with emissions without control). This increase was for the most part the result of adaptations to animal housing and low NH_3 application of manure. These control options are cost-effective in reducing NH_3 emissions, but are assumed to cause an increase emissions of N_2O . Total CH_4 emissions in Europe were calculated to decrease due to NH_3

abatement by about 0.8 megatons CO₂ equivalents (0.2% compared with emissions without control). Differences in effects were observed between countries as a result of different levels of NH₃ abatement and different abatement options applied.

Abatement of N₂O and CH₄ emissions from agriculture caused a reduction in NH₃ emissions in Europe. In some countries NH₃ emissions were reduced sufficiently to meet the targets of the Gothenburg protocol. In other countries additional abatement options were required to simultaneously meet the restrictions on NH₃, N₂O and CH₄. Total abatement cost for Europe to simultaneously achieve reduction targets for the three gases were about EUR 5 billion higher if first cost-effective strategies for NH₃ abatement were established and subsequently emissions of N₂O and CH₄ were reduced, than if cost-effective abatement strategies for the three gases were simultaneously determined. The cost-effective allocation of abatement over all countries and over different sources within a country changed as a result of considering interrelations.

Emissions in 2010 were also calculated for scenarios with more drastic reduction targets for NH₃, N₂O and CH₄. We calculated that country-specific targets for NH₃, yielding a total reduction in NH₃ emissions in Europe of 14%, may have an impact on agricultural emissions of N₂O (3% increase) and CH₄ (0.5% reduction). Reducing NH₃ emissions in Europe as much as possible by the technical control measures that were included in the analysis yields a 38% reduction in total NH₃ emissions. For this scenario we calculated a larger impact on agricultural emissions of N₂O (9% increase) and CH₄ (5% reduction). Abatement of N₂O emissions from agriculture by 13% simultaneously reduced NH₃ emissions (7%), but increased CH₄ emissions from agriculture (4%). Abatement of CH₄ emissions from agriculture by 9% simultaneously reduced NH₃ emissions (6%) but increased N₂O emissions from agriculture (6%).

The results presented in this chapter illustrate the importance of explicitly considering side effects of abatement activities in environmental policy-making in the agricultural sector. Despite many interrelations between policies for acidification and policies for climate change, however, up to now policymakers in Europe have dealt with these two environmental problems separately. Agriculture's important role in these environmental problems, mainly through the emissions of NH₃, N₂O and CH₄, has been known for years. In European policy, this did, however, not yet result in specific reduction targets for N₂O and CH₄ emissions from agriculture, although the potential contribution of the agricultural sector in implementing the greenhouse gas emission reduction target set by the Kyoto Protocol is recognised by many countries. An international agreement about reducing NH₃ emissions has been established in the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, that was signed in 1999 (UNECE, 1999a). The Gothenburg Protocol has been ratified by not more than two countries and did not yet come into force. Only a few countries in Europe (including the Netherlands and Denmark) have addressed the NH₃ emission problem through specific legislation targeting NH₃ emissions. In the Netherlands, currently the emphasis in the NH₃ policy is on low-emission manure application techniques, low-emission livestock housing systems and covering stored manure. Moreover, NH₃ emissions decrease as a result of nitrogen loss standards associated with the mineral accounting system (MINAS). In other countries, legislation resulting in NH₃ reductions is mainly driven by the European Community's Directive on Nitrates and the IPPC (Integrated Pollution Prevention and Control) Directive as well as by good agricultural practice advises. Besides emission targets for NH₃, the Gothenburg Protocol also contains a series of mandatory control measures that the parties shall employ for the control of NH₃ emissions from agricultural sources, including manure application techniques, manure storage techniques and livestock housing systems with low NH₃

emissions (UNECE, 2001). The results in our study indicate that an emphasis on these control options may have a substantial impact on emissions of N_2O and CH_4 from agriculture.

Our results indicate the importance of countries being aware of possible side effects of control measures when developing policies towards compliance with the Gothenburg Protocol. Given the efforts European countries have to make to meet the greenhouse gas emission targets set by the Kyoto Protocol, it is recommended on the basis of this study to put less emphasis on NH_3 control measures that result in an increase in N_2O and CH_4 emissions, such as low-emission housing systems and low-emission application techniques. Our study indicates that, if reduction targets exist not only for NH_3 but also for N_2O and CH_4 emissions, substantial cost savings can be obtained when in the policy-making process interrelations between NH_3 abatement and greenhouse gas emissions are considered. Although low-emission animal housing systems and low-emission application techniques will still be required to meet the NH_3 reduction targets in some countries, the emphasis in the NH_3 policies will then shift to measures that simultaneously reduce NH_3 and N_2O or CH_4 emissions, such as reducing the nitrogen content in livestock feed and increasing the efficiency of synthetic fertilisers and animal manure used as a fertiliser.

It should be noted that these results may not only be valid for the agricultural sector and air pollution and climate change policies. This kind of interrelations may also occur in other sectors and between other environmental problems.

6

An extension of the model and its application for geographically specific deposition targets

Prologue

This chapter presents an extension of the model described in Chapter 4 to include (i) atmospheric transport of pollutants from the source to the location where the environmental impact occurs and (ii) restrictions on indicators for environmental impacts rather than emissions. This chapter has been published in *TheScientificWorld* (Brink et al., 2001c) and contains the complete text of this article. First, it briefly repeats the model that was presented in Chapter 4. Next, it presents the extension of this model. Finally, the extended model is used to analyse cost-effective strategies for the reduction of acidification and eutrophication, caused by emissions of SO₂, NO_x and NH₃, and reductions in emissions of N₂O and CH₄ from agricultural sources in Europe.

Atmospheric transport of emissions is included in the model by a source-receptor matrix. This source-receptor matrix makes it possible to analyse nitrogen and sulphur deposition (contributing to acidification and eutrophication) at various locations in Europe as a result of emissions of SO₂, NO_x and NH₃ in various countries. The geographical specificity is important for acidification and eutrophication, because the environmental damage due to nitrogen and sulphur deposition depends on characteristics of the ecosystems they fall into. With the extended model it is possible to specify targets for nitrogen and sulphur deposition for grid cells of 150 × 150 km in Europe that are based on specific characteristics of ecosystems within these grids.

Because it makes no sense to apply an effect-based approach regarding acidification and eutrophication considering NH₃ only, we included in our model SO₂ and NO_x emissions and control options for these pollutants, that were taken from the RAINS model. Interrelations were only considered for reducing NH₃, N₂O and CH₄ emissions from agricultural sources. The model is implemented in the GAMS programming language. The full specification of the model is given in Appendix I.

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Abstract

Agriculture is an important source of ammonia (NH₃), which contributes to acidification and eutrophication, as well as emissions of the greenhouse gases nitrous oxide (N₂O) and methane (CH₄). Controlling emissions of one of these pollutants through application of technical measures might have an impact (either beneficial or adverse) on emissions of the others. These side effects are usually ignored in policy-making.

This study analyses cost-effectiveness of measures to reduce acidification and eutrophication as well as agricultural emissions of N₂O and CH₄ in Europe, taking into account interrelations between abatement of NH₃, N₂O and CH₄ in agriculture. The model used is based on the RAINS model for air pollution in Europe, which includes emissions, abatement options and atmospheric source-receptor relationships for pollutants contributing to acidification and eutrophication. We used an optimisation model that is largely based on the RAINS model but also includes emissions of N₂O and CH₄ from agriculture and technical measures to reduce these emissions. For abatement options for agricultural emissions we estimated side effects on other emissions. The model determines abatement strategies to meet restrictions on emission and/or deposition levels at least cost.

Cost-effective strategies to reduce acidification and eutrophication in Europe were analysed. We found that NH₃ abatement may cause an increase in N₂O emissions. If a reduction target for total agricultural N₂O and CH₄ emissions in Europe was included, cost-effective allocation of emission reductions over countries in Europe changed considerably.

Keywords: Environmental policy interrelations; Emission abatement; Cost-effectiveness; Acidification; Greenhouse gases

6.1 Introduction

Many European countries agreed to reduce emissions contributing to acidification, eutrophication and ground-level ozone (Gothenburg Protocol (UNECE, 1999a)) and greenhouse gas emissions (Kyoto Protocol (UNFCCC, 1997)). Interrelations exist between policies for reducing emissions of air pollutants and greenhouse gases (Grennfelt et al., 1994). Several recent studies focus on ancillary benefits of efforts to reduce CO₂ emissions from fossil fuel use (Davis et al., 2000). In earlier work, we showed the existence of interrelations between acidification and greenhouse gas mitigation policies in European agriculture (Brink et al., 2000; 2001a; 2001b).

For greenhouse gases, the location of emissions is not important for their environmental impact. For pollutants contributing to acidification and eutrophication, however, the environmental impact depends on emission location and atmospheric transport before deposition. Moreover, the same level of deposition may have different environmental impacts at different locations because of differences in ecosystem sensitivities. A consideration of the side effects on emissions of air pollutants may therefore change the cost-effective geographical distribution of greenhouse gas emission reductions (Pearce, 2000).

In this study we extend earlier work on interrelations between abatement of ammonia (NH₃), nitrous oxide (N₂O) and methane (CH₄) from European agriculture (Brink et al., 2000; 2001a; 2001b). Here we also consider emissions of acidifying compounds other than NH₃ (namely sulphur dioxide (SO₂) and nitrogen oxides (NO_x)), the location of emissions and environmental effects and atmospheric transport of emissions in between, and environmental sensitivity of various locations. We analyse the impact of interrelations among abatement policies in agriculture on the cost-effective allocation of abatement over sources of emissions.

6.2 Modelling interrelated emission reductions with geographically specific deposition targets

A comparative static optimisation model was used to determine cost-effective abatement strategies in Europe for acidification, eutrophication, and agricultural emissions of N₂O and CH₄ simultaneously, considering interrelations between abatement activities in the agricultural sector. The model is largely based on the RAINS (Regional Air Pollution Information and Simulation) model developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for integrated assessment of alternative strategies to reduce air pollution in Europe (Alcamo et al., 1990; Amann et al., 1998). The RAINS model includes data to estimate emissions of SO₂, NO_x and NH₃ in Europe, as well as a large number of technical measures to abate these emissions. The model we used for this analysis is described in detail in Chapter 4 of this thesis. This section will briefly describe this basic model and present some extensions to include several environmental effects and atmospheric transport of pollutants from the location of emissions to the location of the environmental impact.

6.2.1 Basic model

The model is used to calculate emissions of various pollutants and determine cost-effective abatement strategies for restrictions on emission levels. Unabated emissions are calculated from (exogenous) data

on various economic activities and can be reduced by applying abatement options at various sources. The model minimises total cost of abatement:

$$\min \sum_{k \in K} C_k(v_k) \quad (6.1)$$

where v_k is a vector with elements $a_{k,n}$ ($n \in N$);

$$C_k(v_k) = \sum_{n \in N} a_{k,n} \cdot \gamma_{k,n} \cdot \bar{X}_k \quad \forall k \in K \quad (6.2)$$

subject to

$$\sum_{k \in K} e_{k,p} \leq \bar{E}_p \quad \forall p \in P \quad (6.3)$$

$$e_{k,p} = \varepsilon_{k,p} \cdot \bar{X}_k \cdot \left(1 - \sum_{n \in N} a_{k,n} \cdot \rho_{k,n,p} \right) \quad \forall p \in P, k \in K \quad (6.4)$$

$$\sum_{n \in N} a_{k,n} \leq 1 \quad \forall k \in K \quad (6.5)$$

$$a_{k,n} \geq 0 \quad \forall k \in K, n \in N \quad (6.6)$$

Decision variables in the model are application rates ($a_{k,n}$) for abatement options (n) at source k (lower case letters indicate individual elements of sets and upper case letters indicate sets). Abatement costs at source k (C_k) depend on the (exogenous) activity level (\bar{X}_k) and on application rates ($a_{k,n}$) and per unit costs ($\gamma_{k,n}$) for all abatement options ($n \in N$) (Eq. (6.2)). Annual emissions of pollutant p from source k ($e_{k,p}$) depend on activity level (\bar{X}_k), emission factor ($\varepsilon_{k,p}$) and application rate ($a_{k,n}$) and effectiveness ($\rho_{k,n,p}$) of abatement options (Eq. (6.4)). An upper level for emissions of each pollutant p is indicated by \bar{E}_p (Eq. (6.3)) and application rates ($a_{k,n}$) are constrained in Eqs. (6.5) and (6.6).

Emissions can be reduced by applying add-on abatement techniques. For each source the model chooses application rates for all abatement options included in set N such that emission targets are obtained at minimum cost. Abatement options are not attributed to a specific pollutant; instead, an option may have impacts on various pollutants, either reducing or increasing emissions, but reducing emissions of at least one pollutant. The effect of abatement option n on emissions of pollutant p from source k is given as the fraction of unabated emissions that is reduced ($\rho_{k,n,p}$). Emissions of pollutant p can be reduced ($0 < \rho_{k,n,p} \leq 1$; i.e. a reduction to a maximum of 100%), unaffected ($\rho_{k,n,p} = 0$), or increased ($\rho_{k,n,p} < 0$; i.e. an increase can be more than 100%). The changes in emissions by abatement option n at source k depend linearly on the level of unabated emissions and on the application rate ($\varepsilon_{k,p} \times \bar{X}_k \times a_{k,n} \times \rho_{k,n,p}$).

There may be interaction between different measures to reduce emissions. For instance, measures may exclude, reinforce or weaken each other, or some measures can only be applied in combination with others. To take this into consideration, possible combinations of measures and their combined effect were included as new abatement options. This may result in a large number of abatement options included in set N . Moreover, a certain level of detail about sources and abatement options is required in the model because side effects of emission-reduction measures may depend on specific characteristics of sources and measures. As a result, the model includes a large number of variables. To be able to solve such a large problem, the model applies a (stepwise) linear approach to calculate emissions, costs and effects of abatement.

In the optimisation procedure, the abatement options that are applied for specific emission constraints are determined. Cost-effectiveness of abatement strategies depends on the cost of abatement

options, the magnitude of effects of abatement options on emissions of various pollutants, and reduction targets for emissions of various pollutants.

6.2.2 Multiple environmental targets

To reflect the contribution of various pollutants to different types of environmental damage, the model includes indicators for environmental problems ($q \in Q$), reflecting the size of the environmental impact. These indicators depend linearly on the emissions of pollutants¹. The indicator for environmental problem q (h_q) is determined by:

$$h_q = \sum_{k \in K} \sum_{p \in P} \psi_{p,q} \cdot e_{k,p} \quad (6.7)$$

where $\psi_{p,q}$ represents the contribution of one unit of pollutant p to environmental problem q in terms of the indicator used for this environmental problem (for example, $\psi_{p,q}$ may be the global warming potential (GWP) for greenhouse gas p , indicating the relative contribution of this pollutant to global warming). Constraints in the model can be specified in terms of these indicators:

$$h_q \leq \bar{H}_q \quad \forall q \in Q \quad (6.8)$$

where \bar{H}_q indicating the target level for indicator h_q .

6.2.3 Location of emissions and effects

Emissions occur at different locations. For some pollutants (e.g. air pollutants) the environmental impact depends on the location of the emissions and transport of pollutants through the atmosphere, whereas for others (e.g. greenhouse gases) the location does not matter since emissions are uniformly mixing in the atmosphere. In the case of air pollutants, the environmental impact does not necessarily occur at the place of emissions because pollutants may be transported through the atmosphere over long distances before they have an effect on environmental quality (Alcamo et al., 1990). For pollutants of this type, it is important to take into account the location of emissions, the atmospheric transport and the location of the environmental effect when determining cost-effective abatement strategies. To this end, the model is extended to include a set I of source locations (i.e. where the emissions occur) and a set J of receptor locations (i.e. where the environmental effects occur)². All sources (and hence emissions) are assigned to a source location ($i \in I$). Consequently, the dimension i is added to economic activity level (\bar{X}_k), emission level ($e_{k,p}$) and application rate ($a_{k,n}$) (i.e. they become $\bar{X}_{i,k}$, $e_{i,k,p}$ and $a_{i,k,n}$, respectively). Because of different characteristics of sources at different locations, both the emission factors and the parameters for the cost and effect of abatement options are also location specific (i.e. $\epsilon_{k,p}$, $\gamma_{k,n}$ and $\rho_{k,n,p}$ are replaced by $\epsilon_{i,k,p}$, $\gamma_{i,k,n}$ and $\rho_{i,k,n,p}$, respectively). In accordance with these changes, Eqs. (6.1), (6.2), (6.4), (6.5) and (6.6) are respectively replaced by

$$\min \sum_{i \in I} \sum_{k \in K} C_{i,k} (v_{i,k}) \quad (6.9)$$

where $v_{i,k}$ is a vector with elements $a_{i,k,n}$ ($n \in N$);

¹ This is an accepted approach for some environmental problems, such as acidification and for adding up emissions of various greenhouse gases. For other environmental problems, such as the formation of ground-level ozone, which is the result of a non-linear relationship between several pollutants, this approach is not possible. In principle, this kind of non-linear relationships can be included in the model using a stepwise linear approach.

² Both source (i) and receptor (j) locations can be countries, but a higher or lower level of aggregation is possible as well. Moreover, the level of aggregation is not necessarily the same for source and receptor.

$$C_{i,k}(v_{i,k}) = \sum_{n \in N} a_{i,k,n} \cdot \gamma_{i,k,n} \cdot \bar{X}_{i,k} \quad (6.10)$$

$$e_{i,k,p} = \varepsilon_{i,k,p} \cdot \bar{X}_{i,k} \cdot \left(1 - \sum_{n \in N} a_{i,k,n} \cdot \rho_{i,k,n,p} \right) \quad (6.11)$$

$$\sum_{n \in N} a_{i,k,n} \leq 1 \quad \forall i \in I, k \in K \quad (6.12)$$

$$a_{i,k,n} \geq 0 \quad \forall i \in I, k \in K, n \in N \quad (6.13)$$

The process of atmospheric transport of pollutants is included in the model, assuming a linear relationship between emissions of pollutant p at source location i that are deposited at receptor location j . The constant parameter $\tau_{i,j,p}$ represents the fraction of emissions of pollutant p at i that is deposited at j . The same approach is used in the RAINS model to include atmospheric transport of air pollutants (Alcamo et al., 1990; Amann et al., 1998). Restrictions can be specified for emissions and environmental effects at various (source or receptor) locations (Eqs. (6.14), (6.15) and (6.16)) or for overall emissions and environmental effects (Eqs. (6.17) and (6.18)).

$$\sum_{k \in K} e_{i,k,p} \leq \bar{E}_{i,p} \quad \forall i \in I \quad (6.14)$$

$$\sum_{k \in K} \sum_{p \in P} \psi_{p,q} \cdot e_{i,k,p} \leq \bar{H}_{i,q} \quad \forall i \in I \quad (6.15)$$

$$\sum_{i \in I} \sum_{p \in P} \left(\tau_{i,j,p} \cdot \psi_{p,q} \cdot \sum_{k \in K} e_{i,k,p} \right) \leq \bar{H}_{j,q} \quad \forall j \in J \quad (6.16)$$

$$\sum_{i \in I} \sum_{k \in K} e_{i,k,p} \leq \bar{E}_p \quad (6.17)$$

$$\sum_{i \in I} \sum_{k \in K} \sum_{p \in P} \psi_{p,q} \cdot e_{i,k,p} \leq \bar{H}_q \quad (6.18)$$

6.3 Cost-effective abatement of SO₂, NO_x, NH₃, N₂O and CH₄ emissions in Europe

The model was used to analyse cost-effective policies to reduce acidification and eutrophication in Europe, as well as emissions of greenhouse gases such as N₂O and CH₄ from agriculture, considering interrelations between technical abatement measures in the agricultural sector. Acidification in Europe is mainly the result of emissions of SO₂, NO_x and NH₃. Both NO_x and NH₃ also play an important role in eutrophication. SO₂ and NO_x emissions are to a large extent caused by fossil fuel combustion, whereas the major source of NH₃ is agriculture. Important gases contributing to global warming are carbon dioxide (CO₂), N₂O and CH₄. In this study only greenhouse gas emissions related to agricultural activities are included. In Europe, N₂O and CH₄ are to a large extent the result of agricultural activities. In the 1990s, agriculture was responsible for about 8% of total greenhouse gas emissions in Europe (UNFCCC, 2000). European agriculture is a minor source of CO₂ emissions, but may play a role in reducing CO₂ emissions by replacing fossil fuels with biomass and by removing CO₂ through sinks (Paustian et al., 1998); however, these considerations are not included in this analysis.

6.3.1 Application of the model

Environmental problems included in the model (set Q) are acidification, eutrophication and greenhouse gas emissions; only emissions of N₂O and CH₄ from agriculture are considered. Pollutants considered

(set P) are SO_2 , NO_x , NH_3 , N_2O and CH_4 . For acidification and eutrophication, the analysis considers atmospheric transport of pollutants before they are deposited. Moreover, targets for acidification and eutrophication take into account ecosystem sensitivity at the location of deposition. For N_2O and CH_4 from agriculture, restrictions are on the sum of CO_2 equivalent emissions of these gases³, which is justified because N_2O and CH_4 are uniformly mixed in the atmosphere. Indicators for the environmental impacts (h_q) are acid equivalents (acidification), nitrogen (eutrophication) and CO_2 equivalents (greenhouse gas emissions).

Furthermore, the model includes emissions from 36 European countries (set I). For SO_2 , NO_x and NH_3 , the model considers atmospheric transport of emissions from each country to about 500 grids of 150×150 km in Europe (set J). The source-receptor relationship ($\tau_{i,j,p}$, indicating the fraction of pollutant p emitted in country i that is deposited in grid j) was taken from the RAINS model. Source-receptor matrices in the RAINS model were derived from a model of long-range transport of air pollution developed by EMEP (the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) (Barrett and Berge, 1996; Amann et al., 1998).

Within each country, the model distinguishes various sources of emissions (set K). The focus of this study is on the agricultural sector; therefore, agricultural activities (as sources of NH_3 , N_2O and CH_4) are considered in more detail than non-agricultural activities (as sources of SO_2 and NO_x). For agriculture, the model includes 14 sources of emissions in each country (viz. 11 animal categories, 2 types of fertiliser used and production of nitrogen fertilisers). For SO_2 and NO_x , all sources in a country were aggregated in one source for SO_2 and one source for NO_x emissions (with activity levels $\bar{X}_{i,k}$ for these sources representing emissions of SO_2 and NO_x). Activity levels for the various sources in each country ($\bar{X}_{i,k}$) and the associated emission factors for NH_3 ($\epsilon_{i,k,\text{NH}_3}$) were taken from databases in the RAINS model. This model includes data for 1990, 1995 and projections up to 2010. Agricultural emissions of N_2O and CH_4 were estimated on the basis of the databases in the RAINS model using emission factors as described in Brink et al. (2001a).

The model includes a set N of abatement options. Information on costs per unit of activity ($\gamma_{i,k,n}$) and effects on emissions ($\rho_{i,k,n,p}$) was taken from the RAINS model (Klaassen, 1994; Amann et al., 1998) and from studies for the EU (Hendriks et al., 1998; Bates, 2001). For abatement options applicable to agricultural activities, we estimated effects on other emissions (Brink et al., 2000; 2001a).

For each grid cell, we used the fifth percentiles of the critical loads of sulphur and nitrogen (both acidifying and nutrient)⁴. These values were calculated using critical loads for many ecosystems that occur within a grid cell (Posch et al., 1999; Hettelingh et al., 2001). If the deposition in a grid cell does not exceed these values, 95% of the ecosystem area within the grid cell is protected.

Emissions and abatement costs in 2010 were estimated for four scenarios. First, the no-control (NOC) scenario assumes no technical abatement measures applied in any European country (this scenario also excludes measures that have to be taken in the future according to adopted national and international legislation for emission control). Second, the 40% gap-closure (GAP) scenario reflects a

³ N_2O and CH_4 emissions are converted to CO_2 equivalent emissions using Intergovernmental Panel on Climate Change's global warming potentials (GWP) for a time horizon of 100 years (310 for N_2O ; 21 for CH_4).

⁴ A critical load for acidification and eutrophication has been defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nilsson and Grennfelt, 1988; Posch et al., 1999).

reduction in emissions of acidifying compounds in Europe such that for each grid cell, the critical load exceedance⁵ for acidification and eutrophication in the NOC scenario is reduced by at least 40% at minimum total abatement cost. Third, the 40% gap-closure-plus (GAP⁺) scenario requires a 5% reduction in the sum of N₂O and CH₄ emissions (in CO₂ equivalents) from agriculture in Europe relative to their NOC levels by measures additional to the abatement options applied in the cost-effective solution in the GAP scenario. Finally, the 40% gap-closure double-plus (GAP⁺⁺) scenario combines the 40% gap-closure requirement for acidification and eutrophication with the 5% reduction requirement for N₂O and CH₄ emissions (in CO₂ equivalents) from agriculture in Europe. In the GAP⁺⁺ scenario, cost-effective abatement strategies are determined for both the 40% gap-closure and the 5% emission-reduction requirements simultaneously, considering interrelations and side effects of abatement options in agriculture.

6.3.2 Results and discussion

To achieve the reduction in critical-load exceedance, emissions of SO₂, NO_x and NH₃ have to be reduced considerably (Table 6.1). NH₃ abatement without restrictions on N₂O and CH₄ emissions (GAP) caused an increase in total N₂O emissions from European agriculture of 8% relative to NOC (Table 6.1) as a result of negative side effects of NH₃ abatement options. Total agricultural emissions of CH₄ decrease a little as a result of the side effects of NH₃ abatement. The net increase in N₂O and CH₄ emissions from agriculture in CO₂ equivalents is 4%.

Adding a reduction target for N₂O and CH₄ emissions from European agriculture (GAP⁺ and GAP⁺⁺) obviously results in higher total abatement costs than in the GAP scenario (Table 6.1). Results for GAP⁺ are different from GAP⁺⁺ because GAP⁺ analyses optimal abatement strategies for acidification and greenhouse gases separately; GAP⁺⁺ reflects an integrated approach reducing acidifying emissions and agricultural N₂O and CH₄ emissions simultaneously, considering interrelations between abatement of NH₃, N₂O and CH₄ in European agriculture. In GAP⁺, the GAP abatement strategy is maintained, including abatement options causing an increase in N₂O emissions. The required reduction in N₂O and CH₄ can only be obtained by applying additional abatement options so that the reduction target for N₂O and CH₄ is obtained without violating restrictions for acidification and eutrophication. In GAP⁺⁺, total abatement costs are 15% lower than in GAP⁺ because in GAP⁺⁺, it is possible to apply abatement options that simultaneously reduce NH₃ and N₂O emissions instead of

Table 6.1

Estimated emissions and total abatement cost in Europe in 2010 for four scenarios (NOC, GAP, GAP⁺ and GAP⁺⁺)

| | NOC | GAP | GAP ⁺ | GAP ⁺⁺ |
|-------------------------------|-------------|------------|------------------|-------------------|
| SO ₂ | 15.9 (100%) | 12.4 (78%) | 12.4 (78%) | 12.4 (78%) |
| NO _x | 16.7 (100%) | 13.6 (82%) | 13.4 (80%) | 12.9 (78%) |
| NH ₃ | 6.7 (100%) | 4.8 (72%) | 4.9 (73%) | 4.9 (74%) |
| N ₂ O ^a | 1.7 (100%) | 1.8 (108%) | 1.6 (95%) | 1.6 (95%) |
| CH ₄ ^a | 16.6 (100%) | 16.3 (98%) | 15.7 (95%) | 15.6 (94%) |
| Abatement cost ^b | | 41.7 | 55.8 | 47.6 |

Note: Emissions are in million tons SO₂, NO₂, NH₃, N₂O and CH₄ /year; abatement costs are in billion EUR₁₉₉₀/year; percentages given represent emissions relative to emissions in NOC scenario.

^a Emissions from agricultural activities only

^b Total cost for technical measures to reduce emissions in Europe

⁵ A critical load exceedance is defined as “the sum of the nitrogen and sulphur deposition reduction required to reach the critical load function by the ‘shortest’ path” (Posch et al., 1999).

Table 6.2
Differences in country-specific emissions and abatement costs between GAP⁺⁺ and GAP⁺ scenarios^{a,b}

| | NO _x (GAP ⁺⁺ –GAP ⁺) | | NH ₃ (GAP ⁺⁺ –GAP ⁺) | | N ₂ O ^c (GAP ⁺⁺ –GAP ⁺) | | CH ₄ ^c (GAP ⁺⁺ –GAP ⁺) | | Abatement cost ^d (GAP ⁺⁺ –GAP ⁺) | |
|-----------------------|---|--------------|---|-------------|---|-------------|--|--------------|---|---------------|
| Albania | 0 | (1%) | 0 | (0%) | –0 | (0%) | –1 | (–1%) | 0 | (2%) |
| Austria | — | | 0 | (0%) | –1 | (–5%) | 4 | (2%) | –19 | (–4%) |
| Belarus | –10 | (–6%) | –3 | (–3%) | 2 | (6%) | –3 | (–1%) | –290 | (–30%) |
| Belgium | –8 | (–6%) | –2 | (–3%) | –1 | (–5%) | –5 | (–2%) | 186 | (8%) |
| Bosnia Herzegovina | –8 | (–16%) | 0 | (0%) | –0 | (–1%) | 0 | (0%) | 9 | (12%) |
| Bulgaria | –1 | (0%) | 1 | (1%) | 1 | (4%) | –2 | (–2%) | –296 | (–75%) |
| Croatia | –9 | (–17%) | 1 | (4%) | 0 | (2%) | 0 | (0%) | –65 | (–27%) |
| Czech Republic | — | | 1 | (1%) | 1 | (5%) | –6 | (–2%) | –278 | (–15%) |
| Denmark | — | | –5 | (–8%) | 0 | (1%) | –11 | (–6%) | –82 | (–22%) |
| Estonia | 8 | (12%) | 0 | (0%) | –0 | (0%) | –1 | (–3%) | –2 | (–11%) |
| Finland | — | | –1 | (–3%) | –0 | (–1%) | –1 | (–2%) | 5 | (21%) |
| France | –7 | (–1%) | –12 | (–2%) | 3 | (2%) | 15 | (1%) | –830 | (–21%) |
| Germany | — | | –5 | (–1%) | –5 | (–4%) | 13 | (1%) | –25 | (–1%) |
| Greece | — | | 1 | (1%) | 0 | (0%) | –1 | (–1%) | –28 | (–59%) |
| Hungary | — | | 4 | (6%) | –2 | (–5%) | 1 | (1%) | –327 | (–18%) |
| Ireland | — | | –0 | (0%) | 1 | (2%) | –1 | (0%) | –223 | (–41%) |
| Italy | –0 | (0%) | 6 | (2%) | –9 | (–10%) | –14 | (–2%) | –113 | (–1%) |
| Latvia | — | | –0 | (–1%) | –0 | (–1%) | –1 | (–2%) | 2 | (6%) |
| Lithuania | –8 | (–8%) | 0 | (1%) | 1 | (4%) | –2 | (–1%) | –146 | (–54%) |
| Luxembourg | — | | 0 | (1%) | 0 | (3%) | 0 | (0%) | –11 | (–7%) |
| Netherlands | — | | –8 | (–7%) | 0 | (0%) | 4 | (1%) | 38 | (4%) |
| Norway | 13 | (8%) | –1 | (–3%) | 0 | (1%) | –0 | (0%) | –164 | (–48%) |
| Poland | –7 | (–1%) | 4 | (1%) | 3 | (3%) | –12 | (–1%) | –579 | (–9%) |
| Portugal | — | | –0 | (0%) | 0 | (3%) | –1 | (–1%) | –91 | (–62%) |
| Republic of Macedonia | — | | 0 | (0%) | –0 | (0%) | –0 | (0%) | –1 | (–26%) |
| Republic of Moldova | –2 | (–4%) | 0 | (1%) | 0 | (4%) | –0 | (0%) | –125 | (–67%) |
| Romania | –35 | (–14%) | 4 | (2%) | –2 | (–2%) | –3 | (0%) | –338 | (–21%) |
| Russia | –189 | (–8%) | 43 | (6%) | 1 | (0%) | –18 | (–1%) | –1085 | (–43%) |
| Slovak Republic | –41 | (–31%) | 3 | (10%) | 0 | (2%) | –3 | (–3%) | 327 | (122%) |
| Slovenia | — | | 1 | (5%) | 0 | (3%) | 0 | (0%) | –61 | (–43%) |
| Spain | — | | –0 | (0%) | 2 | (2%) | — | | –541 | (–57%) |
| Sweden | — | | 0 | (0%) | 1 | (5%) | –4 | (–3%) | –124 | (–59%) |
| Switzerland | — | | –0 | (0%) | 0 | (0%) | 1 | (0%) | –6 | (–1%) |
| Ukraine | –159 | (–16%) | 25 | (5%) | 4 | (3%) | –26 | (–2%) | –1176 | (–40%) |
| United Kingdom | 56 | (5%) | –7 | (–3%) | 5 | (4%) | –14 | (–1%) | –1678 | (–22%) |
| Yugoslavia | –21 | (–23%) | 4 | (6%) | 0 | (1%) | –0 | (0%) | –79 | (–19%) |
| Total | –426 | (–3%) | 54 | (1%) | 6 | (0%) | –93 | (–1%) | –8215 | (–15%) |

Note: Emissions are given as kilotons NO₂, NH₃, N₂O and CH₄ /year; abatement costs are in million Euro/year; percentages represent a percentage of GAP⁺ values.

^a SO₂ emissions calculated for the GAP⁺ and GAP⁺⁺ scenarios are the same for all countries.

^b — indicates that there is no change; 0 indicates an increase smaller than 0.5; –0 indicates a reduction smaller than 0.5.

^c Emissions from agricultural activities only.

^d Total cost for technical measures to reduce emissions in Europe.

abatement options that reduce NH_3 emissions but cause a simultaneous increase in N_2O emissions. The cost-effective allocation of abatement over countries also differs between GAP^+ and GAP^{++} (Table 6.2). In particular, the change in abatement costs in GAP^{++} relative to GAP^+ differs between countries. For most countries we calculated lower total abatement costs in GAP^{++} than in GAP^+ , but in some countries (e.g. Belgium and Finland) calculated costs are higher in GAP^{++} than in GAP^+ (Table 6.2).

6.4 Conclusions

Interrelations between policies aiming at different environmental problems may have an effect on cost-effective strategies to meet reduction targets for these environmental problems. This paper describes a stepwise linear, comparative static optimisation model that can be used to analyse cost-effective emission reduction strategies to meet various environmental targets, considering several pollutants, atmospheric transport of pollutants, a large number of abatement options and their effects on emissions of several pollutants.

The model was used to analyse cost-effective strategies to reduce acidification and eutrophication in Europe on the basis of information from the RAINS model. Moreover, we analysed the impact of NH_3 abatement on emissions of greenhouse gases such as N_2O and CH_4 from agricultural activities. For abatement options applicable to agricultural activities, we estimated possible side effects on emissions. Reduction targets were specified for nitrogen and sulphur deposition exceeding critical loads for acidification and eutrophication in grid cells of 150×150 km over Europe. We calculated a cost-effective allocation of abatement over sources to meet these targets with and without a restriction on emissions of N_2O and CH_4 . Without a restriction on N_2O and CH_4 emissions, N_2O emissions were calculated to increase 8% as a result of NH_3 abatement. A 5% reduction target for agricultural N_2O and CH_4 emissions in Europe in addition to the acidification and eutrophication targets resulted in higher total abatement costs. We analysed a separate approach and an integrated approach to achieve the reduction targets for acidification and eutrophication and the reduction target for N_2O and CH_4 emissions. The separate approach first determines a cost-effective abatement strategy for acidification and eutrophication targets only; this strategy is maintained when subsequently an additional abatement strategy is determined to achieve the required reduction in N_2O and CH_4 emissions. The integrated approach determines a cost-effective abatement strategy for all targets simultaneously. NH_3 abatement options that involve an increase in N_2O emissions are maintained in the separate approach. In the integrated approach, however, it is possible to apply NH_3 abatement options without an effect on N_2O or abatement options that simultaneously reduce N_2O and NH_3 emissions instead of NH_3 abatement options causing an increase in N_2O . Consequently, total abatement costs are 15% lower in the integrated approach than in the separate approach. Moreover, the allocation of abatement costs over countries is different, with most countries facing lower costs with the integrated approach than with the separate approach, but some countries facing higher costs.

This study focused on interrelations between acidification and greenhouse gas mitigation policies in the agricultural sector, considering technical emission-control options. Interrelations between these policies may, however, also exist in other sectors, and other areas of policy-making may be interrelated with these policies. Moreover, in addition to the technical control options, structural changes may play an important role in reducing greenhouse gas emissions in the longer term. Several of these aspects can be included in the model, although for some extensions the linearised approach might be unsuitable. Major limitations are data availability (in particular data on side effects of control options) and also the

size of the problem (because of the large number of abatement options that have to be included). The case presented in this study indicates that interrelations between different environmental problems affect cost-effective policies.

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7

Summary, discussion and conclusions

7.1 Introduction

Many European countries have developed policies to reduce emissions of air pollutants, including those contributing to acidification (sulphur dioxide (SO₂), nitrogen oxides (NO_x) and ammonia (NH₃)), eutrophication (NO_x and NH₃) and ground-level ozone (NO_x and volatile organic compounds (VOC)). An international agreement on further emission reductions for these pollutants was laid down in the 1999 Gothenburg Protocol. In addition to regional air pollution policies, many European countries will also have to substantially reduce their emissions of greenhouse gases as agreed in the 1997 Kyoto Protocol, because of their contribution to global climate change.

Emissions of the major greenhouse gases (carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O)) stem to a large extent from the same sources as air pollutants. In particular, fossil fuel combustion is a major source of emissions of CO₂, SO₂, NO_x, VOC and CH₄, whereas agricultural activities are a major source of NH₃ as well as N₂O and CH₄ emissions. Consequently, policies for regional air pollution and for reducing greenhouse gas emissions have to be linked. Up to now, interrelations have not yet been fully considered in the actual development of policies for regional air pollution and climate change. There is, however, an increasing amount of environmental economic literature devoted to this issue. Most studies deal with the so-called ancillary benefits of CO₂ mitigation by reducing fossil fuel use (Chapter 1 presents a brief overview of literature in this area).

This thesis adds to this literature by providing an environmental economic analysis of interrelations between air pollution and climate change policies in the European agricultural sector. Interrelations exist because agricultural activities are an important source of emissions of air pollutants (in particular NH₃) as well as greenhouse gases (in particular N₂O and CH₄). The main objective of this thesis is to investigate how interrelations in abatement of NH₃, N₂O and CH₄ emissions related to agricultural activities in Europe affect cost-effective abatement strategies for emissions of both regional air pollutants and greenhouse gases. Particular attention was given to the allocation of abatement over different sources and countries such that given targets for reductions in acidification and eutrophication in Europe and targets for greenhouse gas emission reductions are met at total minimum cost.

Three specific objectives were formulated in Chapter 1 and these have been dealt with in the subsequent chapters of this thesis. The objectives were to: (1) identify possible sources of interrelations between policies to reduce NH₃, N₂O and CH₄ emissions from European agriculture; (2) include these

interrelations in an integrated cost-effectiveness analysis for simultaneous reductions in regional air pollution (in particular acidification) and greenhouse gas emissions in European agriculture by a newly developed environmental economic model; and (3) analyse side effects of abatement strategies for NH_3 , N_2O and CH_4 in European agriculture and their impact on a cost-effective allocation of emission reductions over various sources in different countries, and on total abatement cost. The following sections will summarise this thesis and the main conclusions regarding these three objectives. Section 7.5 discusses several aspects that were not considered in this thesis and provides recommendations for future research.

7.2 Interrelations between air pollution and climate change policies in the European agricultural sector

Agricultural emissions of NH_3 , N_2O and CH_4 have to a large extent common sources (viz. animal production and fertiliser use) and can largely be quantified on the basis of the same information. Chapter 2 presents a methodology to estimate emissions of NH_3 , N_2O and CH_4 from European agriculture on the basis of consistent data. This is an important first step towards an integrated analysis of reducing emissions of these pollutants from European agriculture. Information on agricultural activities were taken from the RAINS model databases, which include information for 36 European countries for 1990, 1995 and projections up to and including 2010 to estimate NH_3 emissions. The IPCC method for estimating national agricultural emissions of N_2O and CH_4 was adjusted in order to use it in combination with the information in the RAINS databases.

NH_3 abatement is interrelated with N_2O and CH_4 emissions primarily because a decrease in the activities causing NH_3 emissions also reduces emissions of N_2O and CH_4 . This is shown by the results presented in Chapter 3. Calculated emissions of all three gases simultaneously decline between 1990 and 2010 as a result of projected reductions in animal numbers and fertiliser consumption in Europe. This result is analogous to the findings of many studies dealing with interrelations between climate change policies and air pollution that reductions in fossil fuel use to reduce CO_2 emissions produce ancillary benefits because emissions of air pollutants are reduced simultaneously.

Interrelations may also exist because measures to reduce emissions of one of the three pollutants may affect emissions of the others. Quantitative information on these side effects of specific measures to reduce emissions of NH_3 , N_2O and CH_4 was hardly available. Therefore, the direction (increasing or decreasing emissions) and the magnitude of these effects were estimated using information on the underlying processes involved¹. Chapter 2 investigates the impact of measures to reduce NH_3 emissions that are included in the RAINS model on emissions of N_2O and CH_4 . Some NH_3 abatement options, such as a lower nitrogen content of the fodder and covered storage of manure, simultaneously reduce NH_3 and N_2O emissions. Other measures to reduce NH_3 emissions, however, such as livestock housing adaptations and low NH_3 application of manure, may result in an increase in N_2O emissions. For some types of animal housing, N_2O emission may even triple because of modifications to the housing to reduce NH_3 emissions. NH_3 emissions also indirectly contribute to N_2O emissions, because deposition of NH_3 contributes to formation of N_2O in soils and aquatic systems. Consequently, NH_3 abatement results in a decrease of these indirect N_2O emissions. The effect of NH_3 abatement on total

¹ The estimates were made in close cooperation with Dr C. Kroeze from the Environmental Systems Analysis Group, Wageningen University.

CH₄ emissions is moderate because only a few NH₃ abatement options were estimated to affect CH₄ emissions. Modifications to animal housing may reduce associated CH₄ emissions by 90%, whereas covering manure storage may result in an increase in associated CH₄ emissions by up to 10%.

Chapter 4 (Appendix 4.B) discusses several measures to reduce agricultural emissions of N₂O and CH₄ in Europe and their possible side effects on NH₃ and on each other. The analysis indicates that reduction of N₂O or CH₄ may be accompanied by an effect on emissions of NH₃. Measures for reducing N₂O and CH₄ emissions may also affect each other. A more efficient use of nitrogen fertilisers will simultaneously reduce NH₃ and N₂O emissions and feed additives increasing animal productivity simultaneously reduce NH₃, N₂O and CH₄ emissions. On the other hand, restrictions on timing of fertiliser application and restrictions on grazing reduce N₂O emissions, but at the same time may result in an increase in NH₃ and CH₄ emissions. Daily spread of manure simultaneously reduces CH₄ and NH₃ (up to about 20%), but N₂O emissions may increase by up to almost 20%.

The costs and effects of measures differ between sources. Therefore, it is not possible to indicate a general preference for specific measures. Although adverse side effects will make measures less attractive in an integrated analysis, they may still be selected in a cost-effective abatement strategy if their adverse side effects can be compensated for by other measures at relatively low cost.

7.3 A model for integrated cost-effectiveness analysis

To perform integrated cost-effectiveness analyses for simultaneous reductions in regional air pollution (in particular acidification) and greenhouse gas emissions from agricultural sources in Europe, we developed a model. The model was primarily designed to be applied to the European agricultural sector, but can be used for or extended to other sectors as well. Chapter 4 presents the general formulation of the model and the input data used in the application for the European agricultural sector. Below, first the main characteristics of the general model will be summarised. Subsequently, I will describe characteristics of the model applied for the agricultural sector in 36 European countries.

Characteristics of the general model

The model is formulated as a static optimisation model, minimising total abatement cost to meet given restrictions on emissions. The formulation of the model was based on the RAINS model. We added to the RAINS structure the feature to consider effects of control measures on emissions of various pollutants in order to analyse interactions between reduction efforts for several pollutants.

The model includes several pollutants, emitted by different sources within various countries. Emissions are calculated on the basis of source- and country-specific emission factors and activity levels that are exogenous. Restrictions on emissions can be imposed at various aggregation levels, including restrictions on emissions per source, on emissions per country, and on the sum of emissions in all countries. In order to reduce emissions, several abatement measures are included. Each measure results in emission reductions of at least one pollutant and it may also have an effect on emissions of others. This side effect can be a decrease or an increase in emissions. The model explicitly takes into account all effects (including side effects) of specific control measures when determining the optimal (least-cost) solution for the given restrictions on emissions. Possible combinations of measures are separately entered in the model to consider possible interactions (i.e. if the cost or the effect of two or more measures is not just the sum of the individual costs or effects). Moreover, this allows for the exclusion of combinations of measures that cannot be applied together.

In the model, non-linear relationships are approximated by a piecewise linear approach. The marginal cost of specific abatement measures is assumed constant. Consequently, marginal costs of an increasing reduction in emissions rise step by step, represented by a piecewise linear abatement cost curve. This enables identification of those measures that have to be applied in order to meet the specified emission constraints at minimum cost. The model identifies first-best solutions to support decision makers in developing policies for various environmental problems considering interrelations.

In Chapter 6, the model is extended to allow for considering geographically specific environmental impacts. To this end, the model takes into account atmospheric transport of pollutants from the location of emissions to the location where environmental effects occur. Emissions can be translated into indicators reflecting the size of an environmental impact. Constraints can also be specified in terms of these indicators. This extension of the model allows for identifying a cost-minimal allocation of resources to reduce environmental impacts, considering geographical differences in, for instance, ecosystem sensitivity or population density.

The number of parameters and variables in the model can be very large because of a large number of sources and control measures and the geographic specificity. Moreover, combinations of measures are included in the model as separate options, further increasing the total number of control options. To be able to deal with large-scale problems, the model applies a linear approach to calculate emissions, costs and effects of abatement, while maintaining the most important non-linear characteristics of the model, such as the increasing and convex abatement cost functions.

Because of several critical assumptions underlying the model, analyses with the model are an abstraction from reality in several aspects. Important assumptions include exogenous economic activity levels, constant unit costs for control measures and a static approach. Section 7.5 discusses the limitations of the model and implications of the assumptions for the results. Notwithstanding these limitations, the model can be used to improve our understanding of the impact of considering side effects of abatement measures for several pollutants on cost-effective control strategies. Moreover, the model is useful in identifying robust control measures that are included in cost-effective strategies for various combinations of constraints for the pollutants involved.

Characteristics of the model applied for the European agricultural sector

The model described in Chapter 4 and the extended model described in Chapter 6 were implemented in GAMS and applied to the agricultural sector in Europe to perform the analyses that are described in this thesis. Emissions of NH_3 , N_2O and CH_4 from agriculture were calculated for 36 European countries in 1990 and 2010. Emission sources include livestock categories, synthetic fertiliser use and nitrogen fertiliser production in each country (altogether more than 500 sources). Data on activity levels for these sources in each country in 1990 and projections for 2010 were taken from the RAINS model databases. Emission factors for NH_3 were also adopted from the RAINS model, whereas N_2O and CH_4 emissions were calculated according to the methodology as described in Chapter 2. We considered 20 measures to reduce emissions of NH_3 , N_2O and CH_4 from agriculture and included estimates of their effects on emissions of all three gases as presented in Chapter 2 and Appendix 4.B.

In addition to the above, the extension of the model in Chapter 6 included emissions of SO_2 and NO_x from non-agricultural sources and abatement cost curves for these pollutants, adopted from the RAINS model. No side effects were considered for SO_2 and NO_x abatement options. We also adopted from the RAINS model a source-receptor matrix representing atmospheric transport of emissions from countries to 150×150 km grids within Europe. For each grid cell we obtained data on deposition

levels for nitrogen and sulphur for which 95% of the ecosystems within the grid cell are protected against harmful effects due to acidification and eutrophication. These data were used to specify deposition targets that were considered in a cost-effectiveness analysis, together with constraints on N_2O and CH_4 emissions from agriculture.

7.4 Lessons from integrated cost-effectiveness analyses of NH_3 , N_2O and CH_4 abatement in the European agricultural sector

Chapters 5 and 6 present the results of various comparative static optimisation analyses that were performed with the model developed in Chapter 4 and extended in Chapter 6. We analysed abatement cost curves for NH_3 , N_2O and CH_4 under different assumptions to investigate how, in the presence of interrelations, cost curves for one pollutant depend on restrictions on emissions of other pollutants. Furthermore, we identified cost-effective abatement strategies for various specific emission constraints for NH_3 , N_2O , CH_4 and for combinations of these pollutants. It should be noted that the results of our analyses depend on the assumptions on the costs, effects and applicability of emission control measures that are applied. Information on the relevant assumptions is provided in Chapters 2 and 4.

Calculations to identify cost-effective strategies for achieving various country-specific reduction targets for NH_3 emissions in 2010 indicate that NH_3 abatement in Europe may cause an increase in emissions of N_2O . The levels of increase in N_2O emissions vary for different NH_3 reduction targets. Larger increases in N_2O emissions were calculated for more stringent NH_3 abatement scenarios. For example, a 14% reduction in European NH_3 emissions results in a 3% increase in N_2O emissions, whereas a 38% NH_3 reduction results in a 9% increase in N_2O . Moreover, different effects on N_2O emissions were observed in different countries as a result of different levels of NH_3 abatement and different abatement options applied. CH_4 emissions are hardly affected by NH_3 abatement.

Abatement cost curves reflect the relation between emission reduction levels and the costs of realising these reductions. Abatement cost curves for one pollutant can be determined by ranking abatement options according to their cost-effectiveness in reducing that pollutant. However, if some of these abatement options have side effects on emissions of other pollutants that are restricted in any way, the cost-effective ranking of abatement options for one pollutant cannot be determined independent of the impact on emissions of other pollutants. To study this phenomenon, in Chapter 5 we analysed abatement cost curves for NH_3 , N_2O and CH_4 focusing on the interrelations. We determined a cost curve for NH_3 abatement in the Netherlands with the additional restriction that N_2O and CH_4 emissions may not exceed their initial level, and compared this to an NH_3 abatement cost curve without restrictions on N_2O and CH_4 . We found that with restrictions on N_2O and CH_4 , NH_3 abatement was more expensive, although to a limited extent. Total abatement costs do not increase by more than 3% for the largest part of the curve (i.e. < EUR 6 million). To avoid an increase in N_2O emissions, additional abatement options had to be applied, particularly catalytic conversion of N_2O in nitric acid production, which has relatively low cost per ton N_2O reduced.

Abatement of N_2O and CH_4 emissions from agriculture caused a reduction in NH_3 emissions in Europe. Here also different effects were observed for countries as a result of different levels of N_2O and CH_4 abatement and other abatement options applied. Abatement options mainly responsible for the simultaneous reduction in NH_3 , N_2O and/or CH_4 emissions are (i) reductions in the amount of nitrogen in the animal feed, (ii) improvements in the efficiency of nitrogen used as fertiliser and (iii) animal productivity improvements through feed additives. We also calculated an increase in CH_4 emissions

due to N_2O abatement (mainly caused by restrictions on timing of fertiliser application) and an increase in N_2O emissions due to CH_4 abatement (mainly caused by daily spread of manure).

To analyse the consequence of neglecting interactions on total abatement costs, we compared cost-effective abatement strategies for NH_3 , N_2O and CH_4 in two cases. In the first case, strategies for NH_3 abatement were determined independently from strategies for reducing N_2O and CH_4 emissions. In the second case, strategies for the same reductions in the emissions of all three pollutants were determined simultaneously in an integrated analysis. We found that for given NH_3 reduction levels, larger reductions in N_2O and CH_4 emissions could be obtained at lower total costs in the second case compared with the first case. Results for Europe indicated that total abatement costs were up to 60% higher (i.e. an increase in total abatement costs of up to EUR 5.7 billion per year) in the first case than in the second case. Moreover, the maximum feasible reduction in N_2O and CH_4 emissions was almost 10 megatons CO_2 equivalents higher (i.e. 1% of unabated emissions of N_2O and CH_4 from the European agricultural sector in 2010) in the second case than in the first case. In an integrated cost-effectiveness analysis, control options that are cost-effective in reducing NH_3 emissions but cause an increase in N_2O emissions, such as livestock housing adaptations and low NH_3 manure application, became less attractive. Instead, abatement options without adverse side effects or with beneficial side effects were applied, such as catalytic conversion of N_2O in nitric acid production, fertiliser efficiency improvements and feed additives improving animal productivity.

Finally, in Chapter 6 we used an extended version of the model to analyse cost-effective strategies to reduce acidifying and eutrophying deposition in Europe exceeding certain threshold values, in order to reduce the risk of harmful effects on the most sensitive ecosystems, combined with emission constraints for N_2O and CH_4 . In this analysis, we also included emissions of SO_2 and NO_x and abatement options for these pollutants, taken from the RAINS model. To achieve reduction targets for acidification and eutrophication, emissions of SO_2 , NO_x and NH_3 were reduced. We found that the optimal (i.e. cost-effective) allocation of emission reductions over these three pollutants depends on restrictions for agricultural emissions of N_2O and CH_4 . Indeed, reductions in NO_x emissions increased in favour of smaller reductions in NH_3 emissions if a restriction on N_2O and CH_4 emissions was added. In fact, NH_3 abatement became more expensive because of its negative side effect on N_2O emissions. NO_x abatement became more attractive giving the same environmental effect without negative side effects (note that SO_2 and NO_x abatement may also have side effects, but these were not considered in our analysis). Moreover, the results indicated that the distribution of emission reduction efforts (and associated abatement costs) over countries and sources also depends on restrictions on N_2O and CH_4 emissions.

Policy implications

In Europe, specific reduction targets for N_2O and CH_4 emissions from agriculture do not yet exist, although the potential contribution of the agricultural sector in implementing the greenhouse gas emission reduction targets set by the Kyoto Protocol is recognised by many countries. Reduction targets for NH_3 emissions have been established in the Gothenburg Protocol, which was signed in 1999. Up to now, only a few countries in Europe (including the Netherlands and Denmark) have addressed the NH_3 emission problem through specific legislation targeting NH_3 emissions. Besides emission targets for NH_3 , the Gothenburg Protocol also contains a series of mandatory control measures that the parties shall employ for the control of NH_3 emissions from agricultural sources. These include manure application techniques, manure storage techniques and livestock housing

systems with low NH_3 emissions. The results presented in this thesis, however, indicate that implementation of these control options may lead to increased emissions of N_2O and CH_4 from agriculture.

European countries have to make considerable efforts to meet the greenhouse gas emission targets laid down in the Kyoto Protocol. Therefore, it is recommended on the basis of this thesis to consider side effects of NH_3 abatement on N_2O and CH_4 emissions, as well as side effects of N_2O and CH_4 abatement on NH_3 emissions and on each other in the development of policies for reducing these emissions in Europe. The cost-effectiveness criterion indicates that less emphasis should be put on NH_3 control measures that result in an increase in N_2O and CH_4 emissions (such as low-emission housing systems and low-emission application techniques) in favour of control measures that may simultaneously reduce emissions of NH_3 , N_2O and CH_4 , such as *improved efficiency of fertiliser application, feed additives improving animal productivity for milk and growth and lower nitrogen content of animal feed*. In the analyses in this thesis, abatement options were selected on the basis of their cost-effectiveness only. Other aspects of abatement options will, however, also be important factors in policy-making, but were not included in this thesis (this issue is discussed in Section 7.5).

The analyses of cost-effective strategies to simultaneously achieve reductions in NH_3 , N_2O and CH_4 emissions presented in this thesis indicated that it may be highly inefficient to determine strategies for NH_3 abatement and for reducing N_2O and CH_4 independently. Moreover, if emission constraints exist not only for NH_3 but also for N_2O and CH_4 emissions, cost savings can be obtained if interrelations between NH_3 abatement and greenhouse gas emissions are considered in the policy-making process. In our analyses, low-emission animal housing systems and low-emission application techniques were still required to meet the NH_3 reduction targets in some countries. The emphasis in the NH_3 abatement strategies shifted, however, to measures that simultaneously reduce NH_3 , N_2O and CH_4 emissions mentioned above. Similarly, if a restriction on NH_3 was added to reduction targets for N_2O and CH_4 emissions, cost-effective abatement strategies shifted from measures with an adverse side effect on NH_3 , such as restrictions on grazing and restrictions on the timing of fertiliser application, to measures that simultaneously reduce NH_3 , N_2O and CH_4 emissions mentioned above.

Moreover, the results in this thesis indicate the impact of considering side effects of abatement on the optimal allocation of emission reductions over countries and sources. This thesis only considered side effects in European agriculture, but it is likely that side effects also exist in other sectors, as indicated by studies on ancillary benefits of greenhouse gas abatement policies. Considering interrelations in these sectors will also have an impact on control options selected and the allocation of abatement efforts over sources and countries. Therefore, it is recommended to pay particular attention to side effects of control measures in future agreements on country-specific emission reduction targets (e.g. follow-up agreements to the Gothenburg Protocol or the EU burden-sharing agreement).

7.5 Discussion and suggestions for future research

Like all models, the one presented in this thesis attempts to improve our understanding of a complex reality through a number of abstractions from this reality. This section will discuss the limitations of this model and the implications for interpreting the results. Based on this discussion, we will provide recommendations for further research. Aspects that are discussed include (i) types of interrelations, (ii) exogenous activity levels, (iii) linear vs. non-linear approach, (iv) uncertainties, (v) selection criteria for

control measures, (vi) policy instruments and (vii) the scope of the analysis regarding emission sources and environmental impacts considered.

Types of interrelations

The cost-effectiveness analyses in this thesis were used to reveal how policies concerning air pollution and climate change in the European agricultural sector are interrelated and how these interrelations affect cost-effective abatement strategies. Interrelations may exist when (a) one pollutant contributes to several environmental problems, (b) one source emits several pollutants contributing to different environmental problems, (c) technical abatement measures for the reduction of one pollutant also affects other emissions (either beneficially or adversely) and/or (d) one environmental problem influences other environmental effects (see Chapter 4 for a discussion of these four different types). The focus in this thesis was in particular on (c), although (a) and (b) were also considered.

Type (c) concerns the side effects of technical abatement measures for one pollutant on emissions of other pollutants. These were extensively discussed in this thesis. Type (b) includes the change in emissions of various pollutants as a result of a change in the activity level of a certain source. Resulting changes in emissions of the various pollutants involved are typically in the same direction. This is the type of interrelations most studies on ancillary benefits of greenhouse gas mitigation policies focus on, viz. a reduction in CO₂ emissions due to diminished fossil fuel use, accompanied by a reduction in SO₂, NO_x, VOC and PM emissions. Chapters 3 and 5 analysed this type of interrelation in reducing NH₃, N₂O and CH₄ emissions from the European agricultural sector by comparing emissions for different activity levels *ceteris paribus* (viz. 1990 and unabated 2010 emissions) and also by incorporating measures that imply decreasing activity levels as a result of efficiency improvements for animals or fertiliser use. Type (a) was considered in Chapter 6 by including the contribution of NH₃ and NO_x emissions to two environmental problems, viz. acidification and eutrophication.

Interrelations of type (d) were not considered in this thesis. Only a few studies deal with this type of interrelations, such as the impact of climate change on precipitation patterns and ecosystem sensitivity. These may have major implications for cost-effective abatement strategies, but are highly uncertain. This type of interrelations can possibly be investigated with the model presented in this thesis by comparing analyses with different source-receptor matrices (reflecting the impact of climate change on atmospheric transport of emissions) or different critical levels for sulphur and nitrogen deposition (reflecting the impact of climate change on sensitivity of ecosystems).

Exogenous activity levels

A limitation of this thesis is that the level of agricultural production in each country is fixed and exogenous in the model. Consequently, it is not possible to consider a decrease in the demand for agricultural products and the consequent reduction in emissions that may result from increased production costs due to abatement obligations. Moreover, it is not possible to examine possible shifts in agricultural production from one country to another in reaction to country-specific emission reduction targets. Consideration of these aspects and the associated economic costs require a more comprehensive modelling of various economic feedback mechanisms, which is beyond the scope of this thesis. Follow-up studies may investigate possibilities to extend the model using price elasticities of demand to incorporate the impact of increased production costs on activity levels. An alternative may be to use other existing models (e.g. general equilibrium models) for the European agricultural sector

to determine plausible projections of agricultural activities under various conditions, which can be used as input for analyses with the model presented in this thesis.

Linear vs. non-linear approach

The model developed and applied in this thesis is a linear programming model. Several relationships that actually may be non-linear were assumed to be linear, for instance constant emission factors for each source, constant unit costs of abatement options² and constant coefficients for atmospheric transport. In principle, a reformulation of the model into a non-linear optimisation problem to introduce non-linear relationships, e.g. making unit costs of abatement options dependent on the application rate, would be possible. This would, however, lead to problems in solving the optimisation problem given its size (in the empirical application in this thesis, the number of single variables and equations may amount to 470,000 and 2 million respectively).

Uncertainties

Uncertainties were not explicitly quantified in this thesis. Obviously, there are many uncertainties involved with the analyses. Uncertainties in estimating emissions from agriculture (in particular N₂O) are large. Moreover, there are uncertainties associated with the model structure, parameter values and input data. There are also many uncertainties in estimating side effects of abatement options. Quantitative information about side effects of abatement options or about the associated uncertainties was, however, hardly available. Therefore, more research is required on the effects of various control measures for emissions from agriculture, in particular on possible side effects, to get a more sound assessment of interrelations in abatement of agricultural emissions of NH₃, N₂O and CH₄. In this thesis we do not include uncertainties because this is considered an extensive research project in itself. In order to assess the uncertainties involved, a useful follow-up study to this thesis would be a sensitivity analysis for parameters of effects of control measures in this thesis and an evaluation of the results presented in this thesis in the context of existing studies on uncertainties concerning the RAINS model and emissions from agriculture.

Selection criteria for control measures

Cost-effectiveness is the only criterion employed in this thesis in determining abatement strategies. A number of other criteria may, however, also play an important role in policy design and selection of control measures, including equity impacts, practicability of the measure, acceptance by the public and by the sector involved, and the possibility of quantifying and monitoring the effects. For instance, in agriculture, feed adjustments are more difficult to enforce and monitor than adaptations to livestock housing. Therefore, policy makers may decide to make livestock housing adaptations for reducing NH₃ emissions mandatory, although feed adjustments may be more cost-effective to achieve the objective. Moreover, in addition to their effect on NH₃, N₂O and CH₄ emissions, control measures may have other (environmental and non-environmental) effects that were not considered in this thesis. Most of these considerations are difficult to incorporate in an optimisation model, but should be considered when the results will be used for policy-making purposes.

² Indeed, marginal costs of single abatement options are constant, but overall marginal abatement costs increase with emission reduction levels because several abatement options have to be applied together (see Chapter 4).

Alternative tools for analysing interrelations in reducing NH_3 , N_2O and CH_4 emissions would be a cost-benefit analysis or a multi-criteria analysis. Both tools offer the possibility to include a full array of potential side effects, even those for which no policy target has been specified. Several studies dealing with ancillary benefits of greenhouse gas mitigation apply a cost-benefit framework, using monetary values for side effects. There is, however, much controversy around monetary valuation of various environmental effects, in particular with regard to climate change. Results of a multi-criteria analysis are highly dependent on the choice of weighing factors, which is a subjective one. Given the drawbacks of these tools, in this thesis we applied a cost-effectiveness framework to analyse interrelations in policies for regional air pollution and climate change regarding the European agricultural sector.

Policy instruments

No attention was paid in this thesis to the implications of the interrelations for the choice of policy instruments (e.g. taxes, tradable permits, command and control). Only a few studies deal with this issue. With respect to the agricultural sector, the choice of policy instruments will also be an interesting subject of future research. As demonstrated in this thesis, widely divergent effects of specific control measures may occur in agriculture, which should be considered if a technology-based standards setting was opted for. Moreover, it will be worthwhile to analyse the cost-effectiveness of a tax on mineral nitrogen fertiliser in achieving reductions in both NH_3 and N_2O emissions. The model presented in this thesis is, however, not suitable for analysing the impact of a tax because it lacks economic feedback mechanisms that are important for such an analysis.

Scope of the analysis regarding emission sources and environmental impacts

The analyses in this thesis are to a large extent limited to emissions from the agricultural sector in Europe. Chapter 6 also includes non-agricultural emissions of SO_2 and NO_x . Emissions of greenhouse gases (in particular CO_2) stem to a large extent from non-agricultural sources (mainly fossil fuel use), which were not considered in this thesis. Neglecting these sources resulted in relatively high marginal cost for reducing N_2O and CH_4 emissions, compared with those reported in other studies (see Chapter 5). Moreover, in our analyses it is not possible to compensate increases in N_2O emissions due to NH_3 abatement by possibly cheap greenhouse gas mitigation in other sectors. Including this possibility may result in lower total abatement costs. Therefore, an integrated assessment of policies for regional air pollution and climate change in Europe should include all emission sources as well as their interrelations. The model presented in this thesis can be extended to include a large number of emission sources and options to reduce their emissions. This requires, however, an assessment of side effects of control options that are applicable to non-agricultural sources in order to be able to perform a really comprehensive analysis.

The environmental problems considered in this thesis include climate change, acidification and eutrophication. Interrelations may, however, also exist with other environmental problems, for instance emissions of fine particles and nitrate leaching into aquatic systems. Considering nitrate leaching, for instance, will further promote a reduction in nitrogen inputs to agricultural systems by measures such as a lower nitrogen content of animal feed and fertiliser efficiency improvements. Moreover, when emission sources beyond the agricultural sectors will be included, the range of interrelated environmental issues may further increase. This thesis must therefore be considered a first step towards a broader assessment of interactions in environmental policies that may be extended in further research.

Epilogue

This thesis presents a framework for integrated cost-effectiveness analysis of interrelated emission reduction and an application for reductions in NH_3 , N_2O and CH_4 emissions from agricultural sources in Europe. Several caveats and potential improvements of the analysis have been mentioned in the previous section. Nevertheless, this thesis is a useful contribution to the investigation of the role of interrelations in environmental policy-making in general and to the analysis of side effects of reducing NH_3 , N_2O and CH_4 emissions from European agriculture in particular. It demonstrates the need to consider these side effects in policy-making and to carry out further research on their extent. Moreover, this thesis improved the understanding of the role of interrelations in cost-effective strategies to achieve multiple objectives simultaneously. The model presented in this thesis can be used as a framework for further analysis of interrelations between policies for various environmental problems, focusing on various economic sectors, and for identifying abatement options that may receive more and options that may receive less emphasis in policy design. Moreover, it can help in determining an optimal allocation of abatement activities over countries and/or emission sources.

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Appendix I: Specification of the model in GAMS

This appendix presents the specification of the model presented in Chapter 4 in its application for European agriculture. The model was implemented in the GAMS programming language (General Algebraic Modelling System), which has been developed for the solution of large mathematical optimisation models (Brooke et al., 1998).

The data were read in from external data files, which were not included in this appendix. A complete version of the model, including the data files, is available from the author on request.

GAMS specification of the model in Chapter 4 used for the results in Chapter 5

** definition of sets of the model for the agricultural sector in Europe*

SETS

```
PR    processes during which emissions occur
      /PR1,PR2,PR3,PR4,PR5,PR6/
REG   regions
      /W_EUR_COOL,E_EUR_COOL,W_EUR_TEMP,E_EUR_TEMP,W_EUR,E_EUR/
COU   European countries including countries subdivided into regions
      /ALBA,AUST,BELA,BELG,BOHE,BULG,CROA,CZRE,DENM,ESTO,FINL,FRAN,GERM,GE_N,GE_O,GREE,HUNG,IREL,
      ITAL,LATV,LITH,LUXE,NETH,NORW,POLA,PORT,MOLD,ROMA,RUSS,RUKA,RUKO,RURE,RUSP,SKRE,SLOV,SPAI,
      SWED,SWIT,MACE,UKRA,UNKI,YUGO,ATLO,BALS,BLAS,MEDS,NORS,ICEL,INDA,NATU,REMA,TURK/
```

**subdivision of countries into major regions*

```
EEUCOOL(cou) Eastern European countries in cool regions
      /BELA,BOHE,BULG,CROA,CZRE,ESTO,HUNG,LATV,LITH,POLA,
      MOLD,ROMA,RUKA,RUKO,RURE,RUSP,SKRE,SLOV,MACE,UKRA,YUGO/
EEUTEMP(cou) Eastern European countries in temperate regions
      /ALBA,GREE/
WEUCOOL(cou) Western European countries in cool regions
      /AUST,BELG,DENM,FINL,FRAN,GE_N,GE_O,IREL,LUXE,NETH,NORW,SWED,SWIT,UNKI/
WEUTEMP(cou) Western European countries in temperate regions
      /ITAL,PORT,SPAI/
EXO_REG(cou) regions from which emissions are exogenous to the model
      /ICEL,INDA,NATU,REMA,TURK/
COOL(cou)    Countries in cool regions
TEMP(cou)    Countries in temperate regions
EEU(cou)     Eastern European countries
WEU(cou)     Western European countries
```

```
F    sources of emissions - categories in agricultural sector
/DS  dairy cattle - solid waste systems
DL  dairy cattle - liquid (slurry) waste systems
OS  other cattle - solid waste systems
OL  other cattle - liquid (slurry) waste systems
PS  pigs - solid waste systems
PL  pigs - liquid (slurry) waste systems
LH  laying hens
OP  other poultry
SH  sheep and goats
HO  horses
FU  fur animals
FR  fertiliser use - urea
FN  fertiliser use - other nitrogen
IN  fertiliser production
IO  other industry
WT  waste management
OT  other emissions
```

**some additional categories for emissions of N₂O, CH₄, SO₂ and NO_x*

```
RC  rice cultivation
NF  biological nitrogen fixation
CR  crop residue
CH  cultivated histosols
HS  human sewage
SRC_SO2  source of SO2 emissions outside agricultural sector (exogenous)
SRC_NOX  source of NOx emissions outside agricultural sector (exogenous)
/
```

**subsets of categories*

ANI(f) /DS,DL,OS,OL,PS,PL,LH,OP,SH,HO,FU/
 CATTLE(f) /DS,DL,OS,OL/
 DAIRY(f) /DS,DL/
 OTHCA(f) /OS,OL/
 PIGS(f) /PS,PL/
 LIQ(f) /DL,OL,PL/
 SOL(f) /DS,OS,PS/
 POULTRY(f) /LH,OP/
 USE(f) /FR,FN/
 IND(f) /IN/
 OTH(f) /IO,WT,OT,RC,NF,CR,CH,HS/

ABAT_TECHN all single abatement measures included in analysis
 /NC no control

**measures taken from RAINS model:*

LNF low nitrogen feed
 BF biofiltration and bioscrubbing
 SA stable adaptation
 CS_high covering manure storage - high
 CS_low covering manure storage - low
 LNA_high low nitrogen application - high
 LNA_low low nitrogen application - low
 SUB substitution of ammonia nitrate for urea
 STRIP stripping

**measures added for reducing N₂O and CH₄:*

N2O_KAT N2O catalyst in nitric acid production process
 FERTSUBST substitution of synthetic fertilisers by manure
 FERTTIMING restrictions on timing of fertiliser application
 FERTEFFIMPR fertiliser efficiency improvement
 GRASSL_IMPROV improvement of grassland management by adjusting groundwater levels
 GRAZ_RESTRICT restrictions on grazing of dairy cattle
 PROPIONATE propionate precursors
 PROBIOTICS probiotics
 DAILYSPREAD daily spread
 AD_CENTRALISED anaerobic digestion centralised
 AD_SMALLSCALE anaerobic digestion small scale

**fictional control options for SO₂ and NO_x included in RAINS cost curves:*

10000*10100
 20000*20150
 /

**subsets of abatement measures:*

ABT_FICT(abat_tech) fictional abatement options to reduce SO₂ and NO_x emissions
 /10000*10100,20000*20150/
 ABT_FICT_SO2(abat_tech) fictional abatement options to reduce SO₂ emissions
 /10000*10100/
 ABT_FICT_NOX(abat_tech) fictional abatement options to reduce NO_x emissions
 /20000*20150/

AWMS animal waste management systems
 /AWMS1 anaerobic lagoons
 AWMS2 liquid systems
 AWMS3 daily spread
 AWMS4 solid storage and drylot
 AWMS6 other systems/

SCEN set of all scenarios that can be selected in the model
 /NOC,GOT,ENV,MFR,NOM,CHM,NMR,GOT_NMR1,GOT_NMR2,GAP,GAP_PLUS/
 SC_OPT(scen) subset of scenarios for optimisation
 SC_ALL(scen) subset of scenarios included in the analysis

M environmental problems /AC,CC/
 P pollutants /NH3,N2O,CH4,SO2,NOx/
 ACID(p) acidifying compounds /NH3,NOX,SO2/
 S(p) acidifying compounds - Sulphur /SO2/
 N(p) acidifying compounds - Nitrogen /NH3,NOX/
 GHG(p) greenhouse gases /CH4,N2O/

**definition of subsets for countries*

COOL(cou) = EEUCOOL(cou) + WEUCOOL(cou);
 TEMP(cou) = EEUTEMP(cou) + WEUTEMP(cou);
 EEU(cou) = EEUCOOL(cou) + EEUTEMP(cou);
 WEU(cou) = WEUCOOL(cou) + WEUTEMP(cou);

PARAMETERS

```

ECOEF(cou,p,f,pr)          emission coefficient
COST_ANIM(cou,abat_techn,f) 'costs of abatement technologies - Euro/animal/yr'
RCOEF(p,abat_techn,f,pr)   removal efficiencies single techniques
RCOSP(cou,p,abat_techn,f,pr) 'rem-eff. for specific country (if different from RCOEF)'
AGRACT(cou,f)              'agricultural activity levels (million heads or ktons)'
APPL_POT(cou,abat_techn,f) 'potential application abatement techniques (percentage)'
;

```

**read input data and parameters from RAINS databases*

** - parameters for calculating NH₃ emissions*

```

$libinclude xlimport ECOEF      input\amoemvec.xls NH3_ECOEF
$libinclude xlimport COST_ANIM  input\amoemvec.xls NH3_COST
$libinclude xlimport RCOEF      input\amoemvec.xls NH3_RCOEF
$libinclude xlimport RCOSP      input\amoemvec.xls NH3_RCOSP
$libinclude xlimport APPL_POT   input\appl_pot.xls NH3_APP_p

```

** - data on agricultural activities*

```

$libinclude xlimport AGRACT      input\agrdba3.xls AGRACT

```

PARAMETERS

```

ECOFCH4REG(reg,f,pr)        fixed emission coefficients for regions
ECOEF_N(cou,p,f,pr)         'emission factors in amounts of nitrogen (for NH3 and N2O)'
OTH_N2O(cou,f,pr)           exogenous emissions of N2O from agricultural sources
OTH_CH4(cou,f,pr)           exogenous emissions of CH4 from agricultural sources
N_CONV(p)                   conversion of NH3 and N2O to nitrogen amounts
RCOEF_CH4(abat_techn,f,pr)  fixed emission reduction factors CH4
RCOSP_CH4(cou,abat_techn,f,pr) country-specific fixed emission reduction factors CH4
RCOEF_N2O(abat_techn,f,pr)  fixed emission reduction factors N2O
RCOSP_N2O(cou,abat_techn,f,pr) country-specific fixed emission reduction factors N2O
COST_POLL(cou,p,abat_techn,f) 'costs of techniques (mill. EUR/kton emissions reduced)'
NEXS(cou,f)                 nitrogen excretion in stable
NEXM(cou,f)                 nitrogen excretion in meadow
SH_AWMS(reg,f,awms)         'share of AWMS in total nitrogen excretion from source (IPCC defaults)'
;

```

**read values for CH₄ and N₂O emission coefficients*

```

$libinclude xlimport ECOFCH4REG  input\ecof_ch4.xls      EF_CH4
$libinclude xlimport OTH_CH4     input\oth_emiss_ch4.xls OTH
$libinclude xlimport OTH_N2O     input\oth_emiss_n2o.xls OTH

```

**read values for CH₄ removal efficiencies*

```

$libinclude xlimport RCOEF_CH4   input\rcoef_ch4.xls    RE_CH4
$libinclude xlimport RCOSP_CH4   input\rcosp_ch4.xls    RCOSP_CH4

```

**read values for N₂O removal efficiencies*

```

$libinclude xlimport RCOEF_N2O   input\rcoef_n2o.xls    RE_N2O
$libinclude xlimport RCOSP_N2O   input\rcosp_n2o.xls    RCOSP_N2O

```

**read values for calculating N₂O emission coefficients*

```

$libinclude xlimport NEXS        input\excretio.xls     NEXS
$libinclude xlimport NEXM        input\excretio.xls     NEXM
$libinclude xlimport SH_AWMS     input\cou_spec.xls     SH_AWMS

```

**determine emission factors for N₂O and CH₄ for all categories in the model*

**parameters used for determining N₂O emission factors*

SCALARS

** emission factors*

```

EF1      'for direct soil emissions (kg N2O-N kg-1 N input)'           /0.0125/
EF35     'for direct emissions from grazing (kg N2O-N kg-1 N input)'    /0.02/
EF4      'for indirect emissions after N-deposition (kg N2O-N kg-1 N emitted)' /0.01/
EF5      'for nitrogen leaching (kg N2O-N kg-1 N leaching or runoff)'   /0.025/
EF7      'for synthetic fertiliser production (kg N2O-N kg-1 HNO3-N produced)' /0.027/
EF_NOx   'for NOx-N from fertiliser-N application'                     /0.003/
EF_BF    'for N removed by biofiltration (kg N2O-N kg-1 N removed)'     /-0.01/
FRACGASM 'fraction of livestock N excreted volatilising as NH3 and NOx
          (kg NH3-N and NOx-N of N excreted)'                          /0.2/
FRACLEACH 'fraction of nitrogen lost to leaching and runoff (kg N kg-1 N applied)' /0.3/
;

```

PARAMETER

```

EF3(awms)      N2O emission factor for emissions from AWMS
/ AWMS1        0.001
  AWMS2        0.001
  AWMS3        0.02
  AWMS4        0.02
  AWMS6        0.005/

```

```

FRACNITR(cou) fraction of nitrate in total nitrogen fertiliser production in country
;
$include input\fracnitr.txt

*conversion rates for NH3 and NOx to nitrogen
N_CONV('NH3') = 14/17;
N_CONV('N2O') = 28/44;

*conversion of NH3 emission coefficients in nitrogen amounts
ECOEF_N(cou,'NH3',f,pr) = ECOEF(cou,'NH3',f,pr)*N_CONV('NH3');

*emission factors for CH4 (kg CH4/head)
ECOEF(eeu_cool,'CH4',ani,pr) = ECOFCH4REG('E_EUR_COOL',ani,pr);
ECOEF(weu_cool,'CH4',ani,pr) = ECOFCH4REG('W_EUR_COOL',ani,pr);
ECOEF(eeu_temp,'CH4',ani,pr) = ECOFCH4REG('E_EUR_TEMP',ani,pr);
ECOEF(weu_temp,'CH4',ani,pr) = ECOFCH4REG('W_EUR_TEMP',ani,pr);

*CH4 emissions from rice cultivation (RC)
ECOEF(cou,'CH4','RC','PR3') = OTH_CH4(cou,'RC','PR3');

*emission factors for N2O-N (kg N2O-N/head or kg N2O-N/kg fertiliser-N)

*direct soil emissions N2O resulting from livestock
ECOEF_N(cou,'N2O',ani,'PR1') = EF1*(NEXS(cou,ani)*(1-EF_NOX)-
(ECOEF_N(cou,'NH3',ani,'PR1')+ECOEF_N(cou,'NH3',ani,'PR2')+ECOEF_N(cou,'NH3',ani,'PR3')))
$( (NEXS(cou,ani)*(1-EF_NOX)) gt
(ECOEF_N(cou,'NH3',ani,'PR1')+ECOEF_N(cou,'NH3',ani,'PR2')+ECOEF_N(cou,'NH3',ani,'PR3'))) +
EF1*(NEXS(cou,ani)*(1-EF_NOX-FRACGASM))
$( (NEXS(cou,ani)*(1-EF_NOX)) le
(ECOEF_N(cou,'NH3',ani,'PR1')+ECOEF_N(cou,'NH3',ani,'PR2')+ECOEF_N(cou,'NH3',ani,'PR3')));

*direct soil emissions N2O resulting from fertiliser use
ECOEF_N(cou,'N2O',use,'PR1') = (1-(ECOEF_N(cou,'NH3',use,'PR5')+EF_NOX))*EF1;

*direct emissions N2O from animal production - Western Europe
ECOEF_N(cou,'N2O',ani,'PR2')$WEU(cou) =
NEXS(cou,ani)*SUM(awms,SH_AWMS('W_EUR',ani,awms))*EF3(awms))+NEXM(cou,ani)*EF35;

*direct emissions N2O from animal production - Eastern Europe
ECOEF_N(cou,'N2O',ani,'PR2')$EEU(cou) =
NEXS(cou,ani)*SUM(awms,SH_AWMS('E_EUR',ani,awms))*EF3(awms))+NEXM(cou,ani)*EF35;

*indirect emissions N2O after N-deposition - livestock
ECOEF_N(cou,'N2O',ani,'PR3') =
(SUM(pr,ECOEF_N(cou,'NH3',ani,pr)))+(NEXS(cou,ani)+NEXM(cou,ani))*EF_NOX*EF4;

*indirect emissions N2O after N-deposition - fertiliser use
ECOEF_N(cou,'N2O',use,'PR3') = (ECOEF_N(cou,'NH3',use,'PR5')+ EF_NOX)*EF4;

*indirect emissions N2O after N-deposition due to fertiliser production
ECOEF_N(cou,'N2O',ind,'PR3') = ECOEF_N(cou,'NH3',ind,'PR5')*EF4;

*indirect emissions N2O after N-deposition due to other emission sources
ECOEF_N(cou,'N2O',oth,'PR3') = ECOEF_N(cou,'NH3',oth,'PR5')*EF4;

*indirect emissions N2O (leaching and runoff) - livestock
ECOEF_N(cou,'N2O',ani,'PR4') = (NEXS(cou,ani)+NEXM(cou,ani))*FRACLEACH*EF5;

*indirect emissions N2O (leaching and runoff) - fertiliser use
ECOEF_N(cou,'N2O',use,'PR4') = FRACLEACH*EF5;

*emission factors N2O for other emissions (exogenous in model)
*(NF: biological N-fixation; CR: crop residues; CH: cultivated histosols, HS: human sewage)
ECOEF_N(cou,'N2O',oth,pr) = OTH_N2O(cou,oth,pr);

*emission factors N2O emissions from fertiliser production (nitric acid)
ECOEF_N(cou,'N2O',ind,'PR5') = EF7 * FRACNITR(cou);

*conversion between N2O-N and N2O emission coefficients
ECOEF(cou,'N2O',f,pr) = ECOEF_N(cou,'N2O',f,pr) / N_CONV('N2O');

*cost parameters, removal efficiencies and applicability of measures added to those in RAINS

*N2O KAT - N2O catalyst in nitric acid production process
COST_POLL(cou,'N2O','N2O_KAT','IN') = 0.25;
RCOEF('N2O','N2O_KAT','IN','PR5') = 0.80;
APPL_POT(cou,'N2O_KAT','IN') = 0.3;

*FERTSUBST - substitute organic with inorganic fertiliser, limiting use of inorganic fertilisers
COST_POLL(cou,'N2O','FERTSUBST',use) = 200;
RCOEF('NH3','FERTSUBST',use,pr) = 0.15;
RCOEF('N2O','FERTSUBST',use,'PR1') = 0.15;

```



```

RCOEF('N2O', 'FERTSUBST', use, 'PR4') = 0.15;
APPL_POT(cou, 'FERTSUBST', use) = 1;
*limited applicability in Germany and the Netherlands (Bates, 2001, p. 26)
APPL_POT('GE_O', 'FERTSUBST', use) = 0;
APPL_POT('GE_N', 'FERTSUBST', use) = 0;
APPL_POT('NETH', 'FERTSUBST', use) = 0;

*FERTTIMING - changes in fertiliser timing
COST_POLL(cou, 'N2O', 'FERTTIMING', ani) = 6;
*cost for synthetic fertiliser are much lower since no storage costs
COST_POLL(cou, 'N2O', 'FERTTIMING', use) = 1;
RCOEF('N2O', 'FERTTIMING', ani, 'PR4') = 0.15;
RCOEF('N2O', 'FERTTIMING', use, 'PR4') = 0.15;
*side effect on NH3 emissions: increase
RCOEF('NH3', 'FERTTIMING', ani, 'PR3') = -0.01;
RCOEF('NH3', 'FERTTIMING', use, 'PR5') = -0.01;
*increase in emissions due to 20% longer storage times
RCOEF('N2O', 'FERTTIMING', ani, 'PR2') = -0.20;
RCOEF('NH3', 'FERTTIMING', ani, 'PR2') = -0.20;
RCOEF('CH4', 'FERTTIMING', ani, 'PR2') = -0.20;
APPL_POT(cou, 'FERTTIMING', dairy) = 1;
APPL_POT(cou, 'FERTTIMING', pigs) = 1;
APPL_POT(cou, 'FERTTIMING', poultry) = 1;
APPL_POT(cou, 'FERTTIMING', use) = 1;
*in the Netherlands fertiliser application is already restricted to certain periods of the year
APPL_POT('NETH', 'FERTTIMING', ani) = 0;

*FERTEFFIMPR - fertiliser efficiency improvements
COST_POLL(cou, 'N2O', 'FERTEFFIMPR', use) = 5;
RCOEF('N2O', 'FERTEFFIMPR', use, 'PR1') = 0.05;
RCOEF('N2O', 'FERTEFFIMPR', use, 'PR4') = 0.05;
RCOEF('NH3', 'FERTEFFIMPR', use, pr) = 0.05;
APPL_POT(cou, 'FERTEFFIMPR', use) = 1;

*GRASSL_IMPROV - improvement of grassland management by adjusting groundwater level
COST_POLL(cou, 'N2O', 'GRASSL_IMPROV', dairy) = 5;
RCOEF('N2O', 'GRASSL_IMPROV', f, 'PR1') = 0.10;
APPL_POT(cou, 'GRASSL_IMPROV', dairy) = 1;

*GRAZ_RESTRICT - restrictions on grazing (full application assumes a 100% reduction of N excreted during grazing)
COST_ANIM(cou, 'GRAZ_RESTRICT', liq) = NEXM(cou, liq);
COST_ANIM(cou, 'GRAZ_RESTRICT', sol) = NEXM(cou, sol);
COST_ANIM(cou, 'GRAZ_RESTRICT', poultry) = 0.15 * NEXM(cou, poultry);
*effect on NH3 emissions:
RCOSP(cou, 'NH3', 'GRAZ_RESTRICT', ani, 'PR1') = -NEXM(cou, ani)/NEXS(cou, ani);
RCOSP(cou, 'NH3', 'GRAZ_RESTRICT', ani, 'PR2') = -NEXM(cou, ani)/NEXS(cou, ani);
RCOSP(cou, 'NH3', 'GRAZ_RESTRICT', ani, 'PR3') = -NEXM(cou, ani)/NEXS(cou, ani);
RCOEF('NH3', 'GRAZ_RESTRICT', ani, 'PR4')$sum(cou, ECOEF(cou, 'NH3', ani, 'PR4')) = 1;
*effect on emissions N2O directly from soils
RCOSP(cou, 'N2O', 'GRAZ_RESTRICT', ani, 'PR1')$ECOEF_N(cou, 'N2O', ani, 'PR1') =
(ECOEF_N(cou, 'N2O', ani, 'PR1')-EF1*((NEXS(cou, ani)+NEXM(cou, ani))*(1-EF_NOX)
- (ECOEF_N(cou, 'NH3', ani, 'PR1')+ECOEF_N(cou, 'NH3', ani, 'PR2')+ECOEF_N(cou, 'NH3', ani, 'PR3'))
$( (NEXS(cou, ani)+NEXM(cou, ani))*(1-EF_NOX) gt
(ECOEF_N(cou, 'NH3', ani, 'PR1')+ECOEF_N(cou, 'NH3', ani, 'PR2')+ECOEF_N(cou, 'NH3', ani, 'PR3'))))
+ (EF1*(NEXS(cou, ani)+NEXM(cou, ani))*(1-EF_NOX-FRAGASM)
$( (NEXS(cou, ani)+NEXM(cou, ani))*(1-EF_NOX)) le
(ECOEF_N(cou, 'NH3', ani, 'PR1')+ECOEF_N(cou, 'NH3', ani, 'PR2')+ECOEF_N(cou, 'NH3', ani, 'PR3'))))
/ ECOEF_N(cou, 'N2O', ani, 'PR1');
*effect on emissions N2O directly from animal production livestock Western Europe
RCOSP(cou, 'N2O', 'GRAZ_RESTRICT', ani, 'PR2')$WEU(cou) = (ECOEF_N(cou, 'N2O', ani, 'PR2')
- (NEXS(cou, ani)+NEXM(cou, ani))*SUM(awms, SH_AWMS('W_EUR', ani, awms)*EF3(awms)))
/ ECOEF_N(cou, 'N2O', ani, 'PR2');
*effect on emissions N2O directly from animal production livestock Eastern Europe
RCOSP(cou, 'N2O', 'GRAZ_RESTRICT', ani, 'PR2')$EEU(cou) = (ECOEF_N(cou, 'N2O', ani, 'PR2')
- (NEXS(cou, ani)+NEXM(cou, ani))*SUM(awms, SH_AWMS('E_EUR', ani, awms)*EF3(AWMS)))
/ ECOEF_N(cou, 'N2O', ani, 'PR2');
*effect on CH4 emissions from manure management:
RCOSP(cou, 'CH4', 'GRAZ_RESTRICT', ani, 'PR2') = -NEXM(cou, ani)/NEXS(cou, ani);
*applicability
APPL_POT(cou, 'GRAZ_RESTRICT', f)$NEXM(cou, f) = 0.50;

```

**PROPIONATE - propionate precursors*

```

COST_ANIM(cou, 'PROPIONATE', dairy) = 60;
COST_ANIM(cou, 'PROPIONATE', othca) = 25;
RCOEF('CH4', 'PROPIONATE', dairy, 'PR1') = 0.25;
RCOEF('CH4', 'PROPIONATE', othca, 'PR1') = 0.1;
RCOEF('NH3', 'PROPIONATE', cattle, pr) = 0.05;
RCOEF('CH4', 'PROPIONATE', cattle, 'PR2') = 0.05;
RCOEF('N2O', 'PROPIONATE', cattle, 'PR1') = 0.05;
RCOEF('N2O', 'PROPIONATE', cattle, 'PR2') = 0.05;
RCOEF('N2O', 'PROPIONATE', cattle, 'PR4') = 0.05;

```

**applicability*

```

APPL_POT(cou, 'PROPIONATE', cattle) = 0.25;

```

**read country-specific applicabilities for EU countries*

```

$include input\appl_pot_propionate.txt

```

**PROBIOTICS - probiotics*

```

COST_ANIM(cou, 'probiotics', dairy) = 35;
COST_ANIM(cou, 'probiotics', othca) = 15;
RCOEF('CH4', 'PROBIOTICS', dairy, pr) = 0.075;
RCOEF('CH4', 'PROBIOTICS', othca, pr) = 0.03;

```

**effect on NH₃ and N₂O due to increase productivity*

```

RCOEF('NH3', 'PROBIOTICS', dairy, pr) = 0.075;
RCOEF('NH3', 'PROBIOTICS', othca, pr) = 0.03;
RCOEF('N2O', 'PROBIOTICS', dairy, 'PR1') = 0.075;
RCOEF('N2O', 'PROBIOTICS', dairy, 'PR2') = 0.075;
RCOEF('N2O', 'PROBIOTICS', dairy, 'PR4') = 0.075;
RCOEF('N2O', 'PROBIOTICS', othca, 'PR1') = 0.03;
RCOEF('N2O', 'PROBIOTICS', othca, 'PR2') = 0.03;
RCOEF('N2O', 'PROBIOTICS', othca, 'PR4') = 0.03;

```

**applicability*

```

APPL_POT(cou, 'PROBIOTICS', cattle) = 0.5*APPL_POT(cou, 'PROPIONATE', cattle);

```

**DAILYSPREAD - daily spread of manure*

```

COST_ANIM(cou, 'DAILYSPREAD', dairy) = 75;
COST_ANIM(cou, 'DAILYSPREAD', othca) = 37.5;
COST_ANIM(cou, 'DAILYSPREAD', pigs) = 7.5;

```

```

RCOEF('CH4', 'DAILYSPREAD', cattle, 'PR2') = 0.9;
RCOEF('CH4', 'DAILYSPREAD', pigs, 'PR2') = 0.9;
RCOEF('NH3', 'DAILYSPREAD', f, 'PR2') = 0.50;
RCOEF('NH3', 'DAILYSPREAD', f, 'PR3') = -0.10;
RCOEF('N2O', 'DAILYSPREAD', f, 'PR1') = -0.80;
RCOEF('N2O', 'DAILYSPREAD', f, 'PR4') = -0.80;

```

**applicability*

```

APPL_POT(cou, 'DAILYSPREAD', LIQ) = 0.25;

```

anaerobic digestion*PARAMETER**

```

COST_MANURE(cou, abat_techn, f) annual cost of abatement technology per kton manure produced;

```

conversion factor from kg N excreted to kton manure produced is 0.1/275*AD_CENTRALISED - anaerobic digestion centralised*

```

COST_MANURE(cou, 'AD_CENTRALISED', liq) = 727.9;
COST_ANIM(cou, 'AD_CENTRALISED', liq) = 0.1/275*NEXS(cou, liq)*COST_MANURE(cou, 'AD_CENTRALISED', liq);
RCOSP(cool, 'CH4', 'AD_CENTRALISED', liq, 'PR2') = 0.50;
RCOSP(temp, 'CH4', 'AD_CENTRALISED', liq, 'PR2') = 0.75;

```

**AD_SMALLSCALE - anaerobic digestion small scale*

```

COST_MANURE(cou, 'AD_SMALLSCALE', liq) = 4385.4;
COST_ANIM(cou, 'AD_SMALLSCALE', liq) = 0.1/275*NEXS(cou, liq)*COST_MANURE(cou, 'AD_SMALLSCALE', liq);
RCOSP(cool, 'CH4', 'AD_SMALLSCALE', liq, 'PR2') = 0.50;
RCOSP(temp, 'CH4', 'AD_SMALLSCALE', liq, 'PR2') = 0.75;

```

**applicability*

```

APPL_POT(cou, 'AD_SMALLSCALE', liq) = 0.15;

```

**read country-specific applicability rates for EU countries (taken from Bates (2001), App.B)*

```

$include input\appl_pot_ad_centra.txt

```

**applicability AD_CENTRALISED:*

```

APPL_POT('BELG', 'AD_CENTRALISED', liq) = 0.5*APPL_POT('BELG', 'AD_SMALLSCALE', liq);
APPL_POT('DENM', 'AD_CENTRALISED', liq) = 0.2*APPL_POT('DENM', 'AD_SMALLSCALE', liq);
APPL_POT('NETH', 'AD_CENTRALISED', liq) = 0.5*APPL_POT('NETH', 'AD_SMALLSCALE', liq);
APPL_POT('UNKI', 'AD_CENTRALISED', liq) = 0.5*APPL_POT('UNKI', 'AD_SMALLSCALE', liq);

```

**calculate effects (removal efficiencies) of NH₃ abatement options from RAINS model on N₂O and CH₄*

**removal efficiencies CH₄*

```
RCOEF('CH4', abat_tech, f, pr) $RCOEF_CH4(abat_tech, f, pr) = RCOEF_CH4(abat_tech, f, pr);
RCOSP(cou, 'CH4', abat_tech, f, pr) $RCOSP_CH4(cou, abat_tech, f, pr) = RCOSP_CH4(cou, abat_tech, f, pr);
```

**removal efficiencies N₂O PR3*

```
RCOSP(cou, 'N2O', abat_tech, f, 'PR3') $ECOEF_N(cou, 'N2O', f, 'PR3') =
EF4 * SUM(pr, ECOEF_N(cou, 'NH3', f, pr)) * (RCOEF('NH3', abat_tech, f, pr)
$(not RCOSP(cou, 'NH3', abat_tech, f, pr)) + RCOSP(cou, 'NH3', abat_tech, f, pr)))
/ECOEF_N(cou, 'N2O', f, 'PR3');
```

**removal efficiencies N₂O LNF PR1*

```
RCOSP(cou, 'N2O', 'LNF', ani, 'PR1') = RCOEF('NH3', 'lnf', ani, 'PR3')
$(not RCOSP(cou, 'NH3', 'LNF', ani, 'PR3')) + RCOSP(cou, 'NH3', 'LNF', ani, 'PR3');
```

**removal efficiencies N₂O LNF process 2*

```
RCOSP(cou, 'N2O', 'LNF', ani, 'PR2') = RCOEF('NH3', 'LNF', ani, 'PR1')
$(not RCOSP(cou, 'NH3', 'LNF', ani, 'PR1')) + RCOSP(cou, 'NH3', 'LNF', ani, 'PR1');
```

**removal efficiencies N₂O LNF PR4*

```
RCOSP(cou, 'N2O', 'LNF', ani, 'PR4') = RCOEF('NH3', 'LNF', ani, 'PR3')
$(not RCOSP(cou, 'NH3', 'LNF', ani, 'PR3')) + RCOSP(cou, 'NH3', 'LNF', ani, 'PR3');
```

**removal efficiencies N₂O BF PR2*

```
RCOSP(cou, 'N2O', 'BF', ani, 'PR2') = EF_BF * ECOEF_N(cou, 'NH3', ani, 'PR1') * (RCOEF('nh3', 'bf', ani, 'PR1')
$(not RCOSP(cou, 'nh3', 'bf', ani, 'PR1')) + RCOSP(cou, 'nh3', 'bf', ani, 'PR1'))
/ECOEF_N(cou, 'N2O', ani, 'PR2');
```

**removal efficiencies N₂O SA PR1*

```
RCOSP(cou, 'N2O', 'SA', ani, 'PR1') = -EF1 * (ECOEF_N(cou, 'NH3', ani, 'PR1') * (RCOEF('nh3', 'sa', ani, 'PR1')
$(not RCOSP(cou, 'nh3', 'sa', ani, 'PR1')) + RCOSP(cou, 'nh3', 'sa', ani, 'PR1'))
+ ECOEF_N(cou, 'NH3', ani, 'PR2') * (RCOEF('nh3', 'sa', ani, 'PR2')
$(not RCOSP(cou, 'nh3', 'sa', ani, 'PR2')) + RCOSP(cou, 'nh3', 'sa', ani, 'PR2'))))
/ECOEF_N(cou, 'N2O', ani, 'PR1');
```

**removal efficiencies N₂O SA PR2*

```
RCOEF('N2O', 'SA', f, 'PR2') = RCOEF_N2O('SA', f, 'PR2');
RCOSP(cou, 'N2O', 'SA', ani, 'PR2') $RCOSP_N2O(cou, 'SA', ani, 'PR2') = RCOSP_N2O(cou, 'SA', ani, 'PR2');
```

**removal efficiencies N₂O SA PR4*

```
RCOSP(cou, 'N2O', 'SA', ani, 'PR4') $ECOEF_N(cou, 'N2O', ani, 'PR4') =
-EF5 * FRACLEACH * (ECOEF_N(cou, 'NH3', ani, 'PR1') * (RCOEF('nh3', 'sa', ani, 'PR1')
$(not RCOSP(cou, 'nh3', 'sa', ani, 'PR1')) + RCOSP(cou, 'nh3', 'sa', ani, 'PR1'))
+ ECOEF_N(cou, 'NH3', ani, 'PR2') * (RCOEF('nh3', 'sa', ani, 'PR2')
$(not RCOSP(cou, 'nh3', 'sa', ani, 'PR2')) + RCOSP(cou, 'nh3', 'sa', ani, 'PR2'))))
/ECOEF_N(cou, 'N2O', ani, 'PR4');
```

**removal efficiencies N₂O CS-high PR1*

```
RCOSP(cou, 'N2O', 'CS_high', ani, 'PR1') = -EF1 * ECOEF_N(cou, 'NH3', ani, 'PR2') *
(RCOEF('nh3', 'cs_high', ani, 'PR2') $(not RCOSP(cou, 'nh3', 'cs_high', ani, 'PR2')) +
RCOSP(cou, 'nh3', 'cs_high', ani, 'PR2')) / ECOEF_N(cou, 'N2O', ani, 'PR1');
```

**removal efficiencies N₂O CS-high PR2*

```
RCOEF('N2O', 'CS_high', ani, 'PR2') = RCOEF_N2O('CS_high', ani, 'PR2');
RCOSP(cou, 'N2O', 'CS_high', ani, 'PR2') $RCOSP_N2O(cou, 'CS_high', ani, 'PR2') =
RCOSP_N2O(cou, 'CS_high', ani, 'PR2');
```

**removal efficiencies N₂O CS-high PR4*

```
RCOSP(cou, 'N2O', 'CS_high', ani, 'PR4') $ECOEF_N(cou, 'N2O', ani, 'PR4') =
-EF5 * FRACLEACH * ECOEF_N(cou, 'NH3', ani, 'PR2') *
(RCOEF('nh3', 'cs_high', ani, 'PR2') $(not RCOSP(cou, 'nh3', 'cs_high', ani, 'PR2')) +
RCOSP(cou, 'nh3', 'cs_high', ani, 'PR2')) / ECOEF_N(cou, 'N2O', ani, 'PR4');
```

**removal efficiencies N₂O CS-low PR1*

```
RCOSP(cou, 'N2O', 'CS_low', ani, 'PR1') = -EF1 * ECOEF_N(cou, 'NH3', ani, 'PR2') *
(RCOEF('nh3', 'cs_low', ani, 'PR2') $(not RCOSP(cou, 'nh3', 'cs_low', ani, 'PR2')) +
RCOSP(cou, 'nh3', 'cs_low', ani, 'PR2')) / ECOEF_N(cou, 'N2O', ani, 'PR1');
```

**removal efficiencies N₂O CS-low PR2*

```
RCOEF('N2O', 'CS_low', f, 'PR2') = RCOEF_N2O('CS_low', f, 'PR2');
RCOSP(cou, 'N2O', 'CS_low', ani, 'PR2') $RCOSP_N2O(cou, 'CS_low', ani, 'PR2') =
RCOSP_N2O(cou, 'CS_low', ani, 'PR2');
```

**removal efficiencies N₂O CS-low PR4*

```
RCOSP(cou, 'N2O', 'CS_low', ani, 'PR4') = -EF5 * FRACLEACH * ECOEF_N(cou, 'NH3', ani, 'PR2') *
(RCOEF('nh3', 'cs_low', ani, 'PR2') $(not RCOSP(cou, 'nh3', 'cs_low', ani, 'PR2')) +
RCOSP(cou, 'nh3', 'cs_low', ani, 'PR2')) / ECOEF_N(cou, 'N2O', ani, 'PR4');
```

**removal efficiencies N₂O LNA-high PR1*

```
RCOEF('N2O', 'LNA_high', f, 'PR1') = RCOEF_N2O('LNA_high', f, 'PR1');
RCOSP(cou, 'N2O', 'LNA_high', ani, 'PR1') $RCOSP_N2O(cou, 'LNA_high', ani, 'PR1') =
RCOSP_N2O(cou, 'LNA_high', ani, 'PR1');
```

**removal efficiencies N₂O LNA-high PR4*

```
RCOSP(cou, 'N2O', 'LNA_high', ani, 'PR4') = -EF5 * FRACLEACH * ECOEF_N(cou, 'NH3', ani, 'PR3') *
(RCOEF('nh3', 'lna_high', ani, 'PR3') $(not RCOSP(cou, 'nh3', 'lna_high', ani, 'PR3')) +
RCOSP(cou, 'nh3', 'lna_high', ani, 'PR3')) / ECOEF_N(cou, 'N2O', ani, 'PR4');
```

**removal efficiencies N₂O LNA-low PRI*

```
RCOEF('N2O','LNA_low',f,'PR1') = RCOEF_N2O('LNA_low',f,'PR1');
RCOSP(cou,'N2O','LNA_low',ani,'PR1')$RCOSP_N2O(cou,'LNA_low',ani,'PR1') =
RCOSP_N2O(cou,'LNA_low',ani,'PR1');
```

**removal efficiencies N₂O LNA-low PR4*

```
RCOSP(cou,'N2O','LNA_low',ani,'PR4')$ECOEF_N(cou,'N2O',ani,'PR4') =
-EF5*FRACLEACH*ECOEF_N(cou,'NH3',ani,'PR3')*
(RCOEF('NH3','LNA_low',ani,'PR3')$(not RCOSP(cou,'NH3','LNA_low',ani,'PR3')) +
RCOSP(cou,'NH3','LNA_low',ani,'PR3'))/ECOEF_N(cou,'N2O',ani,'PR4');
```

**abatement technology not applicable if no reduction is obtained*

```
APPL_POT(cou,abat_techn,f)
$(sum((p,pr),RCOEF(p,abat_techn,f,pr)+RCOSP(cou,p,abat_techn,f,pr)) eq 0) = 0;
APPL_POT(cou,'NC',f)=1;
```

**determine possible combinations of abatement techniques*

```
ALIAS(ABAT_TECHN,a1,a2,a3,a4,a5,a6,a7,a8);
```

SET

```
ABT_COMBS_5(a1,a2,a3,a4,a5) possible combinations of 5 individual abatement techniques
ABT_COMBS(a1,a2,a3,a4,a5,a6) possible combinations of 6 individual abatement techniques
```

```
;
```

```
ABT_COMBS_5(a1,a2,a3,a4,a5)
```

```
$(not ABT_FICT(a1))$(not ABT_FICT(a2))$(not ABT_FICT(a3))$(not ABT_FICT(a4))$(not
```

```
ABT_FICT(a5)) =
```

```
YES$((ord(a1)<ord(a2))OR((ord(a1)=1)AND(ord(a2)=1)))
```

```
AND((ord(a1)<ord(a3))OR((ord(a1)=1)AND(ord(a3)=1)))
```

```
AND((ord(a1)<ord(a4))OR((ord(a1)=1)AND(ord(a4)=1)))
```

```
AND((ord(a1)<ord(a5))OR((ord(a1)=1)AND(ord(a5)=1)))
```

```
AND((ord(a2)<ord(a3))OR((ord(a2)=1)AND(ord(a3)=1)))
```

```
AND((ord(a2)<ord(a4))OR((ord(a2)=1)AND(ord(a4)=1)))
```

```
AND((ord(a2)<ord(a5))OR((ord(a2)=1)AND(ord(a5)=1)))
```

```
AND((ord(a3)<ord(a4))OR((ord(a3)=1)AND(ord(a4)=1)))
```

```
AND((ord(a3)<ord(a5))OR((ord(a3)=1)AND(ord(a5)=1)))
```

```
AND((ord(a4)<ord(a5))OR((ord(a4)=1)AND(ord(a5)=1)))));
```

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)$ABT_COMBS_5(a1,a2,a3,a4,a5)$ABAT_TECHN(a6)$(not ABT_FICT(a6)) =
```

```
YES$(((ord(a1)<ord(a6)) OR ((ord(a1)=1)AND(ord(a6)=1)))
```

```
AND ((ord(a2)<ord(a6)) OR ((ord(a2)=1)AND(ord(a6)=1)))
```

```
AND ((ord(a3)<ord(a6)) OR ((ord(a3)=1)AND(ord(a6)=1)))
```

```
AND ((ord(a4)<ord(a6)) OR ((ord(a4)=1)AND(ord(a6)=1)))
```

```
AND ((ord(a5)<ord(a6)) OR ((ord(a5)=1)AND(ord(a6)=1)))));
```

excluding several combinations of techniques:*SA cannot be combined with CS_high and CS_low*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)$((sameas(a1,'SA')AND(sameas(a2,'CS_high')OR sameas(a2,'CS_low'))
OR(sameas(a1,'SA')AND(sameas(a3,'CS_high')OR sameas(a3,'CS_low'))
OR(sameas(a1,'SA')AND(sameas(a4,'CS_high')OR sameas(a4,'CS_low'))
OR(sameas(a1,'SA')AND(sameas(a5,'CS_high')OR sameas(a5,'CS_low'))
OR(sameas(a1,'SA')AND(sameas(a6,'CS_high')OR sameas(a6,'CS_low'))
OR(sameas(a2,'SA')AND(sameas(a3,'CS_high')OR sameas(a3,'CS_low'))
OR(sameas(a2,'SA')AND(sameas(a4,'CS_high')OR sameas(a4,'CS_low'))
OR(sameas(a2,'SA')AND(sameas(a5,'CS_high')OR sameas(a5,'CS_low'))
OR(sameas(a2,'SA')AND(sameas(a6,'CS_high')OR sameas(a6,'CS_low'))
OR(sameas(a3,'SA')AND(sameas(a4,'CS_high')OR sameas(a4,'CS_low'))
OR(sameas(a3,'SA')AND(sameas(a5,'CS_high')OR sameas(a5,'CS_low'))
OR(sameas(a3,'SA')AND(sameas(a6,'CS_high')OR sameas(a6,'CS_low'))
OR(sameas(a4,'SA')AND(sameas(a5,'CS_high')OR sameas(a5,'CS_low'))
OR(sameas(a4,'SA')AND(sameas(a6,'CS_high')OR sameas(a6,'CS_low'))
OR(sameas(a5,'SA')AND(sameas(a6,'CS_high')OR sameas(a6,'CS_low'))))=NO;
```

**CS_high and CS_low cannot be combined with each other*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)$((sameas(a1,'CS_high')AND sameas(a2,'CS_low'))
OR(sameas(a1,'CS_high')AND sameas(a3,'CS_low'))
OR(sameas(a1,'CS_high')AND sameas(a4,'CS_low'))
OR(sameas(a1,'CS_high')AND sameas(a5,'CS_low'))
OR(sameas(a1,'CS_high')AND sameas(a6,'CS_low'))
OR(sameas(a2,'CS_high')AND sameas(a3,'CS_low'))
OR(sameas(a2,'CS_high')AND sameas(a4,'CS_low'))
OR(sameas(a2,'CS_high')AND sameas(a5,'CS_low'))
OR(sameas(a2,'CS_high')AND sameas(a6,'CS_low'))
OR(sameas(a3,'CS_high')AND sameas(a4,'CS_low'))
OR(sameas(a3,'CS_high')AND sameas(a5,'CS_low'))
OR(sameas(a3,'CS_high')AND sameas(a6,'CS_low'))
OR(sameas(a4,'CS_high')AND sameas(a5,'CS_low'))
OR(sameas(a4,'CS_high')AND sameas(a6,'CS_low'))
OR(sameas(a5,'CS_high')AND sameas(a6,'CS_low'))=NO;
```

**LNA_high and LNA_low cannot be combined with each other*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)$( (sameas(a1,'LNA_high')AND sameas(a2,'LNA_low'))
OR(sameas(a1,'LNA_high')AND sameas(a3,'LNA_low'))
OR(sameas(a1,'LNA_high')AND sameas(a4,'LNA_low'))
OR(sameas(a1,'LNA_high')AND sameas(a5,'LNA_low'))
OR(sameas(a1,'LNA_high')AND sameas(a6,'LNA_low'))
OR(sameas(a2,'LNA_high')AND sameas(a3,'LNA_low'))
OR(sameas(a2,'LNA_high')AND sameas(a4,'LNA_low'))
OR(sameas(a2,'LNA_high')AND sameas(a5,'LNA_low'))
OR(sameas(a2,'LNA_high')AND sameas(a6,'LNA_low'))
OR(sameas(a3,'LNA_high')AND sameas(a4,'LNA_low'))
OR(sameas(a3,'LNA_high')AND sameas(a5,'LNA_low'))
OR(sameas(a3,'LNA_high')AND sameas(a6,'LNA_low'))
OR(sameas(a4,'LNA_high')AND sameas(a5,'LNA_low'))
OR(sameas(a4,'LNA_high')AND sameas(a6,'LNA_low'))
OR(sameas(a5,'LNA_high')AND sameas(a6,'LNA_low')))=NO;
```

**LNF, PROPIONATE and PROBIOTICS cannot be combined with each other*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)
$( (sameas(a1,'LNF')AND(sameas(a2,'PROPIONATE')OR sameas(a2,'PROBIOTICS'))
OR(sameas(a1,'LNF')AND(sameas(a3,'PROPIONATE')OR sameas(a3,'PROBIOTICS'))
OR(sameas(a1,'LNF')AND(sameas(a4,'PROPIONATE')OR sameas(a4,'PROBIOTICS'))
OR(sameas(a1,'LNF')AND(sameas(a5,'PROPIONATE')OR sameas(a5,'PROBIOTICS'))
OR(sameas(a1,'LNF')AND(sameas(a6,'PROPIONATE')OR sameas(a6,'PROBIOTICS'))
OR(sameas(a2,'LNF')AND(sameas(a3,'PROPIONATE')OR sameas(a3,'PROBIOTICS'))
OR(sameas(a2,'LNF')AND(sameas(a4,'PROPIONATE')OR sameas(a4,'PROBIOTICS'))
OR(sameas(a2,'LNF')AND(sameas(a5,'PROPIONATE')OR sameas(a5,'PROBIOTICS'))
OR(sameas(a2,'LNF')AND(sameas(a6,'PROPIONATE')OR sameas(a6,'PROBIOTICS'))
OR(sameas(a3,'LNF')AND(sameas(a4,'PROPIONATE')OR sameas(a4,'PROBIOTICS'))
OR(sameas(a3,'LNF')AND(sameas(a5,'PROPIONATE')OR sameas(a5,'PROBIOTICS'))
OR(sameas(a3,'LNF')AND(sameas(a6,'PROPIONATE')OR sameas(a6,'PROBIOTICS'))
OR(sameas(a4,'LNF')AND(sameas(a5,'PROPIONATE')OR sameas(a5,'PROBIOTICS'))
OR(sameas(a4,'LNF')AND(sameas(a6,'PROPIONATE')OR sameas(a6,'PROBIOTICS'))
OR(sameas(a5,'LNF')AND(sameas(a6,'PROPIONATE')OR sameas(a6,'PROBIOTICS'))
OR(sameas(a1,'PROPIONATE')AND(sameas(a2,'PROBIOTICS'))
OR(sameas(a1,'PROPIONATE')AND(sameas(a3,'PROBIOTICS'))
OR(sameas(a1,'PROPIONATE')AND(sameas(a4,'PROBIOTICS'))
OR(sameas(a1,'PROPIONATE')AND(sameas(a5,'PROBIOTICS'))
OR(sameas(a1,'PROPIONATE')AND(sameas(a6,'PROBIOTICS'))
OR(sameas(a2,'PROPIONATE')AND(sameas(a3,'PROBIOTICS'))
OR(sameas(a2,'PROPIONATE')AND(sameas(a4,'PROBIOTICS'))
OR(sameas(a2,'PROPIONATE')AND(sameas(a5,'PROBIOTICS'))
OR(sameas(a2,'PROPIONATE')AND(sameas(a6,'PROBIOTICS'))
OR(sameas(a3,'PROPIONATE')AND(sameas(a4,'PROBIOTICS'))
OR(sameas(a3,'PROPIONATE')AND(sameas(a5,'PROBIOTICS'))
OR(sameas(a3,'PROPIONATE')AND(sameas(a6,'PROBIOTICS'))
OR(sameas(a4,'PROPIONATE')AND(sameas(a5,'PROBIOTICS'))
OR(sameas(a4,'PROPIONATE')AND(sameas(a6,'PROBIOTICS'))
OR(sameas(a5,'PROPIONATE')AND(sameas(a6,'PROBIOTICS')))=NO;
```

**SUB cannot be combined with FERTSUBST*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)
$( (sameas(a1,'SUB')AND(sameas(a2,'FERTSUBST')OR sameas(a3,'FERTSUBST')OR sameas(a4,'FERTSUBST')
OR sameas(a5,'FERTSUBST')OR sameas(a6,'FERTSUBST'))
OR(sameas(a2,'SUB')AND(sameas(a3,'FERTSUBST')OR sameas(a4,'FERTSUBST')OR sameas(a5,'FERTSUBST')
OR sameas(a6,'FERTSUBST'))
OR(sameas(a3,'SUB')AND(sameas(a4,'FERTSUBST')OR sameas(a5,'FERTSUBST')OR sameas(a6,'FERTSUBST'))
OR(sameas(a4,'SUB')AND(sameas(a5,'FERTSUBST')OR sameas(a6,'FERTSUBST'))
OR(sameas(a5,'SUB')AND(sameas(a6,'FERTSUBST')))=NO;
```

**FERTSUBST cannot be combined with FERTEFFIMPR*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)
$( (sameas(a1,'FERTSUBST')AND(sameas(a2,'FERTEFFIMPR')OR sameas(a3,'FERTEFFIMPR')
OR sameas(a4,'FERTEFFIMPR')OR sameas(a5,'FERTEFFIMPR')OR sameas(a6,'FERTEFFIMPR'))
OR(sameas(a2,'FERTSUBST')AND(sameas(a3,'FERTEFFIMPR')OR sameas(a4,'FERTEFFIMPR')
OR sameas(a5,'FERTEFFIMPR')OR sameas(a6,'FERTEFFIMPR'))
OR(sameas(a3,'FERTSUBST')AND(sameas(a4,'FERTEFFIMPR')OR sameas(a5,'FERTEFFIMPR')
OR sameas(a6,'FERTEFFIMPR'))
OR(sameas(a4,'FERTSUBST')AND(sameas(a5,'FERTEFFIMPR')OR sameas(a6,'FERTEFFIMPR'))
OR(sameas(a5,'FERTSUBST')AND(sameas(a6,'FERTEFFIMPR')))=NO;
```

**FERTTIMING cannot be combined with DAILYSPREAD*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)
$( (sameas(a1,'FERTTIMING')AND(sameas(a2,'DAILYSPREAD')OR sameas(a3,'DAILYSPREAD')
OR sameas(a4,'DAILYSPREAD')OR sameas(a5,'DAILYSPREAD')OR sameas(a6,'DAILYSPREAD'))
```


**AD CENTRALISED cannot be combined with AD SMALLSCALE*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)$((sameas(a1,'AD_CENTRALISED')AND sameas(a2,'AD_SMALLSCALE'))
OR(sameas(a1,'AD_CENTRALISED')AND sameas(a3,'AD_SMALLSCALE'))
OR(sameas(a1,'AD_CENTRALISED')AND sameas(a4,'AD_SMALLSCALE'))
OR(sameas(a1,'AD_CENTRALISED')AND sameas(a5,'AD_SMALLSCALE'))
OR(sameas(a1,'AD_CENTRALISED')AND sameas(a6,'AD_SMALLSCALE'))
OR(sameas(a2,'AD_CENTRALISED')AND sameas(a3,'AD_SMALLSCALE'))
OR(sameas(a2,'AD_CENTRALISED')AND sameas(a4,'AD_SMALLSCALE'))
OR(sameas(a2,'AD_CENTRALISED')AND sameas(a5,'AD_SMALLSCALE'))
OR(sameas(a2,'AD_CENTRALISED')AND sameas(a6,'AD_SMALLSCALE'))
OR(sameas(a3,'AD_CENTRALISED')AND sameas(a4,'AD_SMALLSCALE'))
OR(sameas(a3,'AD_CENTRALISED')AND sameas(a5,'AD_SMALLSCALE'))
OR(sameas(a3,'AD_CENTRALISED')AND sameas(a6,'AD_SMALLSCALE'))
OR(sameas(a4,'AD_CENTRALISED')AND sameas(a5,'AD_SMALLSCALE'))
OR(sameas(a4,'AD_CENTRALISED')AND sameas(a6,'AD_SMALLSCALE'))
OR(sameas(a5,'AD_CENTRALISED')AND sameas(a6,'AD_SMALLSCALE')))=NO;
```

PARAMETER

```
ANI_TECHN_COMBS(a1,a2,a3,a4,a5,a6,f,pr) possible combinations of options in animal categories;
ANI_TECHN_COMBS(a1,a2,a3,a4,a5,a6,f,'PR1')$(ABT_COMBS(a1,a2,a3,a4,a5,a6)
$sum(cou,APPL_POT(cou,a1,f))$sum(cou,APPL_POT(cou,a2,f))$sum(cou,APPL_POT(cou,a3,f))
$sum(cou,APPL_POT(cou,a4,f))$sum(cou,APPL_POT(cou,a5,f))$sum(cou,APPL_POT(cou,a6,f))) = 1;
```

**exclude redundant combinations*

```
ABT_COMBS(a1,a2,a3,a4,a5,a6)$sum(f,ANI_TECHN_COMBS(a1,a2,a3,a4,a5,a6,f,'PR1')) eq 0) = no;
```

**determine emission reduction of possible combinations of techniques*

PARAMETER

```
EMIS_REDU(cou,p,a1,a2,a3,a4,a5,a6,f,pr) relative emission reduction by combination techniques;
EMIS_REDU(cou,p,a1,a2,a3,a4,a5,a6,f,pr)
$(ABT_COMBS(a1,a2,a3,a4,a5,a6)$ANI_TECHN_COMBS(a1,a2,a3,a4,a5,a6,f,'PR1')$ECOEF(cou,p,f,pr)
$APPL_POT(cou,a1,f)$APPL_POT(cou,a2,f)$APPL_POT(cou,a3,f)
$APPL_POT(cou,a4,f)$APPL_POT(cou,a5,f)$APPL_POT(cou,a6,f)) =
(1-(1-(RCOEF(p,a1,f,pr))$(not RCOSP(cou,p,a1,f,pr))+RCOSP(cou,p,a1,f,pr)))*
(1-(RCOEF(p,a2,f,pr))$(not RCOSP(cou,p,a2,f,pr))+RCOSP(cou,p,a2,f,pr)))*
(1-(RCOEF(p,a3,f,pr))$(not RCOSP(cou,p,a3,f,pr))+RCOSP(cou,p,a3,f,pr)))*
(1-(RCOEF(p,a4,f,pr))$(not RCOSP(cou,p,a4,f,pr))+RCOSP(cou,p,a4,f,pr)))*
(1-(RCOEF(p,a5,f,pr))$(not RCOSP(cou,p,a5,f,pr))+RCOSP(cou,p,a5,f,pr)))*
(1-(RCOEF(p,a6,f,pr))$(not RCOSP(cou,p,a6,f,pr))+RCOSP(cou,p,a6,f,pr))));
```

**determine cost per unit for single techniques if only cost per ton emissions reduced is available:*

```
loop(p,
COST_ANIM(cou,abat_techn,f)$COST_POLL(cou,p,abat_techn,f) =
COST_POLL(cou,p,abat_techn,f)*SUM(pr,ECOEF(cou,p,f,pr) *
(RCOEF(p,abat_techn,f,pr))$(not RCOSP(cou,p,abat_techn,f,pr))+RCOSP(cou,p,abat_techn,f,pr)));
);
```

**calculation of abatement cost for combinations of techniques*

PARAMETER

```
ABCOST_COMBI(cou,a1,a2,a3,a4,a5,a6,f) total abatement costs per combination of techniques;
ABCOST_COMBI(cou,a1,a2,a3,a4,a5,a6,f)$(ABT_COMBS(a1,a2,a3,a4,a5,a6)) =
COST_ANIM(cou,a1,f)+COST_ANIM(cou,a2,f)+COST_ANIM(cou,a3,f)+
COST_ANIM(cou,a4,f)+COST_ANIM(cou,a5,f)+ COST_ANIM(cou,a6,f));
```

PARAMETER

```
EQUIVALENT(m,p) 'conversion factor to index (acid equivalents, CO2 equivalents)';
EQUIVALENT('CC','N2O') = 310;
EQUIVALENT('CC','CH4') = 21;
EQUIVALENT('AC','SO2') = 1e9*32/64*2/32;
EQUIVALENT('AC','NOX') = 1e9*14/46*1/14;
EQUIVALENT('AC','NH3') = 1e9*14/17*1/14;
```

POSITIVE VARIABLES

```
EMIS_COU_P(scen,cou,p) emissions of pollutant per country (kilotons per year)
EMIS_TOT_M(scen,m) total emissions contributing to problem (kilotons equivalents per year)
APPL_SCEN(scen,countries,abat_techn,f) total application of abatement technique at source
ABCOSTCO(scen,cou) total abatement costs per country (million Euro per year)
APPL_RATE(SCEN,cou,a1,a2,a3,a4,a5,a6,f) rate of implementation of abatement technique
;
```

VARIABLES

```
TOTEM_NH3 total emissions NH3 (million tons per year)
TOTEM_N2O total emissions N2O (million tons per year)
TOTEM_CH4 total emissions CH4 (million tons per year)
TOTCOST total costs (million Euro per year)
;
```

EQUATIONS**calculation of emissions*

EMIS_COU_P_EQ(scen,cou,p) emissions of pollutant per country
 EMIS_TOT_M_EQ(scen,m) total emissions contributing to problem

**various constraints on application of abatement techniques*

APPL_SCEN_EQ(scen,countries,abat_techn,f) sum of application rates within category
 APPL_CON_EQ(scen,cou,f) constraint on total abatement in sector
 APPL_CON2_EQ(scen,cou,abat_techn,f) constraint on application abatement technique at source
 APPL_GOT_EQ(scen,cou, abat_techn,f) to hold abatement strategy determined in GOT fixed in SC_OPT

**abatement cost calculation*

ABCOSTCO_EQ(scen,cou) total abatement costs per country million Euro per year

**alternative objective functions*

TOTCOST_EQ total abatement costs
 TOTEMNH3_EQ total emissions NH3 (million tons per year) - alternative objective
 TOTEMN2O_EQ total emissions N2O (million tons per year) - alternative objective
 TOTEMCH4_EQ total emissions CH4 (million tons per year) - alternative objective

```
;
EMIS_COU_P_EQ(sc_opt,cou,p)..
EMIS_COU_P(sc_opt,cou,p) =E=
SUM((f,pr)$ (AGRACT(cou,f)$ECOEF(cou,p,f,pr)),AGRACT(cou,f)*ECOEF(cou,p,f,pr)*
(1-SUM(ABT_COMBS(a1,a2,a3,a4,a5,a6)$EMIS_REDU(cou,p,abt_combs,f,pr),
APPL_RATE(sc_opt,cou,abt_combs,f)*EMIS_REDU(cou,p,abt_combs,f,pr))));
EMIS_TOT_M_EQ(sc_opt,m)..
EMIS_TOT_M(sc_opt,m) =E= SUM((cou,p),EQUIVALENT(m,p)*EMIS_COU_P(sc_opt,cou,p));
```

```
APPL_SCEN_EQ(sc_opt,cou,abat_techn,f)$APPL_POT(cou,abat_techn,f)..
APPL_SCEN(sc_opt,cou,abat_techn,f) =e= SUM(ABT_COMBS(a1,a2,a3,a4,a5,a6)
$(sameas(a1,abat_techn) OR sameas(a2,abat_techn) OR sameas(a3,abat_techn)
OR sameas(a4,abat_techn) OR sameas(a5,abat_techn) OR sameas(a6,abat_techn))
$ANI_TECHN_COMBS(a1,a2,a3,a4,a5,a6,f,'PR1'), APPL_RATE(sc_opt,cou,a1,a2,a3,a4,a5,a6,f));
APPL_CON_EQ(sc_opt,cou,f)..
SUM(ABT_COMBS(a1,a2,a3,a4,a5,a6),APPL_RATE(sc_opt,cou,abt_combs,f)) =L= 1;
APPL_CON2_EQ(sc_opt,cou,abat_techn,f)..
APPL_SCEN(sc_opt,cou,abat_techn,f) =L= APPL_POT(cou,abat_techn,f);
APPL_GOT_EQ(sc_opt,cou,abat_techn,f)$((not sameas(abat_techn,'NC'))$APPL_POT(cou,abat_techn,f))..
APPL_SCEN(sc_opt,cou,abat_techn,f) =G= APPL_SCEN.1('GOT',cou,abat_techn,f);
```

```
ABCOSTCO_EQ(sc_opt,cou)..
ABCOSTCO(sc_opt,cou) =E= SUM(f$AGRACT(cou,f),
SUM(ABT_COMBS(a1,a2,a3,a4,a5,a6)
$(ABCOST_COMBI(cou,abt_combs,f)$sum((p,pr),EMIS_REDU(cou,p,abt_combs,f,pr))),
APPL_RATE(sc_opt,cou,abt_combs,f)*ABCOST_COMBI(cou,abt_combs,f)*AGRACT(cou,f)));
```

```
TOTCOST_EQ.. TOTCOST =E= SUM((sc_opt,cou),ABCOSTCO(sc_opt,cou))/1000;
TOTEMNH3_EQ.. TOTEM_NH3 =E= SUM((sc_opt,cou),EMIS_COU_P(sc_opt,cou,'NH3'))/1000;
TOTEMN2O_EQ.. TOTEM_N2O =E= SUM((sc_opt,cou),EMIS_COU_P(sc_opt,cou,'N2O'))/1000;
TOTEMCH4_EQ.. TOTEM_CH4 =E= SUM((sc_opt,cou),EMIS_COU_P(sc_opt,cou,'CH4'))/1000;
```

MODEL

AGRAR 'model to identify cost-effective abatement strategies with restrictions on emissions'
 /EMIS_COU_P_EQ,EMIS_TOT_M_EQ,APPL_SCEN_EQ,APPL_CON_EQ,APPL_CON2_EQ,ABCOSTCO_EQ,TOTCOST_EQ/

AGRAR_MFR 'model for maximising reductions for various pollutants'
 /EMIS_COU_P_EQ,EMIS_TOT_M_EQ,APPL_SCEN_EQ,APPL_CON_EQ,APPL_CON2_EQ,
 TOTEMNH3_EQ,TOTEMN2O_EQ,TOTEMCH4_EQ/

AGRAR_GOT 'model with previously determined abatement strategy from GOT fixed'
 /EMIS_COU_P_EQ,EMIS_TOT_M_EQ,APPL_SCEN_EQ,APPL_CON_EQ,APPL_CON2_EQ,APPL_GOT_EQ,
 ABCOSTCO_EQ,TOTCOST_EQ/

```
;
```

**model run for no control scenario (NOC)*

```
SC_OPT(scen) = NO;
SC_OPT('NOC') = YES;
APPL_RATE.up('NOC',cou,abt_combs,f)$ANI_TECHN_COMBS(abt_combs,f,'PR1') = 0;
APPL_RATE.fx('NOC',cou,'NC','NC','NC','NC','NC',f)=1;
SOLVE AGRAR MINIMIZING TOTCOST USING LP;
```

define parameters for specifying constraints on emissions in various scenarios*PARAMETERS**

EMIS_CON_COU_P(scen,cou,p) constraint on emissions per country;

**read targets for GOT scenario*

```
$include input\GOT_targets.txt
```


**model run for Gothenburg Protocol scenario (GOT)*

```
SC_OPT(scen) = NO;
SC_OPT('GOT') = YES;
EMIS_COU_P.up('GOT',cou,'NH3') = EMIS_CON_COU_P('GOT',cou,'NH3');
SOLVE AGRAR MINIMIZING TOTCOST USING LP;
```

**model run for Nitrous Oxide and Methane reduction scenario (NMR)*

```
SC_OPT(scen) = NO;
SC_OPT('NMR') = YES;
EMIS_TOT_M.up('NMR','CC') = 0.925*EMIS_TOT_M.l('NOC','CC');
SOLVE AGRAR MINIMIZING TOTCOST USING LP;
```

**scenario for simultaneous reductions in NH₃, N₂O and CH₄ emissions in Europe*

```
SC_OPT(scen) = NO;
SC_OPT('GOT_NMR1') = YES;
EMIS_COU_P.up('GOT_NMR1',cou,'NH3') =
  MIN(EMIS_COU_P.l('NOC',cou,'NH3'),EMIS_CON_COU_P('GOT',cou,'NH3'));
EMIS_TOT_M.up('GOT_NMR1','CC') = 0.925*EMIS_TOT_M.l('NOC','CC');
SOLVE AGRAR MINIMIZING TOTCOST USING LP;
```

**scenario for simultaneous reductions in NH₃, N₂O and CH₄ with NH₃ abatement strategy from 'GOT' held fixed*

```
SC_OPT(scen) = NO;
SC_OPT('GOT_NMR2') = YES;
EMIS_COU_P.up('GOT_NMR2',cou,'NH3') =
  MIN(EMIS_COU_P.l('NOC',cou,'NH3'),EMIS_CON_COU_P('GOT',cou,'NH3'));
EMIS_TOT_M.up('GOT_NMR2','CC') = 0.925*EMIS_TOT_M.l('NOC','CC');
SOLVE AGRAR_GOT MINIMIZING TOTCOST USING LP;
```

**scenario for maximisation of reductions in NH₃ (MFR)*

```
SC_OPT(scen) = NO;
SC_OPT('MFR') = YES;
SOLVE AGRAR_MFR MINIMIZING TOTEM_NH3 USING LP;
```

GAMS specification for the extended model in Chapter 6

(specification of additional sets, parameters, variables and equations compared with model in Chapter 4)

**read data input for SO₂ and NO_x emissions and abatement from the RAINS databases*

PARAMETERS

```
VAL_SO2_IMP(abt_fict_so2,cou,*) values imported from SO2 cost curve RAINS
VAL_NOX_IMP(abt_fict_nox,cou,*) values imported from Nox cost curve RAINS
;
$libinclude xlexport VAL_SO2_IMP input\so2_costcurve.xls SO2_CC
$libinclude xlexport VAL_NOX_IMP input\nox_costcurve.xls NOX_CC
```

**determination of SO₂ and NO_x emissions per country, exogenous level taken from RAINS*

```
ECOEF(cou,'SO2','SRC_SO2','PR1') = VAL_SO2_IMP('10000',cou,'REMAIN_EMIS');
ECOEF(cou,'NOX','SRC_NOX','PR1') = VAL_NOX_IMP('20000',cou,'REMAIN_EMIS');
```

**determination of abatement cost for SO₂ and NO_x control options*

```
COST_ANIM(cou,abt_fict_so2,'SRC_SO2') = VAL_SO2_IMP(abt_fict_so2,cou,'TOTAL_COST');
COST_ANIM(cou,abt_fict_nox,'SRC_NOX') = VAL_NOX_IMP(abt_fict_nox,cou,'TOTAL_COST');
```

**determination of emission removal efficiencies for SO₂ and NO_x control options*

```
RCOSP(cou,'SO2',abt_fict_so2,'SRC_SO2','PR1') = VAL_SO2_IMP(abt_fict_so2,cou,'EMIS_REMOVAL');
RCOSP(cou,'NOX',abt_fict_nox,'SRC_NOX','PR1') = VAL_NOX_IMP(abt_fict_nox,cou,'EMIS_REMOVAL');
```

**activity level for non-agricultural sources with exogenous emissions represented by RCOSP(.)*

```
AGRACT(cou,non_agr) = 1;
```

**potential application of fictional abatement options*

```
APPL_POT(cou,abt_fict,non_agr) = 1;
```

**fictional abatement options cannot be applied in combination with other options*

```
ABT_COMBS('NC','NC','NC','NC','NC',abt_fict) = YES;
```

**introduce atmospheric transport of emissions in the model to calculate deposition of sulphur and nitrogen*

SETS

**150×150 km grids in Europe included in the model*

```
GRID_X_ALL x-co-ordinates of grids in Europe /x02*x38/
GRID_Y_ALL y-co-ordinates of grids in Europe /y01*y09,y10*y37/
```

**subsets of grids included in the current analysis*

```
GRID_X(grid_x_all) x-co-ordinates of grids in Europe included in current analysis
/x13*x38/
GRID_Y(grid_y_all) y-co-ordinates of grids in Europe included in current analysis
/y02*y09,y10*y36/
```

**define parameters related to source-receptor relationships*

PARAMETERS

```
EMBASE(cou,p) emissions of SO2 NOx NH3 from country in kilotons for a baseyear
DEPA(grid_x_all,grid_y_all,cou) 'deposition NH3 from country in grid x_y (mg N per m2 per yr)'
DEPN(grid_x_all,grid_y_all,cou) 'deposition NOX from country in grid x_y (mg N per m2 per yr)'
DEPS(grid_x_all,grid_y_all,cou) 'deposition SO2 from country in grid x_y (mg S per m2 per yr)'
SRC_REC_FRAC(cou,grid_x_all,grid_y_all,p)
'fraction of emissions from country (kton SO2/NOx/NH3) deposited in grid x_y (mg S/N per m2)'
```

**read base emissions SO₂, NO_x and NH₃ used to calculate source-receptor relationships (kilotons)*

```
$include input\embase_so2_nox_nh3.txt
```

**read deposition NH₃, NO_x and SO₂ from country deposited in grid x_y (mg N or S per m2 per yr)*

```
$include input\depa_matrix.txt
$include input\depn_matrix.txt
$include input\deps_matrix.txt
```

**calculation of SRC REC FRAC*

```
SRC_REC_FRAC(cou,grid_x,grid_y,'SO2')$EMBASE(cou,'SO2')=DEPS(grid_x,grid_y,cou)/EMBASE(cou,'SO2');
SRC_REC_FRAC(cou,grid_x,grid_y,'NOx')$EMBASE(cou,'NOx')=DEPN(grid_x,grid_y,cou)/EMBASE(cou,'NOx');
SRC_REC_FRAC(cou,grid_x,grid_y,'NH3')$EMBASE(cou,'NH3')=DEPA(grid_x,grid_y,cou)/EMBASE(cou,'NH3');
```

**include deposition due to exogenous emissions (so-called background deposition)*

PARAMETERS

```
BKDEP_A(grid_x_all,grid_y_all,cou) 'deposition NH3 exogenous in model (mg N per m2 per yr)'
BKDEP_N(grid_x_all,grid_y_all,cou) 'deposition NOX exogenous in model (mg N per m2 per yr)'
BKDEP_S(grid_x_all,grid_y_all,cou) 'deposition SO2 exogenous in model (mg S per m2 per yr)'
BKDEP_TOT(grid_x_all,grid_y_all,p) 'total background deposition at grid x_y (mg S or N/m2/yr)'
```

**read background deposition values for SO₂, NO_x and NH₃*

```
$include input\bkdep_s.txt
$include input\bkdep_n.txt
$include input\bkdep_a.txt
```

**calculate total background deposition of SO₂, NO_x and NH₃ for each grid x_y*

```
BKDEP_TOT(grid_x,grid_y,'nh3')=sum(exo_reg,bkdep_a(grid_x,grid_y,exo_reg));
BKDEP_TOT(grid_x,grid_y,'nox')=sum(exo_reg,bkdep_n(grid_x,grid_y,exo_reg));
BKDEP_TOT(grid_x,grid_y,'so2')=sum(exo_reg,bkdep_s(grid_x,grid_y,exo_reg));
```

**specification of parameters, variables and equations for calculating deposition levels*

PARAMETER

```
GAP_CLOSE1(scen) value (fraction) for gap-closure target in scenario
GAP_CLOSE2(scen) value (fraction) for gap-closure target in scenario
CONV_S 'conversion for deposition from mg/m2 S to equivalent/ha'
CONV_N 'conversion for deposition from mg/m2 N to equivalent/ha'
CL_max_S(grid_x_all,grid_y_all)
'maximum critical load of sulfur (5th percentile; eq/ha/yr; more details: Posch et al. (1999))'
CL_min_N(grid_x_all,grid_y_all)
'minimum critical load of nitrogen (5th percentile; eq/ha/yr; Posch et al. (1999))'
CL_max_N(grid_x_all,grid_y_all)
'maximum critical load of nitrogen acidity (5th percentile; eq/ha/yr; Posch et al. (1999))'
CL_nut_N(grid_x_all,grid_y_all)
'critical load of nutrient nitrogen (5th percentile; eq/ha/yr; Posch et al. (1999))'
EXS_GRD_P(grid_x,grid_y) exceedance of S deposition over critical load in NOC scenario
EXN_GRD_P(grid_x,grid_y) exceedance of acidifying N deposition over critical load in NOC scenario
EXNUT_GRD_P(grid_x,grid_y) exceedance of nutrient N deposition over critical load in NOC scenario
EXS_GRD_SC(scen,grid_x,grid_y) exceedance of S deposition over critical load in scenario
EXN_GRD_SC(scen,grid_x,grid_y) exceedance of acid N deposition over critical load in scenario
EXNUT_GRD_SC(scen,grid_x,grid_y) exc. of nutrient N deposition over critical load in scenario
;
CONV_S = 20/32;
CONV_N = 10/14;
GAP_CLOSE(SCEN) = 0.4;
```

**read critical load values from files (data obtained from Coordination Center for Effects (CCE), June 2001)*

```
$include input\clmaxs_5.txt
$include input\clminn_5.txt
$include input\clmaxn_5.txt
$include input\clnut_5.txt
```

POSITIVE VARIABLES

```
DEP_GRID_S(scen,grid_x,grid_y) 'deposition of S at grid (eq/ha/yr)'
DEP_GRID_N(scen,grid_x,grid_y) 'deposition of N at grid (eq/ha/yr)'
;
```

EQUATIONS

**calculation of deposition at grid-cells*

```
DEP_GRID_S_EQ(scen,grid_x,grid_y) 'deposition of S at grid (eq/ha/yr)'
DEP_GRID_N_EQ(scen,grid_x,grid_y) 'deposition of N at grid (eq/ha/yr)'
```

**constraints on deposition at grid-cells*

```
CON_DEPS_EQ(scen,grid_x,grid_y) 'constraint on deposition of S at grid (eq/ha/yr)'
CON_DEPN_EQ(scen,grid_x,grid_y) 'constraint on deposition of acidifying N at grid (eq/ha/yr)'
CON_EXNUT_EQ(scen,grid_x,grid_y) 'constraint on deposition of nutrient N at grid (eq/ha/yr)'
;
```

```
DEP_GRID_S_EQ(sc_opt,grid_x,grid_y)..
DEP_GRID_S(sc_opt,grid_x,grid_y) =E=
SUM(cou,CONV_S*SRC_REC_FRAC(cou,grid_x,grid_y,'SO2')*EMIS_COU_P(sc_opt,cou,'SO2'));
DEP_GRID_N_EQ(sc_opt,grid_x,grid_y)..
DEP_GRID_N(sc_opt,grid_x,grid_y) =E=
SUM((cou,n),CONV_N*SRC_REC_FRAC(cou,grid_x,grid_y,n)*EMIS_COU_P(sc_opt,cou,n));
```

```
CON_DEPS_EQ(sc_opt,grid_x,grid_y)..
DEP_GRID_S(sc_opt,grid_x,grid_y) =L=
DEP_GRID_S.l('NOC',grid_x,grid_y)-GAP_CLOSE(sc_opt)*EXS_GRD_P(grid_x,grid_y);
CON_DEPN_EQ(sc_opt,grid_x,grid_y)..
DEP_GRID_N(sc_opt,grid_x,grid_y) =L=
DEP_GRID_N.l('NOC',grid_x,grid_y)-GAP_CLOSE(sc_opt)*EXN_GRD_P(grid_x,grid_y);
CON_EXNUT_EQ(sc_opt,grid_x,grid_y)..
DEP_GRID_N(sc_opt,grid_x,grid_y) =L=
DEP_GRID_N.l('NOC',grid_x,grid_y)-GAP_CLOSE(sc_opt)*EXNUT_GRD_P(grid_x,grid_y);
```

MODEL

```
AGRAR_EXT_INI 'model (extended) to determine initial emission and deposition levels (NOC)'
/EMIS_COU_P_EQ,EMIS_TOT_M_EQ,APPL_SCEN_EQ,APPL_CON_EQ,APPL_CON2_EQ,ABCOSTCO_EQ,TOTCOST_EQ,
DEP_GRID_S_EQ,DEP_GRID_N_EQ/;
```

```

AGRAR_EXT_ABT 'model (extended) to find cost-effective solutions for various scenarios'
/EMIS_COU_P_EQ,EMIS_TOT_M_EQ,APPL_SCEN_EQ,APPL_CON_EQ,APPL_CON2_EQ,ABCOSTCO_EQ,TOTCOST_EQ,
DEP_GRID_S_EQ,DEP_GRID_N_EQ,CON_DEPS_EQ,CON_DEPN_EQ,CON_EXNUT_EQ/;

```

**model run for no control scenario (NOC)*

```

SC_OPT(scen) = NO;
SC_OPT('NOC') = YES;
APPL_RATE.up('NOC',cou,abt_combs,f)$ANI_TECHN_COMBS(abt_combs,f,'PR1') = 0;
APPL_RATE.fx('NOC',cou,'NC','NC','NC','NC','NC','NC',f)=1;
SOLVE AGRAR_EXT_INI MINIMIZING TOTCOST USING LP;

```

**calculating critical load exceedance; the following is based on Posch et al. (1999, Appendix B)*

PARAMETERS

```

D1(grid_x,grid_y)
D2(grid_x,grid_y)
DD(grid_x,grid_y)
DNN(grid_x,grid_y)
DXN(grid_x,grid_y)
DXS(grid_x,grid_y)
SS(grid_x,grid_y)
V(grid_x,grid_y)
X0(grid_x,grid_y)
Y0(grid_x,grid_y)
;

```

**calculate critical load exceedance for NOC*

```

LOOP(grid_x,grid_y),
  D1(grid_x,grid_y) = CL_MAX_N(grid_x,grid_y)-CL_MIN_N(grid_x,grid_y);
  D2(grid_x,grid_y) = -CL_MAX_S(grid_x,grid_y);
  DD(grid_x,grid_y) = D1(grid_x,grid_y)*D1(grid_x,grid_y) + D2(grid_x,grid_y)*D2(grid_x,grid_y);
  DNN(grid_x,grid_y) = DEP_GRID_N.l('NOC',grid_x,grid_y)-CL_MIN_N(grid_x,grid_y);
  DXN(grid_x,grid_y) = DEP_GRID_N.l('NOC',grid_x,grid_y)-CL_MAX_N(grid_x,grid_y);
  DXS(grid_x,grid_y) = DEP_GRID_S.l('NOC',grid_x,grid_y)-CL_MAX_S(grid_x,grid_y);
  SS(grid_x,grid_y) = DEP_GRID_N.l('NOC',grid_x,grid_y)*D1(grid_x,grid_y) +
  DEP_GRID_S.l('NOC',grid_x,grid_y)*D2(grid_x,grid_y);
  V(grid_x,grid_y) = -CL_MAX_S(grid_x,grid_y)*CL_MAX_N(grid_x,grid_y);
  X0(grid_x,grid_y) = (D1(grid_x,grid_y)*SS(grid_x,grid_y)+D2(grid_x,grid_y)*V(grid_x,grid_y))/
  DD(grid_x,grid_y);
  Y0(grid_x,grid_y) = (D2(grid_x,grid_y)*SS(grid_x,grid_y)-D1(grid_x,grid_y)*V(grid_x,grid_y))/
  DD(grid_x,grid_y);

```

```

IF((DEP_GRID_S.l('NOC',grid_x,grid_y) le CL_MAX_S(grid_x,grid_y)) AND
(DEP_GRID_N.l('NOC',grid_x,grid_y) le CL_MAX_N(grid_x,grid_y)) AND
(CL_MAX_S(grid_x,grid_y)*DXN(grid_x,grid_y) le
-D1(grid_x,grid_y)*DEP_GRID_S.l('NOC',grid_x,grid_y))),
  EXS_GRD_P(grid_x,grid_y) = 0;
  EXN_GRD_P(grid_x,grid_y) = 0;
ELSEIF(DEP_GRID_N.l('NOC',grid_x,grid_y) le CL_MIN_N(grid_x,grid_y)),
  EXS_GRD_P(grid_x,grid_y) = DXS(grid_x,grid_y);
  EXN_GRD_P(grid_x,grid_y) = 0;
ELSEIF(DXN(grid_x,grid_y)*D1(grid_x,grid_y) ge
DEP_GRID_S.l('NOC',grid_x,grid_y)*CL_MAX_S(grid_x,grid_y)),
  EXS_GRD_P(grid_x,grid_y) = DEP_GRID_S.l('NOC',grid_x,grid_y);
  EXN_GRD_P(grid_x,grid_y) = DXN(grid_x,grid_y);
ELSEIF(CL_MAX_S(grid_x,grid_y)*DXS(grid_x,grid_y) ge D1(grid_x,grid_y)*DNN(grid_x,grid_y)),
  EXS_GRD_P(grid_x,grid_y) = DXS(grid_x,grid_y);
  EXN_GRD_P(grid_x,grid_y) = DNN(grid_x,grid_y);
ELSE
  EXS_GRD_P(grid_x,grid_y) = DEP_GRID_S.l('NOC',grid_x,grid_y)-Y0(grid_x,grid_y);
  EXN_GRD_P(grid_x,grid_y) = DEP_GRID_N.l('NOC',grid_x,grid_y)-X0(grid_x,grid_y);
));
EXNUT_GRD_P(grid_x,grid_y)$(DEP_GRID_N.l('NOC',grid_x,grid_y) gt CL_NUT_N(grid_x,grid_y)) =
DEP_GRID_N.l('NOC',grid_x,grid_y)-CL_NUT_N(grid_x,grid_y);

```

**model run for the 40% GAP-closure scenario (GAP)*

```

SC_OPT(scen) = NO;
SC_OPT('GAP') = YES;
SOLVE AGRAR_EXT_ABT MINIMIZING TOTCOST USING LP;

```

**model run for the 40% GAP-closure plus 5% reduction in N₂O and CH₄ emissions (GAP_PLUS) scenario*

```

SC_OPT(scen) = NO;
SC_OPT('GAP_PLUS') = YES;
EMIS_TOT_M.up('GAP_PLUS','CC') = 0.95*EMIS_TOT_M.l('NOC','CC');
SOLVE AGRAR_EXT_ABT MINIMIZING TOTCOST USING LP;

```

Samenvatting

Kosteneffectieve reductie van emissies rekeninghoudend met interacties – een toepassing op de agrarische sector in Europa

Inleiding

Veel landen in Europa voeren beleid dat erop is gericht emissies van stoffen die bijdragen aan grootschalige luchtverontreiniging (zoals verzuring, eutrofiëring en ozon op leefniveau) terug te dringen. Belangrijke stoffen die aan deze milieuproblemen bijdragen zijn zwaveldioxide (SO₂), stikstofoxiden (NO_x), ammoniak (NH₃) en vluchtige organische stoffen (VOS). In 1999 hebben Europese landen het Gothenburg Protocol ondertekend waarin internationaal afspraken zijn gemaakt over emissiereductie doelstellingen voor deze stoffen in 2010. Daarnaast hebben de meeste Europese landen ook verplichtingen om hun emissies van broeikasgassen te reduceren, zoals is vastgelegd in het Kyoto Protocol van 1997.

Emissies van de belangrijkste broeikasgassen – kooldioxide (CO₂), methaan (CH₄) en lachgas (N₂O) – worden voor een groot deel veroorzaakt door bronnen die ook bijdragen aan luchtverontreiniging. Energie uit fossiele brandstoffen is een belangrijke bron van CO₂, SO₂, NO_x, VOS en CH₄. Landbouwactiviteiten zijn een belangrijke bron van NH₃, N₂O en CH₄. Door deze gemeenschappelijke bronnen bestaan interacties in het beleid voor grootschalige luchtverontreiniging en klimaatverandering, maar er wordt niet altijd volledig rekening mee gehouden in het huidige beleid op deze terreinen. Wel is er in de milieu-economische literatuur toenemende aandacht voor deze interacties, met name voor de synergie-effecten van CO₂ reductie door een afname in het gebruik van fossiele brandstoffen.

Dit proefschrift richt zich op interacties tussen maatregelen om NH₃, N₂O en CH₄ emissies uit de landbouwsector in Europese landen te reduceren. Het doel van het onderzoek is om te bepalen hoe deze interacties de kosteneffectiviteit van reductiemaatregelen beïnvloeden. Om dit doel te bereiken wordt eerst in kaart gebracht welke interacties er zijn. Vervolgens wordt een model beschreven waarmee een geïntegreerde kosteneffectiviteit analyse kan worden uitgevoerd voor een gelijktijdige reductie van NH₃, N₂O en CH₄, rekeninghoudend met interacties. Tenslotte wordt dit model gebruikt in een toepassing voor de Europese landbouwsector om te bepalen welke pakketten van maatregelen in 36 Europese landen moet worden ingezet om verschillende reductiedoelstellingen voor NH₃, N₂O en CH₄ te behalen tegen de laagste kosten. In de analyses wordt met name aandacht besteed aan welke maatregelen worden ingezet bij verschillende reductiedoelstellingen en hoe in de optimale uitkomst emissiereducties en bijbehorende kosten over de verschillende landen en emissiebronnen zijn verdeeld.

Interacties tussen beleid voor grootschalige luchtverontreiniging en voor klimaatverandering in de Europese landbouwsector

Aan de landbouw gerelateerde emissies van NH₃, N₂O en CH₄ hebben voor een groot deel gemeenschappelijke bronnen (o.a. vee en kunstmest). Deze emissies kunnen grotendeels worden berekend op basis van dezelfde gegevens over landbouwactiviteiten. Als eerste stap in de richting van een geïntegreerde analyse wordt in hoofdstuk 2 een methode gepresenteerd om emissies van NH₃, N₂O

en CH₄ te kunnen berekenen op basis van dezelfde informatie. Gekozen is voor informatie over de Europese landbouwsector die is opgenomen in het RAINS model om NH₃ emissies in Europa te kunnen berekenen. Vervolgens is op basis van de IPCC methode voor het bepalen van nationale broeikasgasemissies een methode ontwikkeld om N₂O en CH₄ emissies uit landbouwbronnen te kunnen berekenen op basis van de data in RAINS. Als eerste indicatie voor interacties in beleid gericht op het reduceren van NH₃, N₂O en CH₄ laten berekeningen met deze methode zien dat in Europa emissies van zowel NH₃ als N₂O en CH₄ afnemen tussen 1990 en 2010 door een verwachte afname in dieraantallen en kunstmestgebruik.

Interacties kunnen verder worden veroorzaakt doordat maatregelen om emissies van één van de stoffen terug te dringen een neveneffect kunnen hebben op emissies van andere stoffen. Kwantitatieve informatie over neveneffecten van maatregelen om NH₃, N₂O of CH₄ te reduceren is nauwelijks beschikbaar. In hoofdstuk 2 wordt voor de NH₃ reductiemaatregelen die in het RAINS model zijn opgenomen een inschatting gemaakt wat hun effect zal zijn op N₂O en CH₄ emissies. Sommige van deze maatregelen (zoals een lager stikstofgehalte in het voer en het afdekken van mestopslag) resulteren in een reductie van zowel NH₃ als N₂O emissies. Andere maatregelen reduceren weliswaar NH₃ emissies, maar hebben een mogelijk tegengesteld effect op N₂O of CH₄ emissies. Wanneer bijvoorbeeld NH₃ emissies worden gereduceerd door emissie-arme stallen en emissie-arme mesttoediening kunnen N₂O emissies toenemen. Bij sommige typen emissie-arme stallen kunnen N₂O emissies uit die stallen zelfs verdrievoudigen, terwijl de desbetreffende CH₄ emissies in sommige gevallen met 90% kunnen afnemen. Afdekken van mestopslag kan resulteren in een 10% toename van CH₄ emissies. NH₃ is ook een indirecte bron van N₂O. Deze indirecte N₂O emissies zullen afnemen wanneer NH₃ emissies dalen.

In hoofdstuk 4 (appendix 4.B) worden maatregelen beschreven waarmee emissies van N₂O en CH₄ uit landbouwactiviteiten in Europa kunnen worden teruggedrongen. Ook voor deze maatregelen is een inschatting gemaakt van de neveneffecten op NH₃ en op elkaar. Een efficiënter gebruik van kunstmest zal tegelijkertijd NH₃ en N₂O emissies reduceren. Verschillende voeraanpassingen om CH₄ emissies terug te dringen verhogen de productiviteit van dieren en zullen daardoor ook NH₃ en N₂O emissies reduceren. Anderzijds kunnen beperkingen in de periode waarin mest mag worden aangewend of waarin dieren mogen weiden resulteren in een toename in NH₃ of CH₄ emissies.

Model voor geïntegreerde kosteneffectiviteit analyse

Om in een geïntegreerde kosteneffectiviteit analyse te kunnen bepalen welke maatregelen zouden moeten worden ingezet om gelijktijdig doelstellingen voor luchtverontreiniging en klimaatverandering te realiseren tegen de laagste kosten hebben we een model ontwikkeld. Dit model is toegepast voor de agrarische sector in 36 Europese landen op basis van informatie in het RAINS model. Het model is een statisch lineair optimalisatiemodel dat totale kosten van emissiereducties minimaliseert om de gegeven emissiedoelstellingen te behalen. Het RAINS model heeft als startpunt voor de formulering van het model gediend. In aanvulling op het RAINS model is de mogelijkheid toegevoegd om de effecten van reductiemaatregelen op verschillende stoffen mee te nemen in de optimalisatie om interacties in reducties van verschillende stoffen te kunnen analyseren.

Het model kan emissies van meerdere stoffen uit verschillende bronnen berekenen op basis van bron- en landspecifieke emissiefactoren en activiteitenniveaus. Restricties op emissies kunnen worden opgelegd op verschillende aggregatieniveaus (bijvoorbeeld per bron, per land of totaal). Emissies kunnen worden gereduceerd door inzet van reductiemaatregelen, die effecten kunnen hebben op

meerdere stoffen. Neveneffecten kunnen zowel een toe- als een afname in emissies zijn. In het model wordt expliciet rekening gehouden met al deze effecten bij het bepalen van de kosteneffectieve oplossing om te voldoen aan de opgelegde emissierestricties.

Het model is lineair en veronderstelt constante eenheidskosten voor individuele reductietechnieken. Omdat voor toenemende emissiereducties meerdere en duurdere maatregelen worden ingezet nemen de totale marginale kosten van emissiereductie stapsgewijs toe. Door deze lineaire benadering is het mogelijk om te analyseren welke specifieke maatregelen worden ingezet om bepaalde emissiereducties tegen minimale kosten te bereiken. Bovendien maakt de lineaire benadering het mogelijk om voor een groot aantal stoffen, bronnen, maatregelen en locaties relatief snel een optimale oplossing te vinden, terwijl toch recht wordt gedaan aan het niet-lineaire karakter van de emissiereductiekosten.

In hoofdstuk 6 wordt het model uitgebreid om rekening te kunnen houden met atmosferisch transport van emissies van verzurende stoffen. Naast restricties op emissies kunnen ook depositiedoelstellingen worden opgenomen, waarbij het mogelijk is om rekening te houden met verschillen in milieuschade door een bepaald depositieniveau op verschillende plaatsen (bijvoorbeeld door verschillen in de gevoeligheid van ecosystemen voor verzuring).

Door een aantal essentiële veronderstellingen die aan het model ten grondslag liggen (zoals constante productieniveaus en constante eenheidskosten voor individuele reductietechnieken) zijn de resultaten van het model een abstractie van de werkelijkheid. Niettemin vergroot het model het inzicht in het effect van interacties op kosteneffectiviteit en kan het model worden gebruikt om maatregelen te selecteren die in een integrale analyse de voorkeur verdienen.

Om het model te kunnen gebruiken voor het bepalen van kosteneffectieve pakketten van maatregelen om reducties in NH_3 , N_2O en CH_4 emissies uit de Europese landbouw te realiseren is het model geprogrammeerd in GAMS. Op basis van informatie in het RAINS model over agrarische activiteiten in 36 Europese landen in 1990 en 2010 worden emissies berekend volgens de methode zoals beschreven in hoofdstuk 2. Verder zijn maatregelen voor NH_3 , N_2O en CH_4 opgenomen inclusief de ingeschatte neveneffecten zoals eerder beschreven. In de analyses in hoofdstuk 6 worden ook emissies van SO_2 en NO_x meegenomen om een volledig beeld te geven van verzuring in Europa. In de modelberekeningen zijn restricties opgenomen voor de depositie van zwavel en stikstof in cellen van 150×150 km in Europa, gebaseerd op de schade door verzuring en eutrofiëring in deze cellen, gecombineerd met restricties op totale emissies van N_2O en CH_4 uit de Europese landbouw.

Lessen uit geïntegreerde kosteneffectiviteit analyses van reducties in NH_3 , N_2O en CH_4 emissies uit de landbouwsector in Europa

De hoofdstukken 3, 5 en 6 beschrijven resultaten van diverse berekeningen met het model voor verschillende combinaties van restricties op emissies van NH_3 , N_2O en CH_4 . De onzekerheden in zowel de emissieschattingen als de inschattingen van de effecten van maatregelen kunnen groot zijn. Hiermee moet rekening worden gehouden bij het interpreteren van de resultaten. Berekeningen laten zien dat NH_3 reductie in Europa resulteert in een toename in N_2O emissies, afhankelijk van de hoogte van de NH_3 reductie. Het effect op CH_4 emissies is beperkt. Verder hebben zowel een reductie van N_2O als van CH_4 emissies een afname in NH_3 emissies tot gevolg, terwijl CH_4 emissies toenemen door N_2O reductie en N_2O emissies toenemen door CH_4 reductie. Er zijn echter wel verschillen tussen landen. De belangrijkste maatregelen die tegelijkertijd zorgen voor een afname in NH_3 , N_2O en/of CH_4 emissies zijn een lager stikstofgehalte in het voer, een efficiënter gebruik van (kunst-)mest en voeraanpassingen die de productiviteit van dieren verhogen.

Kostencurven voor emissiereductie geven de relatie tussen emissiereductie en bijbehorende kosten. Om te bepalen wat het effect van neveneffecten van maatregelen is op kosteneffectieve emissiereductie, hebben we twee kostencurven voor NH₃ reductie in Nederland vergeleken: één zonder beperkingen voor N₂O en CH₄ emissies en één met als aanvullende beperking dat emissies van N₂O en CH₄ niet mogen toenemen ten opzichte van het initiële niveau. Door de extra beperking op N₂O en CH₄ emissies nemen de totale kosten toe, zij het in beperkte mate: voor het grootste deel van de kostencurve is het verschil kleiner dan EUR 6 miljoen (een kostenstijging van minder dan 3%). Kosten nemen toe omdat de door NH₃-reductiemaatregelen veroorzaakte toename in N₂O emissies gecompenseerd of voorkomen moet worden, wat betekent dat respectievelijk extra of duurere maatregelen worden ingezet. De toename in kosten is beperkt omdat in Nederland relatief goedkope maatregelen beschikbaar zijn om N₂O emissies te reduceren (met name door katalytische conversie van N₂O emissies in de salpeterzuurproductie).

Het belang van een geïntegreerde benadering is geanalyseerd door een kosteneffectieve oplossing voor gelijktijdige reductie van NH₃, N₂O en CH₄ te vergelijken voor twee varianten: één waarin kosteneffectieve maatregelpakketten voor reductie van NH₃ enerzijds en voor de reductie N₂O en CH₄ anderzijds afzonderlijk en na elkaar worden bepaald; en één waarin een kosteneffectief maatregelpakket voor de gelijktijdige reductie van de drie stoffen in een geïntegreerde analyse wordt bepaald. In de tweede variant kan voor dezelfde restricties op NH₃ emissies een grotere reductie in N₂O en CH₄ worden behaald tegen lagere totale kosten dan in de eerste variant. In een analyse voor Europa waren de berekende totale kosten in de eerste variant tot 60% hoger (EUR 5,7 miljard) dan de kosten voor eenzelfde reductie van NH₃, N₂O en CH₄ in de tweede variant. Verder was de maximaal haalbare reductie in N₂O en CH₄ emissies groter in de tweede variant dan in de eerste, namelijk 10 megaton CO₂-equivalenten (dat is 1% van de emissies van N₂O en CH₄ uit landbouwactiviteiten in Europa in 2010 voor reductie). Deze verschillen ontstaan doordat in de geïntegreerde analyse NH₃ reductiemaatregelen met een negatief neveneffect op N₂O en/of CH₄, zoals emissie-arme stallen en emissie-arme mestaanwending, niet of in mindere mate worden ingezet. In plaats daarvan worden maatregelen zonder negatieve bijwerking of met positieve neveneffecten ingezet, zoals katalytische conversie van N₂O in de salpeterzuurproductie (geen neveneffecten), een efficiënter gebruik van kunstmest (reductie van zowel NH₃ als N₂O) en verschillende voeraanpassingen die ofwel het stikstofgehalte verlagen of de productiviteit van dieren verhogen (reductie van NH₃, N₂O en CH₄).

In hoofdstuk 6 is de uitgebreide versie van het model toegepast voor het bepalen van kosteneffectieve maatregelpakketten om depositie van stikstof en zwavel terug te brengen tot een bepaald niveau in combinatie met restricties op totale N₂O en CH₄ emissies uit de Europese landbouw. Voor een volledig beeld van verzuring en eutrofiëring in Europa moeten ook emissies van SO₂ en NO_x worden opgenomen in het model. Deze emissies alsmede maatregelen om ze te reduceren zijn overgenomen uit het RAINS model. Om de doelstellingen voor de depositie van stikstof te bereiken kunnen zowel NH₃ als NO_x emissies worden gereduceerd. De afweging tussen deze stoffen wordt bepaald door de kosteneffectiviteit van maatregelen om deze emissies te reduceren, maar hangt ook af van een gelijktijdige restrictie op N₂O en CH₄ emissies. Als er een reductiedoelstelling voor N₂O en CH₄ is opgenomen vindt er een verschuiving plaats van reductie van NH₃ naar NO_x. Dit komt doordat NH₃ reductie in feite duurder wordt omdat sommige maatregelen een toename in N₂O emissies veroorzaken. De resultaten laten zien dat ook de verdeling van emissiereducties over de verschillende bronnen en landen afhankelijk is van de aanwezigheid van restricties op N₂O en CH₄.

Beleidsimplicaties

In de meeste Europese landen zijn nog geen specifieke reductiedoelstellingen geformuleerd voor N₂O en CH₄ emissies uit de landbouw. Wel is er inzicht in de belangrijke rol die de landbouwsector zou kunnen spelen in het halen van de Kyoto-doelstellingen voor broeikasgasreducties door reducties in N₂O en CH₄ emissies. Landenspecifieke emissiedoelstellingen voor NH₃ zijn vastgelegd in het Gothenburg Protocol, maar dit heeft tot dusver slechts in enkele landen (waaronder Nederland en Denemarken) geleid tot specifieke regelgeving gericht op de reductie van NH₃ emissies. In het Gothenburg Protocol zijn naast emissieplafonds ook afspraken opgenomen over in te zetten maatregelen voor NH₃ reductie. Deze voorschriften betreffen onder andere emissie-arme mestaanwending, het afdekken van mestopslag en emissie-arme stallen. De resultaten in dit proefschrift laten zien dat deze maatregelen een toename in N₂O en CH₄ emissies kunnen veroorzaken.

In veel Europese landen vereist het halen van de Kyoto-doelstellingen de nodige inspanningen. Daarom wordt op basis van dit proefschrift aanbevolen om in de beleidsvorming rekening te houden met neveneffecten van maatregelen voor NH₃ reductie op N₂O en CH₄ emissies. Op grond van de kosteneffectiviteit van maatregelen zou de aandacht moeten verschuiven van maatregelen die een negatieve bijwerking hebben op N₂O of CH₄ emissies (zoals emissie-arme stallen en emissie-arme mestaanwending) naar maatregelen die tegelijkertijd NH₃, N₂O en/of CH₄ emissies reduceren, zoals een efficiënter gebruik van (kunst-)mest en voeraanpassingen die ofwel het stikstofgehalte verlagen of de productiviteit van de dieren verhogen. Wel moet hierbij worden aangetekend dat in de beleidsvorming ook andere factoren dan kosteneffectiviteit een rol spelen die niet in beschouwing zijn genomen in dit proefschrift.

Dit proefschrift laat zien dat wanneer zowel NH₃ als N₂O en CH₄ emissies moeten worden teruggedrongen, het zeer inefficiënt kan zijn om de interacties in de reductie van deze stoffen buiten beschouwing te laten. Door rekening te houden met de diverse interacties kunnen kosten worden bespaard door de keuze voor in te zetten maatregelen af te laten hangen van de effecten van deze maatregelen op alle drie de stoffen. Ook de optimale verdeling van emissiereducties over de verschillende emissiebronnen en landen kan anders uitvallen wanneer rekening gehouden wordt met interacties. Het is waarschijnlijk dat er ook interacties bestaan bij emissiereducties in andere sectoren dan de landbouw en met andere milieuproblemen dan alleen grootschalige luchtverontreiniging en klimaatverandering. Gezien de rol die interacties kunnen spelen moet in de (nationale en internationale) beleidsvorming zeker meer aandacht worden besteed aan neveneffecten van maatregelen.

Curriculum Vitae

Jan Cornelis Brink was born February 21, 1974 in IJsselmuiden, the Netherlands. In 1992, he completed the secondary school (VWO) at the Johannes Calvijn Lyceum in Kampen and started his study in Agricultural and Environmental Economics at Wageningen University, with a specialisation in Environmental Economics. He graduated in 1997 and started his PhD research on 'global warming policies in Europe in relation to acidification and tropospheric ozone' at the Environmental Economics and Natural Resources Group, Wageningen University. The project was financed by the Netherlands Organisation for Scientific Research (NWO) in the context of IIASA/SENSE cooperation. As part of the cooperation, he visited the International Institute for Applied Systems Analysis (IIASA) in Austria several times. In 2001, he received the diploma of the Netherlands Network of Economics (NAKE). Since May 2001, he has been appointed as an environmental economist at the Laboratory for Waste Materials and Emissions (LAE) of the National Institute for Public Health and the Environment (RIVM) in Bilthoven, the Netherlands.