Integrated environmental assessment of agriculture in the Czech Republic. The case of dairy cattle.

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Integrated environmental assessment of agriculture in the Czech Republic. The case of dairy cattle.

Martina Havlíková

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PREFACE

I still remember my first arrival at the train station Ede-Wageningen. It was on the 13th of October 2000, a cloudy and rainy day. Everything looked quite sad, but soon I realized that Holland is not sad, but a wonderful country with a little bit of rain. Together with my friend I came, as an Erasmus exchange student, from the Czech Agriculture University in Prague. I was supposed to stay for a five months period. In the end I stayed to finish my M.Sc. in Environmental Sciences and, one year after my graduation, I decided to continue with my PhD research there.

I worked on the PhD thesis four and a half year, partly at Wageningen University and partly in the Czech Republic at the Czech Hydro meteorological Institute in Prague. For four and a half years I kept coming and going at both places. Sometimes I felt that I was living with my rucksack on my back. In fact it was not easy, not only for me but also for my family. At the beginning they hardly understood where exactly I was living and what I was doing. My answers never satisfied them. Despite all kinds of difficulties I enjoyed my “PhD time” and I still cannot believe that the thesis is finished.

This would probably not have been possible without support and help of many people. Some of them deserve to be mentioned here: *Dick Legger* and *Josef Fanta*. Dick was especially helpful to find appropriate fellowships and contacts, Josef you have a fantastic house in Rhenen, where I always felt at home, not only because of the Czech beers, good wines and delicious dinners but also because of very vital and stimulating discussions on different topics. I have to accept that Dick and Josef are two special men in my life and both are having a place in my heart. I hope we will stay in good contact.

Carolien Kroeze was my daily supervisor, a good friend and person I will always admire. I worked together with Carolien since 2002, when I started my MSc thesis with the Environmental Systems Analysis Group. From her I learnt to be better organized, patient and present my ideas in a more understandable way and, more important, to be proud of my research. In fact there are many things which I am very thankful to her and probably one small paragraph is not enough to express my gratitude to her support. Surely, without her, this thesis would have stayed just a dream of a Czech girl from Prague.

I am glad that Rik *Leemans* became my promoter. All the time he was convincing me that I should not be so modest. Well I think I changed a little bit. I would like to thank him for his advices and suggestions for each chapter of this thesis and mainly for his trust that my research is valuable for the scientific community.

I also would like to thank my colleagues from the Czech Hydrometeorological Institute in Prague. Mainly I am grateful to my former deputy director, *Jaroslav Santroch*, and the head of the Emission Inventory Section, *Pavel Machalek*. They gave me enough time to focus on my thesis, while trusting me enough to represent the Czech Republic during important international meetings. This allowed me to become a part of the political and scientific

community that focuses on air pollution in Europe. This experience was very valuable for my professional career. Although I am not working for CHMI anymore, I hope we can collaborate in future.

In 2005 I joined the three months Young Scientists Summer Program of the Institute for Applied Systems Analysis (IIASA). Here I worked in the Air Pollution and Development Program. I would like to thank the people working there for their useful discussions about the RAINS model. I also would like to thank my fellow students for their stimulating discussions about our PhD research and for our nice trips to Italy (Venice) and Hungary.

I also would like to mention all students or visiting researchers whom I met in Wageningen. But this would require filling several pages. Here I would like to mention mainly people which I met during my last eight months period, from January to August 2008. The reason is that the final stages of the thesis writing, changes in my job and in my private life, made this period very intensive for me. *Carolina Camacho De Villa* and *Charlynne Curiel* are two Mexican ladies with whom I shared an apartment in Heerenstraat 27. Both showed me how colourful the Mexican culture is and they helped me during periods when I was not feeling very well by supporting me through their positive way of thinking and energy. I hope that both will finish their PhD successfully soon. I will definitely be there to support them.

I also would like to thank to all Czech students which I met in Wageningen and hope we can use our knowledge from Wageningen to improve the environmental situation in our country to become a nice and healthy place to live.

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CHAPTER 1 Introduction

1.1. Agriculture and environment in the Czech Republic

Agricultural activities are a source of emissions of various pollutants to air, water and soil. These include compounds contributing to pollution problems at the national scale (surface and ground water pollution), European scale (acidification and eutrophication of soil and aquatic systems) as well as at the global scale (global warming). These pollution problems are mainly associated with emissions of ammonia (NH_3), nitrogen oxides (NO_x) nitrous oxide (N_2O), methane (CH_4), particulate matter (PM), nitrate (NO_3^-) and phosphate (PO_4^{-3}).

This thesis focuses on the assessment of the environmental consequences of agricultural activities in the Czech Republic. For an analysis of agriculture in the Czech Republic, it is important to understand historical agricultural trends and their impact on the environment of this country. There is no doubt that during the period of the centrally planned economy, the Czech agricultural production was non-sustainable and had a series of predominantly negative impacts on the environment (Moldan et al., 1992). Crop production accounted for a large portion of the agriculture land use (75% of total agriculture land). Increasing crop production was the main aim, but this caused land degradation by soil compaction, water and wind erosion, and losses of landscape and biodiversity (OECD, 1999). Fertilizers and pesticides polluted water resources (Moldan et al., 1992, Berankova et al., 1996). Cattle, pigs, and poultry were produced in large–scale units. Due to poor management, manure was an important source of pollution of air, soils and water (OECD, 1999). The pollution caused by the Czech agriculture during the period of the centrally planned economy still damages the environment.

After the political changes in 1989, the transition to a market economy modified the Czech agricultural system. This had some positive effects on the environment (Cudlinova et al., 1999). During the reform period some steps were taken to reduce the adverse effects of farming on the environment. The number of animals and use of fertilizers and pesticides decreased. However, air, soil and water pollution have been declining only slowly. For instance, Berankova et al. (1996) report that surface waters still shows high concentrations of nutrients, particularly nitrogen and phosphorus. This could be related to a lack of proper management of manure in the Czech agricultural system. Recently, the Czech Republic joined the European Union (EU). This means that the country has to comply with European agricultural and environmental regulations. These drive most of today's environmental policies in the Czech Republic.

The current structure of the Czech agriculture is characterised by large farms (more than 50 ha of agricultural land) which cultivate 92% of total agricultural area. Agriculture accounts for 3% of Gross Domestic Products and 4% of the Czech population are working in agriculture. Cattle and pig farming constitute the most important sectors. A long-term study by Kopaček and Veselý (2005) indicates that cattle production is one of the main contributors to ammonia emissions. The contribution decreased from 75% in 1850 to 50% in 2000.

Figure 1.1 shows the long term development of cattle numbers and milk yield per capita in the Czech Republic between 1950 and 2020. Cattle numbers per capita were highest in the eighties when agricultural production was most intensive. The large reduction in cattle and milk production after 1990 was caused by the transition to a market economy. Since that time milk yield per capita has been gradually increasing while the number of cattle has been stabilising. It is interesting to note that the projected per capita numbers of cattle in 2020 are lower than 70 years ago earlier while per capita milk yield is projected to be about 7 times higher. This clearly shows how the number of cattle is decoupled from milk production. This decoupling is closely related to an increase of nitrogen in animal feed (e.g. Smil, 2001).

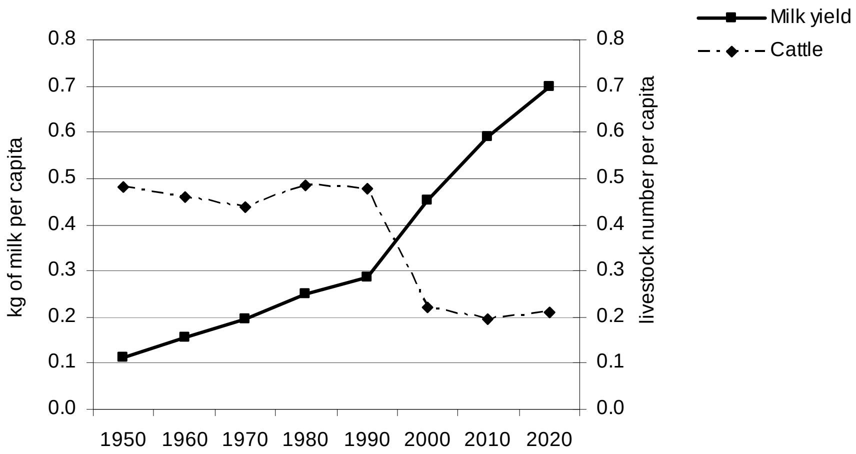

Figure 1.1. Trends in cattle numbers and milk yield per capita between 1950 and 2020 in the Czech Republic (Source: FAO, 2008; Kopaček and Veselý, 2005, IIASA, 2007).

Environmental policy measures in European agriculture

The concern about negative effects of agriculture on the environment and implementation of environmental policies in European agriculture originate from the second half of the 1980s (De Clerq et al., 2001). Environmental policy in European agriculture can, therefore, be considered as a relatively new field and varies between countries depending largely on the intensity of agricultural production.

Currently, the European Commission aims to regulate agricultural emissions by several Directives. The National Emission Ceilings Directive 2001/81/EC (NECD) is at the time that this thesis is written, being revised as part of the implementation of the Thematic Strategy on Air Pollution (TSAP) (European Commissions, 2005). The new proposal will set emission ceilings to be respected by 2020 in all EU member states including the Czech Republic. The new set of emission ceilings will concern sulphur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (NMVOC) and ammonia (NH_3). In addition, ceilings will also be considered for fine particulate matter ($PM_{2.5}$). The revision of the NEC Directive will take into account aims of the European Council to reduce emissions of greenhouse gases by 20% and a 20% share of renewable sources of energy in final energy consumption by 2020. The Czech target for renewable energy is set at 13% (European Commission, 2008).

Climate change policy is related to commitments to the UNFCCC (UN Framework Convention on Climate Change). Parties to the Convention agreed to limit or reduce their greenhouse gas emissions, amongst others N_2O and CH_4. Greenhouse gas emissions from agriculture account for approximately 10% of total amount of greenhouse gas emissions caused by human activities within the European Community. In addition, a report published by the United Nations Food and Agriculture Organization, indicates that the livestock sector generates more greenhouse gas emissions (18%) than transport (Steinfeld, 2006). In 1997, the Kyoto Protocol was adopted at the third Conference of the Parties (COP3) in Kyoto. The Czech Republic approved the Kyoto Protocol in November 2001. This protocol contains an 8% reduction target for greenhouse gas emissions from the Czech Republic in the period 2008-2012 reduction relative to 1990 (UNFCCC, 1997). No specific target for greenhouse gas emissions from agriculture was defined.

The Water Framework Directive (European Commissions, 2000), including the Nitrate Directive and Groundwater Directive contain targets for losses of nitrate and phosphate (European Commissions, 1991). The tools for implementation of the Nitrate Directive in the Czech Republic are "Good Agricultural Practice Aimed on Waters Protection" and an "Action Program". The Action Program was established by Government Ordinance No. 103/2003 Coll. on vulnerable areas establishment, storage and usage of fertilizers, crop rotation and erosion control in these areas. Farmers in vulnerable areas are obliged to follow relevant measures. The first Action Program for vulnerable areas of the Czech Republic was proclaimed on January 2004 (Svoboda, 2006).

The above-mentioned key EU Directives may reduce agricultural emissions. In addition, the Agenda 2000 and the Common Agriculture Policy (CAP) reform (European Commissions, 2007) contribute to overall emission reduction through the "single farm payments" linked to environmental impact, food safety and animal welfare standards. Production of agriculture commodities will make EU farmers more competitive and market oriented, while providing the necessary income stability (Becvarova, 2007).

Another important international body regulating environmental pollution is the Convention on Long Range Transboundary Air Pollution (CLRTAP). This was signed in 1979 by many European countries and North America to control the emissions of air pollutants, including NH_3 from agriculture. The control of these emissions is regulated through different Protocols, focusing either on single pollutants (e.g. the Sulphur Protocols) or groups of pollutants (the Gothenburg Protocol) (United Nations, 1999). The Gothenburg Protocol differs from the earlier CRLTAP protocols in that it simultaneously adopts national reduction targets for four substances (NO_x, NMVOC, SO_2, NH_3) in order to reduce three environmental problems simultanously: acidification and eutrophication of terrestrial and aquatic system and tropospheric ozone (UNECE, 1999). Wettestad (2000) in his book evaluates this protocol as "the most sophisticated environmental agreement ever negotiated, which will yield great benefits, for both our environment and human health". The Gothenburg Protocol is the only international protocol targeting ammonia emissions from agriculture. It includes an advisory Code of Good Agriculture Practice (CGAP) guidance on reducing ammonia emissions from all major agricultural sources. The Czech government ratified the Gothenburg Protocol in August 2004 and implemented CGAP in 2003. Currently this concerns approximately 1500 farms in the Czech Republic (CHMI, 2008).

A recent review of emission reductions in relation to CLRTAP indicates that European ammonia emissions were reduced by 34% between 1990 and 2000 while stabilization is expected between 2010 and 2020 (UNECE, 2007). It is, nevertheless, expected that ammonia emissions will in the near future exceed emissions of NO_x and SO_2 which are mainly emitted during combustion or industrial processes (Figure 1.2). By 2020, NH_3 emissions may be the largest contributor to acidification and terrestrial eutrophication in most of the European countries including the Czech Republic. Apparently emissions from agriculture are more difficult to reduce than emissions from other economic sectors. There may be several reasons for this. First, every farm is a unique source of pollution requiring specific management practices. Second, many agents are involved such as farmers, fertilizer and food industry, consumers and policy makers (Oenema, 2004).

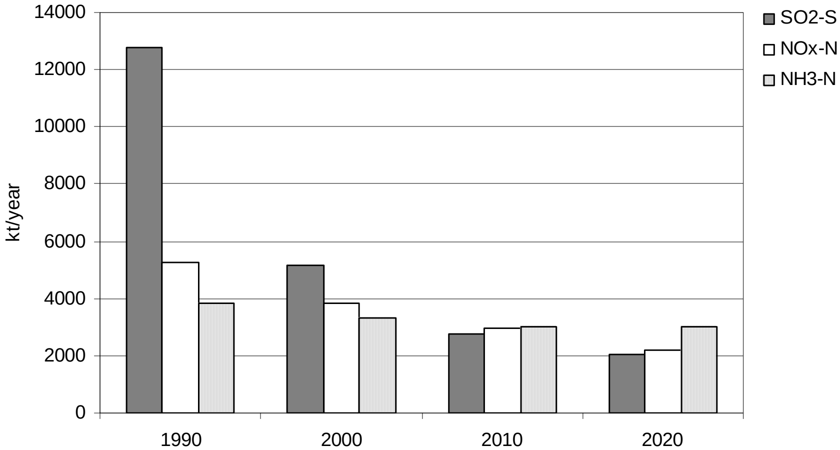

Figure 1.2. Total emissions of SO_2-S, NO_x-N and NH_3-N between 1990 and 2020 in 27 member states of the EU (Modified from UNECE, 2007)

The idea that abatement of one environmental problem will, as a side-effect also reduce other problems is not always correct. For the agricultural sector an overview of interactions was given by Brink, (2003). For instance, some strategies to reduce NH_3 emissions may increase emissions of greenhouse gases. In animal production the types of stables with lowest NH_3 and CH_4 emissions can have relatively high N_2O emissions. In addition, animal waste management systems with high CH_4 emissions seem to have low N_2O emissions. In agricultural fields similar trade-offs can be found. Brink (2003) performed a quantitative analysis for the agricultural sector in Europe. He studied the cost effectiveness of emission reduction strategies for acidification, eutrophication and global warming while taking into account such side-effects. He concluded that taking into account the interrelations between these three problems could reduce the costs of environmental policy considerably.

The interrelations between emissions are often overlooked during implementation of environmental policies and measures at the local, national as well as European level. The interrelations between emissions have always occurred, but have raised the interest of policy makers relatively recently (Oenema and Velthof, 2007).

Several recent examples of consideration of possible interrelations in European policy exist. The European Commission aims to derive new emission ceilings while considering interrelations between emissions of air pollutants and greenhouse gases (see for example Amann et al., 2007). CLRTAP recently established a new Task Force on Reactive Nitrogen (TFRN) aiming at the reduction of different forms of reactive nitrogen, which are responsible for several environmental issues, simultaneously. These forms of nitrogen include particulate matter, greenhouse gases and compounds contribution to eutrophication of freshwater and marine ecosystems (UNECE, 2008).

Integrated environmental models

As a result of the complexity of air, soil and water pollution problems, integration of social, economic, and physical sciences is needed for the identification and evaluation of suitable emission reduction measures. However, an information gap exists between policy makers and science. This gap can be bridged by performing integrated assessments (IA).

Rotmans and Dowlatabadi, (1997) define integrated assessments as:

"An interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines in such a way that the whole cause–effect chain of a problem can be evaluated from a synoptic perspective with two characteristics: (i) it should have added value compared to a single disciplinary assessment; and (ii) it should provides useful information to decision makers".

In such assessments so-called integrated assessment models (IAM) can play an important role. Integrated assessment models typically cover the whole causal chain including causes, effects and solutions (Hordijk and Kroeze, 1997). Environmental pollution by agriculture is driven by socio-economic changes such as market trends leading to intensification or extensification of farming practices. This leads to a pressure on the environment through the emissions to air, water and soil, resulting in changes in the state of the environment, for example increased nitrate in aquatic systems, depletion of resources including soil erosion and genetic diversity. Responses to environmental changes are control measures imposed directly and indirectly through national and international legislations. Van Ittersum et al. (2007) argue that tools for integrated assessment preferably include multi-scale capabilities and are flexible to deal with many policy questions.

Environmental systems analysis tools can form the building blocks for integrated assessments. These analytical tools are usually used either alone or in combination, with the aim to analyse complex environmental problems and to help evaluating possible solutions. Several overviews of analytical tools exist. For example, Finveden and Moberg (2001) discuss selected systems analysis tools with respect to characteristics such as their focus, the impacts considered, and the purpose of the study. They conclude that the purpose of the study at stake and the impact of interest are the two aspects influencing the choice of the tools. In addition, they argue that for analysing complex environmental problems a combination of tools is more appropriate. Neto (2007) evaluated analytical tools with respect to their usefulness in a study for an industrial company and selected seven tools to be combined into one decision support tool to comprehensively assess both the environmental and economic impact of environmental policies.

Table 1.1 presents a number of models dealing with emissions from agriculture that have been developed to advice on environmental policy at the local, national and/or European level. This list includes models of the agricultural sector (A), or a sub-sector (dairy cattle: D) or models that consider agriculture as part of the national economy (E). Here we specifically look at which agricultural emissions are included in the models, how environmental impacts are assessed, and which systems analysis tools are used. The list of models is not meant to be exhaustive.

Table 1.1 allows for the following observations. The European scale models include the RAINS/GAINS model in which agriculture is one of the economic sectors, MITERRA-Europe and the model by Brink (2003) that focus on agriculture only. These three models include emissions NH_3, N_2O and CH_4. These compounds are subject of international directives and protocols (See section 1.2). Indeed all three European models were developed to advice policy makers at the European level. Two of them use atmospheric deposition and critical loads as a basis for cost effectiveness analysis. In addition, scenario analysis is used in all three studies. It is interesting to note that these three models have been used in combination for policy purposes (Klimont et al., 2007).

Table 1.1. Illustrative examples of integrated assessment models that include agricultural emissions.

Study	Sector Level*	Agricultural emissions	Impact indicator	Costs included	Typical model analysis
Europe					
RAINS/GAINS (Amann et al., 2007)	E	NH_3, CH_4,N_2O	atmospheric deposition global warming potentials	yes	Scenario analysis Cost-effectiveness analysis
MITERRA-Europe (Oenema et al.,2007)	A	NH_3, N_2O, CH_4, NO_3	emissions	no	Scenario analysis
Brink (2003)	A	N_2O, NH_3, CH_4	atmospheric deposition global warming potential	yes	Scenario analysis Cost-effectiveness analysis
National					
UKIAM (Oxley et al., 2003)	E	NH_3	atmospheric deposition	yes	Scenario analysis Cost-effectiveness analysis
INITIATOR (De Vries et al., 2003)	A	NH_3, N_2O, CH_4, NO_x, HM, CO_2, NO_3, PO_4, odor	emissions	yes	Scenario analysis Cost-effectiveness analysis Substance-flow analysis
Farm					
Thomassen (2008)	D	NH_3, N_2O, CH_4, NO_3, PO_4	potentials	yes	Life Cycle Assessment
SIMSdairy (del Prado et al., 2006)	D	NH_3,N_2O,CH_4, NO_x NO_3, P_{04}	global warming potential	yes	Life Cycle Assessment Multi-Criteria Analysis
Dairywise (Schils et al., 2007)	D	N_2O, CH_4, CO_2 N and P losses	emissions	yes	Scenario analysis Cost-effectiveness analysis

* Sectoral level of emission reduction: E- national economy, A -agriculture, D-dairy cattle

Examples of national integrated assessment models include UKIAM (Oxley et al., 2003) which is used in the United Kingdom and includes agriculture as part of the economy. INITIATOR (Integrated NITrogen Impact Assessment Tool On a Regional scale), developed in the Netherlands, is an example of a model used specifically for analysis of agriculture at the national level. INITIATOR includes more detailed estimates of agriculture emissions of more pollutants than UKIAM. Both models, however, can be used for cost-effectiveness analyses of emission reduction measures.

Examples of farm scale assessments of dairy cattle can be found in Thomassen, (2008) who used Life Cycle Assessment to assess the environmental impact of dairy cattle in the Netherlands. She used farm-level information to assess several pollutants while calculating their potential environmental impact. The SIMSdairy model (del Prado et al., 2006) is used in the UK to analyse the possible impact of emission reduction measures based on multiple user-defined criteria. Dairywise is a so-called whole-farm model used in the Netherlands to analyse technical, environmental and economical processes on a dairy farm (Schils et. al., 2006). The model can be used for scenario analysis and to analyse the cost-effectiveness of emission reduction measures. Assessment of the environmental impact of emissions is not included in the Dairywise model.

From the above we may conclude that there are many different ways to assess the environmental impact of agriculture in general and dairy cattle in particular. European studies may serve as a starting point in terms of input data for an integrated assessment of Czech agriculture, while national and regional studies illustrate interesting analytical approaches. The models in Table 1 combine approaches from life-cycle assessment, multi-criteria analysis, environmental indicators, substance-flow analysis, optimisation analysis and scenario analysis.

Research objective

The overall objective of this thesis is to assess the future environmental impact by the agricultural sector in the Czech Republic. National and European environmental policies and the interaction between human activities and environmental trends will be considered. The novel aspect of this thesis is to include process-based emission factors in a region specific model to quantify both emissions and their potential environmental and health impacts. Additionally these results are used in another purposely developed model to assess the reduction costs involved. To achieve the overall objective three specific research aims are defined.

The first aim is to analyse different **emission estimation methods** with respect to their usefulness for an integrated assessment at the national scale. The second is to evaluate the **potential environmental impact** of agricultural emissions at the sub-national level while considering different agricultural practices and environmental characteristics. The third aim is to integrate emission estimation methods and impact assessment approaches in a model to assess the **cost-effectiveness of environmental policy measures**. This model is applied in a case study focusing on dairy cattle as one of the most polluting sub-sectors of Czech agriculture. It is used to analyse the current situation and to **explore future trends** up to 2020 as affected by (i) different views of hypothetical model users on importance of environmental impact, (ii) changes in projected cattle numbers and animal management and (iii) changes in application of emission reduction measures.

Outline of the thesis

This thesis consists of several chapters related to the aims defined above. These are outlined in Figure 1.3. The agricultural activities are sources of emissions leading to environmental impact. These drive decisions on emission control imposed by the government (national and European Union) resulting in certain costs. In the second chapter we concentrate on the agricultural sector as whole, while chapters 3-5 focus on dairy cattle as one of the most important agricultural sub-sectors in the Czech Republic.

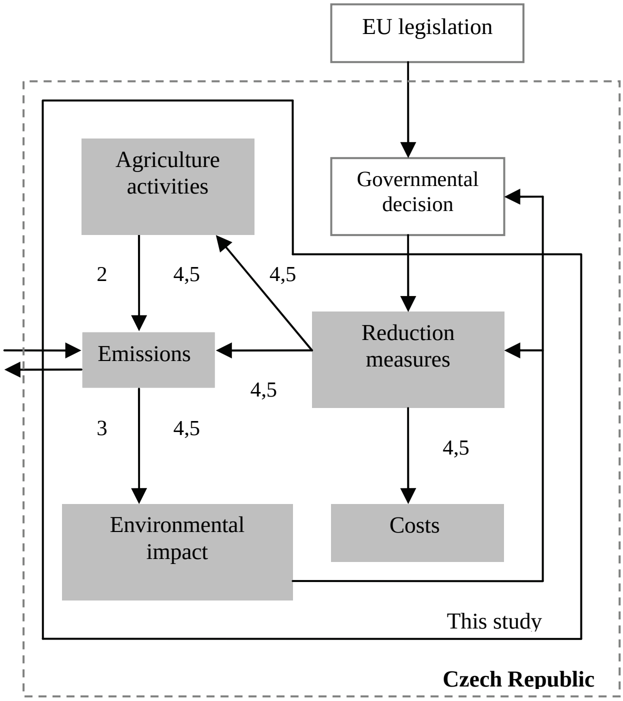

Figure 1.3. Schematic overview of relationships between agricultural activities, emissions, environmental impacts and reduction measures. Numbers indicate which chapters deal with particular parts of the system. The dashed line indicates the boundary of the Czech Republic, while the solid line indicates the part considered in this study.

In the second chapter a comprehensive analysis of selected methods to quantify air, soil and water pollutants from the agricultural sector is performed. Emission factor approaches, process-based models and regression analyses are discussed, and illustrative examples of each of these types are analysed using a three step framework (1) Comparison, (2) Scoring and (3) Multi-Criteria Analysis. We argue that integrated assessments of environmental problems associated with agriculture at the national scale could combine the best parts of all three methods. This chapter has been presented at the *Acid Rain Conference 2005* in Prague (Czech Republic) and published in *The Science of the Total Environment* (Havlikova and Kroeze, 2006).

In the third chapter of the thesis, the emission estimation methods identified in Chapter 2 are combined with country-specific indicators, so-called characterisation factors to assess the potential impact of emissions from dairy cattle. The analysis considers how applicable and useful available characterisation factors are for a study of the Czech Republic. A selected set of characterisation factors is combined with qualitative information on environmental characteristics at the sub-national level. The analysis will indicate that the potential environmental impact of dairy cattle can be assessed without explicit quantification of the specific effects on ecosystems and may be useful in the identification of appropriate targets for emission reduction. This chapter has been published in *The Science of the Total Environment* (Havlikova et al., 2008) and discussed in *Science of Environmental Policy* (June, 2008) a newsletter alert of the European Commission.

Setting a target for emission reduction and selection of appropriate measures is not a straightforward process. In the fourth chapter, responses to environmental pollution by agriculture are analysed. The emission estimation methods identified in Chapter 2 and the country-specific indicators for the potential impact as in Chapter 3 are integrated into one model. The model structure and modelling approach are based on Brink (2003). Our DAIRY model allows for cost-effectiveness analysis of emission reduction measure at the sub-national level. Environmental targets are set either at the level of emissions or for individual environmental impact categories and/or for the overall environmental impact (OEI). This chapter has been submitted to the *Environmental Management* (Havlikova and Kroeze, submitted).

Changes in different perceptions of importance of different environmental problems by various model users (farmers, policy makers etc.) may influence final conclusion of Chapter 4. This also holds for the assumed development of projected dairy cattle number as a result of intensification or extensification of production, and for changes in animal management practices and region-specific application of emission reduction measures. Therefore, in Chapter 5 a systematic analysis of changes in the DAIRY model is performed. The analysis reveals to what extent changes in model parameters may influence the environmental impact, selection of most cost-effective measures as well as total reduction costs. This chapter calls for careful interpretation of results from any optimisation model. This chapter has been submitted to *Agriculture Systems* (Havlikova and Kroeze, submitted).

In Chapter 6 the results of Chapters 2, 3, 4 and 5 are discussed and synthesised. A comparison of the results with the outcomes of other studies is presented. In addition, the results are put into science and policy perspectives. Several recommendations for future research are drawn.

Table 1.2. Overview of the structure of the thesis

Research aim	Chapter	Aim of the chapter
1	2	To comprehensively analyse emissions estimation methods to be used for integrated assessment of environmental problems by agriculture at the national scale
2	3	To evaluate the potential environmental and health impact by dairy cattle at the sub-national level by applying site-dependent methodology
3	4	To describe a linear optimisation model to analyse the cost-effectiveness of policy measures to reduce environmental impact of dairy cattle in the Czech Republic for the current situation and to explore future trends up to 2020
4	5	To explore future environmental impacts by dairy cattle in the Czech Republic as affected by different views of model users on the importance of environmental impact, projected cattle numbers and animal management, and application of reduction measures

References

Amann, M., Asman, W., Bertok, I., Cofala, J., Heyes, C., Klimont, Z., Schöpp, W. and Wagner, F., 2007. Updated Baseline Projections for the Revision of theEmission Ceilings Directive of the European Union. NEC Scenario AnalysisReport #4. International Institute for Applied Systems Analysis (IIASA),Laxenburg, Austria.

Becvarova, V., 2003. EU enlargement and the Common Agricultural Policy. Agric. Econ.-Czech 49: 447-452

Berankova, D.,Ungerman, J.,1996. Non-point sources of pollution in Morava river basin. Water Science Technology. Vol.33. No.4-5 pp 127-135

Brink, J.C, 2003. Modelling cost-effectiveness of interrelated emission reduction strategies, the case of agriculture in Europe. PhD thesis. Wageningen University. The Netherlands

CHMI, 2008. Czech Hydrometeorological Institute. A list of farms with CGAP and emissions of ammonia in different administrative regions. http://www. chmi.cz/uoco/emise/zemedelstvi/index.html

Cudlinova, E., Lapka, M., Bartos, 1999. Problems of agriculture and landscape management as perceived by farmers of the Sumava Mountains (Czech Republic). Landscape and urban planning 46:71-82

Del Prado, A., Scholefield, D., 2006. Use of SIMSDAIRY modelling framework system to specify UK dairy farms. Delivering sustainability within profitable farming systems-is it possible? Aspects Appl. Biol: 3-6

European Commission, 1991. Council Directive of 12 December 1991concerning the protection of waters against pollution caused by nitrates from agriculture sources (91/676 EC)

European Commission, 2000. Directive 2000/60/EC of the European parliament and of the council, 23 October 2000, establishing a framework for community action in field of water policy. Official Journal of European Communities, L327/1

European Commission, 2005. Thematic Strategy on Air Pollution. Commission Communication to the Council and Parliament COM (2005) 446

European Commission, 2007a. The Common Agriculture Policy explained. DG - For agriculture and rural development KF-77-07-075-EN-D. http://ec.europa.eu/agri culture

European Commission, 2008. Package of Implementation measures for the EU's objectives on climate change and renewable energy for 2020. Proposals for Directives for the European parliament and the council COM (2008) 16, COM (2008) 17, COM (2008) 19

UNECE, 2007. Review of the Gothenburg Protocol. Report of Task Forces on Integrated Assessment Modelling of the UNECE Converntion on Long-range Transboundary Air Pollution

UNECE, 2008. Task Force on Reactive Nitrogen: http://www.clrtap-tfrn.org

De Vries, W., Kros, J., Oenema, O.,De Klein, J.,2003. Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. Nutrient Cycling in Agroecosystems 66: 71-102

De Clerq, P., Gertsis, A.C., Hofman, G., Jarvis S.C., Neetson, J.J., Sinabell, F., 2001. Nutrient management legislation in European countries. IBSN 90-806537-2-1. Wageningen Pres, The Netherlands

Finnveden, G., Moberg, A., 2005. Environmental Systems Analysis-an overview. Journal of Cleaner Production 13:1165-1173

FAO, 2008. Food and Agriculture Organization. http://faostat.fao.org/default.aspx

Havlikova, M., Kroeze, C., 2006. Evaluation of methods for quantifying agricultural emissions of air, water and soil pollutants 372: 133-147

Havlikova, M., Kroeze, C., Huijbregts, M. A. J., 2008. Environmental and health impact of dairy cattle livestock and manure managment in Czech Republic. The Science of the Total Environment; 396:121-131

Havlikova, M., Kroeze, C. Cost-effective reduction of environmental impact of dairy cattle in the Czech Republic. Submitted to the Journal of Environmental Management

Havlikova M., Kroeze, C. Exploring future environmental impact by dairy cattle in the Czech Republic. Submitted to Agriculture Systems.

Hordijk, L., Kroeze, C., 1997. Integrated assessment models for acid rain. European Journal of Operational Research 102: 405-417.

Klimont, Z., W.A.H. Asman, I., Bertok, F., Gyarfas, C., Heyes, F., Wagner, W., Winiwarter, L., Höglund-Isaksson, R., Sandler, 2007. Measures in agriculture to reduce ammonia emissions. Service Contract No 070501/2006/433072/FRA/C1 under the framework contract No ENV.G.1/FRA/2004/0081

Kopáček, J., Veselý, J., 2005. Sulphur and nitrogen emissions in the Czech Republic and Slovakia from 1850 till 2000. Atmospheric Environment 39: 2179-2188

Moldan, B., Schnoor, J.L.,1992. Czechoslovakia examining a critically ill environment. Environment. Environmental Science Technology. Vol.26 :14-21

Neto, B.A.F., 2007. MIKADO, A decision support tool for pollution reduction in aluminium pressure die casting. PhD thesis, Wageningen University, The Netherlands

OECD, 1999. The agri-environmental situation and policies in the Czech Republic, Hungary and Poland. COM/AGR/ENV(99)60/FINAL. Organisation for Economic Co-operation and Development

Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. J. Anim. Sci 82:196-2006

Oenema, O., Velthof, G., 2007. Analysis of international and European policy instruments: pollution swapping. Interim report under European Commission. Service contract NO: 070501/2005/422822/Mar/C1. Aterra, Wageningen, The Nederlands

Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. Livestock Science 112; 261-272

Oxley, T. ApSimon, H., Dore, A., Sutton, M., Hall, J., Heywood, E., Gonzales Del Campo, and Waren, R., 2004. The UK Integrated Assessment Model, UKIAM: A national scale approach to the analysis of strategies for abatement of atmospheric pollutants under the Convention on Long-Range Transboundary Air Pollution. Integrated Assessment. 4: 236-249.

Rotmans, J., and Dowlatabadi, H., 1997. Integrated Assessment Modeling, in Human Choice and Climate Change, eds S Rayner and E L Malone, Vol. 3, The Tools for Policy Analysis, Battle Press, Columbus, OH, 291–377.

Schils, R.L. M., Olsen J.E., Del Prado, A., Soussana, J.F., 2007. A review of farm level modeling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livestock Science 112: 240-251

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosh and Transformation of World Food Production. Cambridge, MA: MIT Press

Svoboda, J., 2006. Inspections in the agriculture practice from the Nitrate Directive point of view. Acta Agriculture Slovenica, 87-1: 155-158

Steinfeld, H., Gerber, P. , Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock’s Long Shadow – Environmental issues and options. Food and Agriculture Organisation (FAO) ISBN-978-5-10-55571-7.

Thomassen, M. A., 2008. Environmental impact of dairy cattle production system, an integral assessment. PhD thesis. Wageningen University. The Netherlands

UNFCCC, 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Bonn, Germany. http://www.unfccc.int

Van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A. E., Der Wal, T. Wien, J.E. Wolf, J., 2007. Integrated assessment of agriculture systems-A component based framework for European Union (SEAMLESS). Agriculture Systems: doi: 10.1016/j.agsy.2007.07.009

Wettestad, J., 2002. Cleaning the air: European advances in tackling acid rain and atmospheric pollution. Ashagate publishing Limited, Hampshire, United Kingdom, pp 186

CHAPTER 2

Evaluation of methods for quantifying agricultural emissions of air, water and soil pollutants

Abstract

Integrated assessments that analyze global warming, acidification, eutrophication and ozone related problems simultaneously, need complete, detailed and consistent emission estimates that consider possible interrelations between different pollutants. We discuss three types of emission estimation methods: emission factor, regression analyses and process-based methods. Selected examples of these are reviewed to illustrate the large variety in methods available. We present an approach for the evaluation of emission estimation methods which follows three steps: (1) Comparison, (2) Scoring and (3) Multi-Criteria Analysis (MCA). We demonstrate the usefulness of this approach by applying it to a case study for the Czech Republic. Firstly we compare selected methods with respect to characteristics which we consider as requirements to quantify emissions of air, water and soil pollutants in an integrated way. We observe that none of the selected methods fully meet our defined characteristics. Secondly, we score the methods with respect to three types of criteria. This evaluation reveals large differences between the methods. We conclude that the following methods best meet our criteria: the IPCC Guidelines, methods from INITIATOR, and the detailed method of the EMEP/CORINAIR Guidebook. Finally, we perform a Multi – Criteria Analysis to analyze how our conclusions change if one considers certain criteria as more important than others. Based on this analysis we suggest that combining parts of each of the three methods forms a sound basis for a new emission estimation method for quantifying agricultural emissions of air, water and soil pollution simultaneously.

Key words: agriculture, emission estimate, Multi-Criteria Analysis

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Introduction

Agriculture is an important sector in many European countries and is undergoing rapid change. Farming can directly affect the environment, including nature and landscape values (Millennium Ecosystem Assessment, 2003). Both scientists and policy makers increasingly recognize that the impact of agriculture can not be ignored. However, the issue is complex, because of the many different agricultural activities and actors, the range of environmental pollutants involved, and as a result of that, the various environmental effects. Integrated environmental assessments may assist in the development of policies aiming at minimizing the environmental impact of the agricultural sector. In such assessments, environmental models and scenario analysis typically play an important role (Amann et al., 2005).

Integrated assessments typically analyze global warming, acidification, eutrophication and ozone related problems simultaneously. For such assessments, complete, detailed and consistent emission estimates are required. During the past two decades a number of emissions estimation methodologies have been developed or proposed to estimate emission of pollutants. Examples include guidelines developed to assist countries in reporting national emissions of air pollutants as required by international agreements (e.g. IPCC, 2001; EEA, 2005) or methods included in integrated assessment models (Amann et al., 1998; De Vries et al., 2004) or more disciplinary models (e.g. Li, 2000). These methods include different approaches to calculate emissions, such as emission factor, regression analyses or process based models.

Most of the existing emission estimation methods focus on a particular group of pollutants (e.g. air pollutants) or on a specific environmental compartment (e.g. soils). However, for integrated environmental assessments of the agricultural sector, however, one would prefer a complete and consistent emission inventory, including compounds polluting the atmosphere, terrestrial and aquatic system, and that meanwhile is applicable to the specific agricultural sector at stake. As yet, such a method does not exist. Ignaciuk et al. (2002) evaluated different methods for estimating air pollutants and concluded that existing approaches do not account for the complexity of the relationship between human activities and emissions of air pollutants sufficiently to make them directly useful for integrated assessments. This conclusion probably also holds for inventories of soil and water pollutants. Therefore, a comprehensive analysis of different emission estimation methods, based on characteristics and requirements to be used in an integrated assessment is needed. Such an analysis needs to consider the quality of emission estimation methods, the applicability of the method to a specific agricultural sector in a specific country, and the complexity of the issue given the many interrelations between sources, emissions and environmental problems.

Our study presents an approach for evaluating emission inventory methods. We focus on methods to quantify emissions of air, water and soil pollutants from the agricultural sector at the national scale. We explore the usefulness of our evaluation approach for a case study of the agricultural sector in the Czech Republic. We focus primarily on emissions of compounds associated with major element cycles (C ,N ,P ,S) including ammonia (NH_3), nitric oxide ($NO_{x)}$, nitrous oxide (N_2O), methane (CH_4), particulate matter (PM), nitrate

(NO^-_3) and phosphate (PO_4^{-3}). The reason for this selection is that these compounds significantly contribute to a range of environmental problems, including surface and ground water pollution, eutrophication, acidification, summer smog formation and climate change. Consequently, these compounds are now included in international protocols (e.g. Gothenburg Protocol, Kyoto Protocol) and directives (e.g. National Emission Ceilings Directives, Nitrate Directive) as well as national legislation of the Czech Republic which identifies appropriate reduction targets.

In the next section we discuss three types of methods to estimate emissions and some illustrative examples of these. Section 2.3 presents an approach to evaluate emissions estimation methods. In section 2.4, we apply our approach to the agricultural system in the Czech Republic as a case study.

2.2 Three types of methods to estimate emissions

In this study, we distinguish between three types of methods to estimate agriculture emissions: (1) emission factor based calculations, (2) regression analyses and (3) process-based models. All three are discussed below, and attention is paid to the extent to which interrelations between sources, emissions and environmental problems are taken into account. In addition, for illustrative purposes some examples of methods are given; however, these are not intended to provide a complete overview. Some methods are designed to quantify a single pollutant while others address several pollutants simultaneously. All of them have different objectives, ranging from estimating emissions at the national level to evaluating abatement strategies. We selected ten examples in such a way that they can be considered good illustrations of the different estimation methods. Moreover, the selection is sufficiently complete enough to be used as a basis for the Multi-Criteria Analysis performed in section 2.4.

2.2.1 Emission factor based estimates

The traditional emission factor based estimation uses fixed emission rates of a given pollutant for a given source, relative to units of activity. In other words, this type of emission estimation describes the relationship between the amount of pollutants produced and indicators for human activity, such as the amount of raw material processed (EPA, 2004). The basic equation applies at least two variables, including an averaged *emission factor (F)* and *activity data (A)* (e.g. animal numbers, fertilizer use and crop areas) to calculate emissions *(E)*: $E = F * A$. Emission factors are traditionally used to quantify air, water and soil pollutants at relatively high aggregation levels (e.g. national scale), rather than at the individual source of emissions.

Strength of emission factor based approaches is their simplicity. Generally, the input data needed to calculate emissions are easily available. Some methods provide so-called default emission factors derived from empirical data from several countries. However, this simplicity may give rise to large uncertainties in emission estimates (Brown et al, 2002). Another weakness of emission factor based calculation is that they usually do not consider the variability of emissions in time and space. For example, Pinder et al. (2004) show how important it is to take temporal and spatial variability into consideration when estimating ammonia (NH_3) emissions and subsequently concentrations of secondary particulate matter (PM). This may also hold for other emissions. Furthermore, single emission factors are not always suitable for quantifying the effect of mitigation strategies and thus ignore possible interrelations between abatement measures (Webb and Misselbrook, 2004).

Several emission factor based methods exist for estimating agricultural emissions. Four examples may be worth mentioning here. The IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2001) are applicable to any world country and their main objective is to assist countries in reporting their greenhouse gas emissions to the Climate Secretariat of the UN Framework Convention on Climate Change (UNFCCC). The Joint EMEP/CORINAIR Guidebook is designed to construct emission inventories of conventional air pollutants regulated under the Convention on Long Range Transboundary Air Pollution (CLRTAP) (EEA, 2005). A supplement to the IPCC Guidelines was developed by Freibauer (2003) and allows for calculation of direct biogenic emissions of greenhouse gases from agriculture practices within former EU member states. Our last example is the method included in the integrated assessment model RAINS (Regional Air pollution Information and Simulation model) developed at the International Institute for Applied Systems Analysis (IIASA), Austria. RAINS addresses conventional air pollutants and it is currently being extended to also account for greenhouse gases (Amann et al., 1998, Klaassen et al., 2004).

2.2.2 Regression analyses

Agricultural emissions are controlled by a range of environmental factors such as climate conditions, soil type and farming practices (Freibauer and Kaltschmitt, 2003). Often these can not all be investigated in detail. Regression analyses allow for emission estimates in cases where the available information is not sufficiently detailed enough for process-based modelling (see below). Regression analyses are useful and are widely used to predict agricultural emissions as well as in revealing the most significant factors that control particular pollutants. Moreover, regression analyses can be used to define some interrelations that determine losses of agricultural emissions (Menzi et al., 1998) and possibly also interrelations between emissions. A limitation of regression analyses is that they simplify reality to a larger extent than, for instance, process based models, which may lead to significant errors.

Three illustrative examples of regression analysis models have been selected here. Firstly, the N-model (Kroeze and Seitzinger, 1998), which was developed to quantify nitrous oxide emissions from rivers, estuaries and continental shelves as a function of human activities. Secondly, the models of Freibauer and Kaltschmitt (2003) that were designed to estimate annual nitrous oxide emission from agricultural soils while considering controlling environmental factors (climate, farming practices, and soil properties). And finally, the model ALFAM (Ammonia Loss from Field-applied Animal Manure) to estimate ammonia emissions from applied pig and cattle slurry under various natural and farm conditions (Sogaard et al., 2002).

2.2.3 Process-based models

Process-based models are increasingly recognized as alternatives to emission factor approaches. These models parameterise the interlinked biogenic and abiogenic processes based on their current understanding (Li, 2000). Many process-based models exist and differ in complexity. We distinguish between two groups: detailed and simple models. Detailed process–based models usually require a large amount of data to describe the state of the environment. Their results are generally in good agreement with observations. However, the required input data for these models are often not available for the case study at hand. Moreover, knowledge about the biogenic and biogeochemical processes is often limited. Therefore, simple process-based models are sometimes preferred.

We give three examples of process-based models. They were developed with different aims but all three provide estimates of agricultural emissions. Firstly, the DNDC (Denitrification-Decompositon) model was developed for predicting trace gas emissions from agriculture systems (Li et al., 2000). Secondly, INITIATOR (Integrated Nitrogen Impact Assessment Model On a Regional Scale) aims to evaluate the effectiveness of options to reduce various agricultural emissions of N compounds to air, soil and water (De Vries et al., 2004, De Vries et al. In preparation). Finally, the detailed methodology of EMEP/CORINAIR (EEA, 2005) was developed to quantify N-related emissions (NO, N_2O, NH_3).

2.3. Evaluation of emission estimation methods

2.3.1. Description of the evaluation approach

From the above it is clear that many different emission estimation methods exist. In integrated assessments it is not straightforward to determine which emission estimation method is the most appropriate for a particular analysis. When selecting the most appropriate method, one has to consider for what purpose different methods have been developed and compare these with the objective of the assessment to be performed.

We evaluate emission estimation methods following a three-step approach (Figure 2.1). The first step includes a comparison of methods with respect to preferred characteristics, revealing important similarities and differences between methods. In the second step, we score methods against three types of criteria (general, country specific and interrelations). One can argue that some criteria are more important than others. Therefore, third step in our approach includes a Multi-Criteria Analysis (MCA). We consider our approach to be generally applicable to other cases as well. Nevertheless, it should be noted that the purpose and system boundaries of the case at hand will determine the criteria to be used and their relative weight in the analysis. In the following we describe our three-step approach and indicate how it is applied to our case study for the agricultural sector in the Czech Republic.

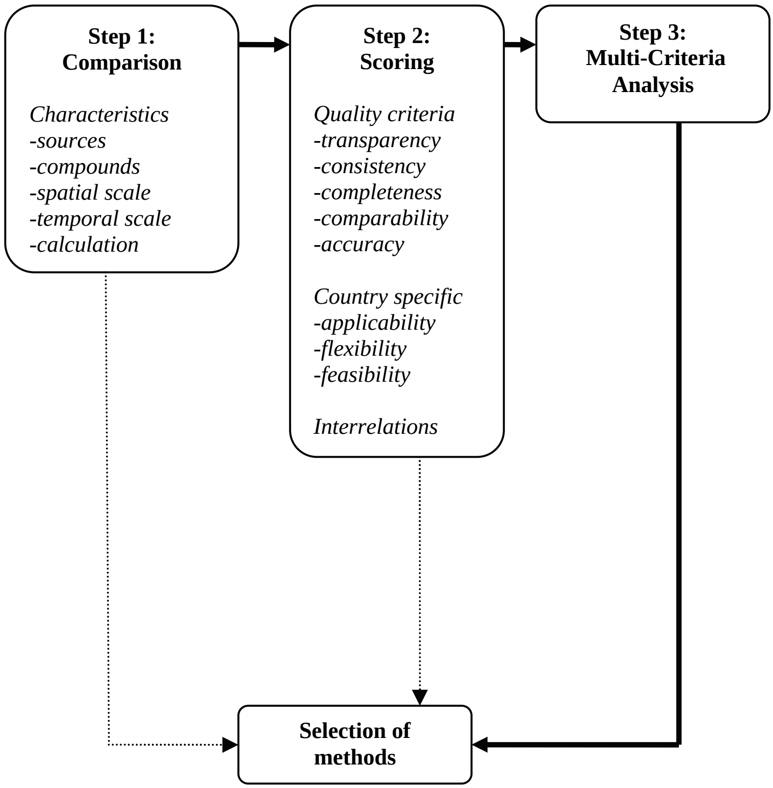

Figure 2.1. An approach for the evaluation of emission estimation methods in three steps: (1) Comparison, (2) Scoring, and (3) Multi-Criteria Analysis. Bold lines indicate the procedure taken in this study. The dashed lines present alternative pathways for method selection. For a detailed explanation of characteristics, quality criteria and interrelations see section 2.3.1.

Step 1: Comparison

In step 1, we define preferred characteristics which are then used to compare selected emission estimation methods. For our case we define requirements for the following characteristics: i) agricultural sources included, ii) compounds included, iii) spatial scale, iv) temporal scale and v) type of approach employed for calculation. These characteristics correspond to a large extent with those used by Ignaciuk et al. (2002), who focused on emissions of air pollutants. The emission estimation methods introduced in the previous section are evaluated with respect to these characteristics, indicating their usefulness in studies that aim to quantify air, water and soil pollutants in a fully integrated way. Such methods should be therefore also applicable at the national scale and in emission projections.

Characteristic i) Agricultural sources included - Table 2.1 shows sources of emissions from the agricultural sector, which we consider relevant. Animals and agricultural soils are the most important sources of emissions from agriculture in Europe (Laegreid et al., 1999). Within these two sources we can distinguish between a number of sub-sources (Table 2.1). For integrated assessments of agriculture, emissions need to be analyzed at least at the level of animals and soils and, if possible, at the level of sub-sources. Some sources are responsible for emissions of more than one pollutant and therefore should be addressed more comprehensively. The various emission estimation methods discussed so far differ with respect to the source categories included. Therefore, we consider the sources included as an important characteristic for comparison of different methods.

Characteristic ii) Compounds considered – In integrated assessments of agricultural pollution, at least seven compounds need to be considered (Table 2.1). Nitric oxide (NO) significantly influences atmospheric chemistry. In the atmosphere, NO oxidizes to nitrogen dioxide (NO_2), contributing to acidification and eutrophication of ecosystems, as well as to the formation of tropospheric ozone. Food production contributes to approximately 10% of global NO emissions (FAO, 2001). Agriculture is a major source of ammonia (NH_3) emissions (Klaassen, 1994). Ammonia plays a key role in acidification and eutrophication of terrestrial and aquatic ecosystems. Once emitted ammonia forms together with oxides of nitrogen and sulphur a secondary particulate matter (PM) (Erisman and Schaap, 2004). Moreover, agriculture significantly contributes to the production of primary particulate matter (Klimont et al., 2001). Farming practices are also a source of nitrous oxide (N_2O) and methane (CH_4) which are powerful greenhouse gases (Monteny et al., 2001). Furthermore, nitrate (NO_3^-) in ground and surface waters is largely from agricultural sources (De Vries et al., 2004). Attention is also paid to phosphate (PO_4^{-3}) which is considered as one of the key compounds causing eutrophication of aquatic ecosystems (Laegreid et al., 1999).

Characteristic iii) Spatial scale – Because of differences in farming practices and in biogeochemical processes, agricultural emissions of air, water and soil pollutants show large spatial variability. Emission estimates can be provided at different scales, ranging from the field scale to the regional, national, continental and global level. Here we consider the country-level as the preferred spatial system boundary. In order to reflect the variability within the country, quantifying emissions at the district level would allow for an appropriate analysis of the actual situation of the agricultural sector and evaluate a potential of emission reduction options.

Characteristic iv) Temporal scale – Agricultural emissions of air, water and soil pollutants exhibit temporal variation. Depending on the aim of the study, emissions can be quantified as annual, seasonal, monthly or hourly totals. In addition, there is a growing need for projection of future emissions. To capture seasonal variability of agricultural emissions associated with, for instance, fertilizer application or grazing periods, a seasonal analysis of emissions is preferred when possible. Emission projections are important for assessments of emission reduction measures and thus proper methods should allow for scenario analysis. For our case study, an appropriate time span of analysis is 30 years, from 2000 till 2030 with 5 year time steps. This timeframe corresponds with current air policy activities within the EC (European Commission) and CLRTAP (Convention on Long Range Transboundary Air Pollution) (Amann et al., 2005).

Table 2.1 Agricultural sources of emissions of NO_x, NH_3, N_2O, CH_4, PM, NO^-_3, PO_4^{3-}

	NO_x	**NH_3**	**N_2O**	**CH_4**	**PM[1]**	**N(NO^-_3)**	**P (PO_4^{3-})**
Animals							
Enteric fermentation				*			
Animal housing		*	*	*	*		
Outside storage		*	*	*			
Manure application	*	*	*			*	*
Grazing		*	*			*	*
Agricultural soil							
Mineral fertilizer use	*	*	*	*		*	*
Crop residues			*				
Biological nitrogen fixation			*				
Cultivation of organic histosols			*				
N-deposition	*	*	*				

[1] primary particulate matter including PM_{10} and $PM_{2.5}$

Step 2: Scoring

In step 2, the methods are scored using different criteria. Here, we distinguish between three groups of criteria: (A) general criteria and (B) country specific criteria, and (C) the extent to which interrelations associated with agricultural emissions are accounted for. The scoring involves a qualitative assessment of the emission estimation methods with respect to these criteria.

A. General criteria

Five general criteria can be used to evaluate the quality of emission inventories, sometimes referred to as TCCCA criteria (*Transparency*, *Consistency*, *Completeness*, *Comparability and Accuracy*) (see for instance IPCC, 2001). These can be applied to reveal the quality of the selected emission estimation methods as follows:

<u>Transparency</u> – emission estimation procedures should be understandable, simple and well-documented, so that it is clear to any user what the methodology is about, without having to contact the persons who compiled the emission inventory

Consistency – emission estimation procedures need to be internally consistent, i.e. to provide a complete set of estimates including all emissions from a source, based on the same approach and input data for a certain time period

Completeness – ideally, all seven compounds emitted from agriculture and their sources (Table 1) are included

Comparability - the emission estimates should be comparable with estimates using other methods and models. We evaluate the extent to which methods have been compared to other methods.

Accuracy – the emission estimate should be realistic and fall within a range that is considered reasonable. We evaluate whether or not uncertainties have been assessed and documented. This then is used as an indicator for accuracy. We thus assume that performing an uncertainty assessment increases the accuracy of a method.

B. Country specific criteria

If one aims to apply emission estimation methods in integrated environmental assessments of the agricultural sector in a specific country while accounting for country-specific conditions, the method chosen must be *applicable*, *flexible, and feasible*. Emission estimation methods should be applicable to the situation of the country. The methods need to be flexible enough to be adjusted to specific agricultural and environmental conditions of a given county. And their application should be feasible with respect to input data availability and the level of complexity of calculation procedures.

C. Interrelations

Linkages between agricultural emissions of air, water and soil pollutants and associated environmental problems are complex and may occur through many mechanisms. Proper quantification is difficult but necessary in integrated assessments. A main challenge is to avoid possible trade-offs in emission reduction and to reach policy targets for all pollutants simultaneously in an efficient way. For evaluation of emission estimation methods we used interrelations defined by Iganciuk et al. (2002) and combined these with those considered by Brink (2003). A brief description of six types of interrelations is given below.

Type 1) Emissions of air, soil and water pollutants can be emitted by the same agricultural source. For example, manure treatment is a source of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), nitrate and phosphate (Laegrid et al., 1999).

Type 2) Emissions of one pollutant may contribute to different air, water and soil pollution problems. Ammonia (NH_3), for example, is important in acidification, eutrophication and in the formation of secondary particles, and thus affects aquatic and terrestrial ecosystems as well as human health.

Type 3) Air, water and soil pollution problems may have an effect on each other and on emissions of pollutants. For example atmospheric deposition of N compounds (NO_y, NH_x) can lead to increased N_2O emissions or result in nitrate leaching to ground water (Kroeze, 1994).

Type 4) Environmental factors such as climate conditions or soil characteristics can affect the formation of agricultural emissions of one or more pollutants. Monteny et al. (2001), for instance, indicate that some factors such as temperature or substrate availability influence both methane (CH_4) and nitrous oxide (N_2O).

Type 5) Technical measures to reduce one pollutant may increase or decrease other pollutants (air, water and soil pollutants). For example, Foy et al. (2004), for instance, mention that cultivation techniques to reduce total phosphorus loss may increase nitrate losses to aquatic systems, which in turn could contribute to eutrophication and increase formation of N_2O. Another example is low NH_3 application techniques from manure, which may increase N_2O emissions and nitrate leaching (Brink, 2003).

Type 6) Non-technical measures such as structural or behavioural changes in agricultural practice may affect emissions of different air, water and soil pollutants simultaneously. De Vries et al. (2001) report on the impact of decreasing livestock numbers on different forms of nitrogen compounds in the Netherlands.

Step 3: Multi-Criteria Analysis

In step 3, we evaluate the emission estimation methods through Multi-Criteria Analysis (MCA). In MCA, the different criteria are weighted, so that an overall assessment can be made. We propose that the analysis is performed for the three groups of criteria separately: (A) general criteria, (B) country specific criteria and (C) criteria associated with interrelations. The results of these three separate MCAs provide insight into how a particular method deals with key features, which we consider to be essential for emission estimation methods. Mixing all categories of criteria together would be an alternative approach, but likely masks the performance of the methods on each of the categories of criteria.

In our approach, we calculate a total weighted score (TWS) following ODPM (2004) for each emission estimation method. TWS is simply the weighted average of scores for all the criteria. To calculate TWS we apply the following formula:

$$TWS = \left(W_1 / 100 \times S_1 \right) + \left(W_2 / 100 \times S_2 \right) + \ldots$$

Where:

TWS = total weighted score of methods (no unit)
S = preference score for the method (result of step 2)
W= weight of the criterion (user-defined)

2.4. Application of the evaluation approach to a case study for the Czech Republic

We aim to evaluate different emission estimation methods with respect to their usefulness in an integrated environmental assessment of the agricultural sector in the Czech Republic. Most of the methods reviewed in section 2.2 have been developed based on data from Western European countries. Therefore, it is interesting to analyze which of these can be applied or adjusted to agricultural and environmental conditions of a Central European country. We evaluate the ten methods mentioned in section 2.2 with respect to criteria identified in section 2.3.

2.4. Comparison, Scoring and Multi-Criteria Analysis

Step 1: Comparison of selected methods

The method preferably includes all relevant sources of pollution (characteristic i). Our analysis shows that only the EMEP/CORINAIR Guidebook and the IPCC Guidelines and model INITIATOR includes all sources listed in Table 2.1 (Table 2.2). The methods used in scientific models typically focus on a few selected sources only. For instance, the DNDC model was designed to quantify only emissions from agricultural soils. The same holds for the regression models by Freibauer and Kaltschmitt (2003) and the model ALFAM.

INITIATOR is the most complete with respect to the compounds included (characteristic ii); this model includes all compounds specified in Table 2.1 (Table 2.2). The simple EMEP/CORINAIR Guidebook, IPCC Guidelines and DNDC include five compounds, but treat them differently. DNDC has been developed for N_2O, NH_3, NO, CH_4, while NO^-_3 leaching is not primarily included in the model (see for instance Brown et al., 2001). The EMEP/CORINAIR Guidebook is mainly focusing on conventional air pollutants such as NH_3, NO and PM. The primary focus of the IPCC Guidelines are greenhouse gases (e.g. N_2O and CH_4), while emissions of NO, NH_3 and NO^-_3 are considered as assisting to their quantification. Other methods tend to be more specific and typically focus on one up to three pollutants.

The selected emission estimation methods are developed for different spatial scales (characteristic iii). ALFAM estimate emissions on the field scale, DNDC and the detailed EMEP/CORINAIR method can be used to quantify emissions at the local, regional as well as national scale (Table 2). INITIATOR is a national scale model, while RAINS covers most of the European region and calculates emissions at the country level. The approaches of Freibauer (2003) and Freibauer and Kaltschmitt (2003) can be used at the national as well as continental (European) level. The N – model is a classical example of a model developed for the global scale and includes 177 watersheds. Nevertheless, it has been successfully applied at the European scale and probably some adaptation will be necessary to make it applicable to the national level in case of relatively large countries. The simple EMEP/CORINAIR method and IPCC Guidelines are applicable to any world country and thus can be used to estimate emissions at the national, continental and global level.

Most methods can be used to quantify emissions as annual totals (characteristic iv; Table 2). Process based models are often able to estimate emissions on smaller time scale. The

DNDC model allows for simulating processes on a daily basis. ALFAM calculates emissions for three seven-day periods. The RAINS model, INITIATOR and the N-model can be used to project future trends in emissions. The EMEP/CORINAIR Guidebook and the IPCC Guidelines include basic instructions for countries to prepare their emission projections.

A last important characteristic is the type of method used to estimate emissions (Table 2.2). The emission factor based approach is mostly used in internationally accepted methodologies such as the simple EMEP/CORINAR methods, and the IPCC Guidelines. The RAINS model is a scientifically and politically accepted model which also uses emission factors. Two models combine at least two approaches; these are the N-model (emission factors and regression analyses) and INITIATOR (emission factors and process based model). The other models listed in Table 2.2 apply only one approach for calculation. The models by Freibauer and Kaltshmitt (2003), and ALFAM use regression analysis while the DNDC model and the detailed EMEP/CORINAIR method are classified as process-based.

From the comparison of the ten methods, it is clear that none of selected emission estimation methods meets all our preferred characteristics (Table 2.2). Therefore, a combination of parts of selected methods may be needed to meet our requirements.

Table 2.2 Comparison of selected emission inventory methods to estimate national NH_3, NO_x PM, N_2O, CH_4, NO^-_3, $PO_4^{-3}$from agriculture. The table is modified from Ignaciuk et al. (2002)

Methods	Sources		Compounds [1]		Spatial scale	Temporal scale	Calculation methods
	Animals	Agriculture soils	Main	Assisting			
EMISSION FACTOR							
IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2001)							
	Enteric fermentation Housing Outside storage Application Grazing	Fertilizer use Crop residues N-fixation Histosols N-deposition	N_2O, CH_4	NH_3,NO,NO_3	Europe, Country level	Annual totals Emission projection	Emission factor
Simple method of EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (3rd edition, EEA.2005)							
	Enteric fermentation Housing Outside storage Application Grazing	Fertilizer use Crop residues N-fixation Histosols N-deposition	NH_3, NO, PM	N_2O,CH_4	Europe Country level	Annual totals Emission projection	Emission factor In preparation: Process-based
Freibauer (2003)							
	Enteric fermentation Housing Outside storage Application Grazing	Fertilizer use Crop residues N-fixation Histosols N-deposition	N_2O, CH_4	NA	Europe Country level	Annual totals	Emission factor Regression Analyses
Regional Air Pollution Information and Simulation model (RAINS Europe, upgraded version 2004, IIASA)							
	Enteric fermentation Housing Outside storage Application Grazing	Fertilizer use Crop residues N-fixation Histosols N-deposition	NH_3, NO, PM	NA	Europe Country level	Annual totals Emission projection (1990-2030)	Emission factor Process-based for some countries
PROCESS - BASED							
Denitrification-Decomposition (DNDC) mechanistic model (Li, 2000)							
		Fertilizer use Crop residues N-fixation N-deposition	N_2O,CH_4 NH_3,NO	NO_3	Field scale	Annual totals Daily totals	Process-based
Integrated Nitrogen Impact Assessment model On a Regional Scale (INITIATOR , De Vries et al., 2004, De Vries et al,. 2006)							
	Enteric fermentation Housing Outside storage Application Grazing	Fertilizer use Crop residues N-fixation N-deposition	NH_3,NO,N_2O CH_4,PM, NO_3 PO_4	NA	Country level 500x500m^2 grid cell	Annual totals	Process-based Emission factor

Table 2.2 Continued

Methods	Sources: Animals	Sources: Agricultural soils	Compounds: Main	Compounds: Assisting	Spatial scale	Temporal scale	Calculation methods
Detailed method of EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (3rd edition, EEA.2005)							
	Housing Outside storage Application Grazing	NA	NH_3, N_2O, NO	NA	Farm level County level	Annual totals Emission projection	Process-based
REGRESSION ANALYSIS							
N–model (Kroeze and Seitzinger,1998)							
	NA	Fertilizer use N-deposition	N_2O	NO_3	Global watersheds	Annual totals 1990-2050	Regression analyses Process-based Emission factor
Model by Freibauer and Kaltschmitt (2003)							
	NA	Fertilizer use	N_2O	NA	Europe Country level	Annual totals	Regression analyses
Statistical model ALFAM by Sogaard et al. (2002)							
	Application	NA	NH_3	NA	Field level	Monthly totals	Regression analysis
Preferred characteristics for present study							
	Animals Agricultural soils If possible all sub-sources		NH_3, NO, N_2O CH_4, PM, NO_3 PO_4	NA	Country level If possible district level	Annual totals Emission projections 2000-2030 If possible seasonal totals	See section 2.4.1

Note: NA-Not applicable means that methods do not account for sources or emissions
[1]Table indicates for which compound the method has been developed primarily (main) and other compounds (assisting)

Step 2: Scoring of methods for different criteria

General criteria

We start with a quality assessment, and analyse the extent to which the ten emission estimation methods meet the TCCCA criteria described in section 2.3.1. Information on the evaluated methods was derived from the literature and is presented in Table 2.3.

An important criterion for application of emission estimation methods is transparency. Clearly, the IPCC Guidelines and the EMEP/CORINAIR Guidebook are the most transparent. These are simple, clear and understandable to a broad audience of users. Moreover, both methods are well documented, and the emission estimation procedures are explained step by step. From the models included in our analysis, only the RAINS model is relatively transparent. The emission estimation method used in the RAINS model is based on methods of EMEP/CORINAIR and the model relevant documentation is readily available. The methods of Freibauer (2003) and the method in the INITIATOR are less transparent. The main reason is the limited accessibility of documentation. On the other hand these methods are kept simple and thus understandable to a broader audience. The other models (DNDC, N-model, the regression models of Freibauer and Kaltshmitt (2003) and ALFAM) are partly transparent. These models use mostly complex emission estimation methods which are clear only to well-informed scientific users.

Second, we evaluated the internal consistency of the different methods. We observed that consistency is ensured by all methods. However, the IPCC Guidelines, the EMEP/CORINAIR Guidebook and RAINS are more internally consistent than others. Simple calculation procedures and easily available input data are main determinants, based on which consistent estimates for emissions within a given time period can be generated.

Completeness is the third criterion. Only INITIATOR includes all compounds that we consider important (see Table 2.1). The IPCC Guidelines, EMEP/CORINAIR Guidebook and DNDC model miss at least two pollutants. The RAINS model, the detailed EMEP/CORINAIR method and the N-model consider a subset of the pollutants mentioned in Table 1, but ignore the rest. Freibauer and Kaltshmitt (2003) and the model ALFAM focus just on one specific compound.

Comparison of different estimation methods can be useful when identifying possible gaps in emission inventories, and differences between emission estimates. We therefore evaluate the extent to which the methods have been used for comparison with, for instance, internationally accepted methodologies or similar methods or models, or with experimental data and results of inverse modelling. The IPCC Guidelines and the EMEP/CORNAIR Guidebook, methods of Freibauer (2003), Freibauer and Kaltschmitt (2003) and the DNDC model received the highest scores. These have been subject to different types of comparison (e.g. Frolking et al., 1998; Brown et al., 2001; Freibauer and Kaltschmitt, 2003; Neufeld et al., 2006). The other methods have been compared to other methods only to a limited extent or the information was not readily available.

Table 2.3. Scoring of emission estimation methods based on general criteria

	Transparency	Consistency	Completeness	Comparability	Accuracy	Total score
IPCC	+++	+++	++	+++	++	**90**
SimpleEMEP/CORINAIR	+++	+++	++	+++	+	85
Freibauer (2003)	++	++	+	+++	+	59
RAINS	+++	+++	+	++	+++	88
DNDC	+	+	++	+++	+/-	46
INITIATOR	++	++	+++	+++	++	83
Detailed EMEP/CORINAIR	++	++	+	++	+	65
N-model	++	++	+	++	+	65
Freibauer and Kaltschmitt (2003)	+/-	+	+/-	+++	+	41
ALFAM	+	+	+/-	+++	+	50
Weights	**35**	**15**	**20**	**10**	**20**	

Note: Conversion of score: +++ = 100 ; ++ =75 ; + = 50; +/-= 25;- = 0

Transparency

(+++) understandable calculation procedure, documentation easily available, (++) understandable, limited documentation available, (+) less understandable, available literature (+/-) less understandable, for documentation have to contact developer (-) not understandable and no documentation available

Consistency

(+++) simple calculation procedure, data set available, (++) simple but data more difficult to obtain to ensure consistency (+) complex procedure, data not available.

Completeness

(+++) all compounds and sources included (++) up to three compounds and sources are missing, (+) four to five compounds and sources are missing (+/-) only one compound and source inluded (-) no compound or source considered

Comparability

(+++) comparison was performed and results are available (++) comparison was performed only to a limited extent

Accuracy

(+++) results and documentation of assessment of accuracy is available (++) only partial analysis, some results presented, documentation on uncertainty assessment available (+) results but not clear documentation available (+/-) only information that the uncertainty analysis was performed, but no results and documentation was found,
(-) no information available

Assessing uncertainty is a crucial step towards more accurate emissions estimates. The methods and models discussed here have been subject to uncertainty assessment in some way. However, the results are not comparable, making it difficult to evaluate the precision of the estimates. Even though a systematic and generally accepted procedure exists to quantify inaccuracies in emission estimates (Van Aardenne, 2002), it is not generally applied. It is outside the scope of this study to perform a quantitative uncertainty analysis of the different methods. Rather we evaluate to what extent information on uncertainty assessment and its results is available and use this as an indicator for accuracy. The RAINS model scores best; clear documentation exists on the calculation of uncertainties in emissions estimates for three pollutants (Schopp et al., 2005) (Table 2.3). The IPCC Guidelines include the recommendation to use error propagation to estimate emissions uncertainty. INITIATOR use Monte Carlo analysis to quantify uncertainties, whereas statistical methods were used to determine the most important parameters responsible for uncertainty in fate of nitrogen (De Vries et al., 2003). Because of the limited scope of the uncertainty analysis, the IPCC Guidelines and INITIATOR score lower than the RAINS model (Table 2.3). Both the simple and detailed methods of the EMEP/CORINAIR

Guidebook provide general information on the uncertainty in emission estimates for ammonia and nitrous oxide. However, the clear procedure is not presented, and no case study was found reporting on results. The N-model, Freibauer (2003), the models of Freibauer and Kaltshmitt (2003) and ALFAM present some results of uncertainty analyses, but do not provide details on the procedure. The DNDC model has been subject to uncertainty analysis (De Vries et al., 2005) but details are not readily available.

Country specific criteria

Next, the methods were evaluated with respect to country specific criteria (Table 2.4). Simple methods of EMEP/CORINAIR Guidebook, the IPCC Guidelines and the RAINS score high on applicability, because these already have been successfully applied to the Czech Republic. The methods of Freibauer (2003), the DNDC model, INITIATOR, detailed EMEP/CORINAIR, the models of Freibauer and Kaltschmitt (2003) and model ALFAM have not yet been used to estimate emissions from the Czech Republic. These, however, were used for national estimates for other countries. We therefore assume that with some modifications, application to the Czech Republic is possible. The N-model is assumed to be less applicable than others, because it models on a watershed basis.

We also evaluated the flexibility of the methods. The process-based and regression models may be able to model the specific agricultural and environmental conditions of the Czech Republic best, and therefore score better than emission factor based methods (Table 2.4). For these only the number of management strategies included may be relatively low. Since the N-model is applied on a large scale it is the only method considered here that is not easily adapted to the Czech Republic.

Finally, we consider to what extent application of the methods to our case study is feasible (Table 2.4). The IPCC Guidelines, the simple EMEP/CORINAIR method and the RAINS model are considered feasible because input data are available and calculation procedures relatively simple. The methods of Freibauer (2003), INITIATOR, the detailed EMEP/CORINAIR method and the models of Freibauer and Kaltschmitt (2003) require more input data. A low feasibility was also assigned to ALFAM, for which specific data on environmental conditions and management practices in the Czech Republic are required that may not be easy to obtain. However, one could apply a simple regression analysis to derive the required input. DNDC is even more complex and needs a larger number of data than ALFAM. We consider it not feasible to apply the N-model to the national scale, because it would requires large adaptations.

Table 2.4 Scoring of emission estimation methods based on country specific criteria

	Applicability	Flexibility	Feasibility	Total score
IPCC	+++	+	+++	66
Simple EMEP/CORINAIR	+++	+	+++	66
Freibauer (2003)	++	+++	+	75
RAINS	+++	+	+++	66
DNDC	++	+++	+/-	60
INITIATOR	++	+++	++	**78**
Detailed EMEP/CORINAIR	++	+++	++	**78**
N-model	+	-	-	10
Freibauer and Kaltschmitt (2003)	++	+++	+	58
ALFAM	++	+++	+	58
Weights	**20**	**45**	**35**	

Note: Conversion of scores: +++ =100; ++ = 75; + = 50; +/- = 25; - = 0
Applicability
(+++) method/model was applied to the Czech Republic, (++) method/model was applied at the national scale but not to the Czech Republic (+) method/model was applied on a different scale than the country scale.
Flexibility
(+++) model is fully changeable to account for country-specific parameters (e.g. management practices and environmental factors), (+) method/model is static but limited parameters could be adjusted (-) method/model is rather static, no changes possible
Feasibility
(+++) input data are easily available from statistics, not time and resource demanding (++) input data could be derived from statistics and based on expert judgement (+) data have to derived from measurements, time and resource demanding (+/-) trade-off between model complexity and data availability and detailed measurements, or not available

Interrelations

We evaluate the methods with respect to six types of interrelations (Table 2.5). Most of the methods take into account the fact that the agricultural sector is a source of more than one pollutant (interrelation type 1, Table 2.5). This was also concluded by Van Ierland et al. (2002) who evaluated another set of emission estimation methods. However, according to our analysis interrelation Type 1 is mostly limited to only a few pollutants, depending on the aim of the methods/models. The second type of interrelation is fully accounted for by DNDC and INITIATOR. By applying one of these, one may address at least three environmental problems. Despite the fact that various environmental problems can affect emissions of agricultural pollutants (interrelation type 3) and thus significantly influence the emission estimates most of selected methods consider this to a limited extent. Predominantly the methods take into account the effect of nitrogen deposition on N_2O emissions. None of these consider the effect of climate change on emissions which according to Mayerhofer et al. (2001) may be significant. Environmental factors that affect the amount of emissions (interrelation type 4) are not included in the simple EMEP/CORINAIR method and the N-model. Process-based models and those applying regression analyses usually sufficiently consider interrelation of type 4. Possible impacts of technical reduction options on emissions of air pollutants (interrelation type 5) are fully reflected by INITIATOR, which quantifies the effect on six compounds (De Vries et al., 2004). This also holds for the detailed EMEP/CORINAIR method, and partly for RAINS and ALFAM. The impact of structural changes (consumption of fertilizer, livestock population) on emissions (interrelation type 6) is considered in all methods, but DNDC, INITIATOR and detailed EMEP/CORINAIR method score highest , because they take into account effects of more than two pollutants.

Table 2.5 Scoring of emission estimation methods based on interrelations. See section 2 for a description of the six types of interrelations

	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Total score
IPCC	++	+	+	++	-	+	48
Simple EMEP/CORINAIR	++	+	-	-	-	+	14
Freibauer (2003)	+	+/-	+	+++	-	+	54
RAINS	+	+	-	-	+	+	25
DNDC	+++	+++	+	+++	-	+++	68
INITIATOR	+++	+++	+	+++	+++	+++	**86**
Detailed EMEP/CORINAIR	++	++	-	++	+++	+++	70
N-model	++	+	+	-	-	+	48
Freibauer and Kaltschmitt (2003)	+	+/-	+	+++	-	+	54
ALFAM	+	+	-	+++	+	+	48
Weights	**5**	**5**	**15**	**35**	**25**	**15**	

Note: Conversion of score: +++ = 100; ++ = 75; + = 50; +/- = 25; - = 0

Type 1

(+++) at least three groups of groups of pollutants (air pollutants, greenhouse gases, water pollutants) considered (++) at least two groups of pollutants considered (+) at least one group of pollutants considered (-) not considered at all.

Type 2

(+++) more than three environmental problems may be addressed by applying the method/model. (++) at least three may be addressed (+) at least two and (+/-) at least one

Type 3

(+) only one environmental problem and its effects on emissions is considered (-) not considered at all

Type 4

(+++) both environmental factors (climate and soil type) are fully considered (++) only one factor considered (e.g. climate), (-) effects of environmental factors not considered

Type 5

(+++) impact of emission reduction measures on more than two compounds considered (+) impact on at least one compound considered (-) not considered at all.

Type 6

(+++) impact of non-technical measures on more than two compounds considered (+) impact on at least one compound considered (-) not considered at all.

Step 3 Multi-Criteria Analysis

In the above we treat all criteria as if they are equally important. Based on the qualitative assessments presented in Tables 2.3, 2.4 and 2.5 we conclude that the following methods score best: the IPCC Guidelines, INITIATOR and the detailed EMEP/CORINAIR method. However, we would like to analyze how our conclusions change if we consider some criteria more important than others. Therefore, in the following we perform a Multi-Criteria Analysis (MCA).

Three performance matrixes were created (Tables 2.3, 2.4, and 2.5). These describe how the methods/models (row) perform for each criterion (column). A numerical assessment of expected consequences of each method was chosen as most appropriate and scores range from 0 to 100. In other words, the results of previous evaluations in terms of "+, +/-, -" were converted into numerical values further referred as a score (S). 100 points are thus assigned to performance of "+++" and mean that method performs best. On the other hand 0 points are assigned to "-" reflecting the worst performance of methods.

Next, weights (W) are assigned to criteria that reflect what value we give to different criteria. 100 points were divided among criteria. We allocated higher weights to criteria for which the methods differ most. In Table 3 we assume transparency matters most to us, so we assign the highest weighting value 35 to this criterion. Completeness and accuracy are also considered important, but less than transparency, thus they both received 20 points. To consistency we allocate a value 15 and 10 for comparability. In Table 2.4 we followed the same weighting procedure; the highest score was given to feasibility and flexibility since there is a large difference between methods. The lowest score was assigned to applicability. Table 2.5 shows that methods vary widely in consideration of influence of environmental factors (interrelations Type 2.4) thus this criterion is considered as a most important in our analysis. On the other hand all methods deal with fact that agricultural is source of more than one pollutant and those emissions may contribute to air, water and soil pollution problems in the same way (interrelation type 2 and 1) therefore we give to these the lowest priority.

Total weighted scores (TWS) of methods reveal which is most preferred, given our valuation of criteria. Table2. 3 shows that based on the TCCCA criteria IPCC Guidelines received the highest TWS which is around two times as high as that of model ALFAM. The last column of Table 2.4 shows TWS values for the three country specific criteria. INITIATOR and detailed EMEP/CORINAIR Guidebook received the highest value. Table 2.5 illustrates the abilities of methods to take into account interrelations; INITIATOR dominates the other methods and scores best.

Based on the MCA results, we conclude that the IPCC Guidelines, the detailed EMEP/CORINAIR method, and INITIATOR provide a sound basis for a new method for estimating emissions from agriculture in the Czech Republic. The challenge is now to select the best parts from each method. As a first step towards a new method, one should consider the input data available for emission estimates. These are typically country specific data (e.g. animal numbers, their performance, manure management, a fertilizer statistics). Emissions of ammonia (NH_3) and nitric oxide (NO) could be based on the EMEP/CORINAIR Guidebook while emissions of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) may be quantified following the IPCC Guidelines. The losses of nitrate (NO_{-3}) may be simply based on the IPCC Guidelines. One may argue that nitrate is considered by the IPCC Guidelines as an assisting compound to calculate N_2O emissions. However, combining country specific information with the IPCC Guidelines may result in better estimates (Silgram et al., 2001). If more detailed data on soil type and associated processes such as nitrification and denitrification are available, the INITIATOR approach to quantify N_2O and N leaching and runoff may be adopted. In addition, INITIATOR is only one able to quantify emissions of phosphate (PO_4^{3-}).

2.5. Discussion

2.5.1 Strengths and weaknesses of our approach

In this study, we present an approach for the evaluation of emission inventory methods. We propose to compare and score different methods in three ways. First, we compare the methods with respect to a number of characteristics that we consider important. Second, we score the methods on the basis of three types of criteria in a qualitative way. Third, a more quantitative Multi-Criteria Analysis (MCA) is performed. The strength of our approach is illustrated by our case study. We show that none of the existing methods meets our requirements. Our approach provides a systematic way to evaluate different emission inventory methods, based on selected evaluation criteria. In our case, the two scoring procedures (step 2 and 3) resulted in the same subset of methods that are to be preferred. Nevertheless, our approach has some weaknesses. First, our comparison and scoring are to a large extent based on literature review. However, we consider our literature sources complete enough to assume that our conclusions are valid. Another potential weakness is related to the criteria used for evaluation. Three types of criteria were used, based on earlier studies. One could question our choice to distinguish between three sets of criteria, instead of using one larger set of criteria. We did not combine the different criteria into one set, because now we can draw conclusions with respect to each set of criteria separately. One may argue that this may unnecessarily complicate the interpretation of the results, in cases where the three MCAs result in different conclusions. In our case, however, this did not happen. As a result, the conclusion that the three selected methods are in fact the best choice is a robust conclusion, being supported by MCA results making use of different sets of criteria.

2.5.2 Sensitivity analysis

In MCA, the valuation of criteria (by assigning weights) is generally considered the most uncertain and disputable part of the analysis. This leads to the question of whether assigning other weights would affect the overall result of the present study. To get insight into this, we performed a sensitivity analysis in which we varied the weights of criteria to analyze how this would affect our choice of methods. Table 2.6 presents the calculated Total Weighted Scores (TWS) for the base case, and one alternative case (A). In the analysis (case A) we examined the effect of using another Multi-Criteria Approaches: the Analytical Hierarchy Process (AHP) (ODPM, 2004). The results do not influence the ranking of the methods to a large extent: the IPCC Guidelines, INITIATOR and detailed EMEP/CORINAIR still have the highest TWSs. From our limited sensitivity analysis we again conclude that the results of our MCA are robust, and are not sensitive to changes in the weights of criteria, or evaluation procedure.

Table 2.6. Sensitivity analysis applied to test the sensitivity of MCA results to variations in weights of the criteria (general, country specific and interrelations). Base case TWS values are compared to alternative cases (A) in which the values of weights (W) are derived by using an alternative MCA approach: AHP (Analytical Hierarchy Process). Highest scores are indicated in bold.

Method	TCCCA		Country specific		Interrelation	
	Base TWS	A	Base TWS	A	Base TWS	A
IPCC Guidelines	**90**	**92**	66	58	48	48
Simple EMEP/CORINAIR	85	86	66	58	14	17
Freibauer (2003)	59	56	75	75	54	55
RAINS	**88**	**92**	66	58	25	26
DNDC	46	40	60	64	68	72
INITIATOR	83	81	**78**	**81**	**86**	**87**
Detailed EMEP/CORINAIR	65	66	**78**	**81**	70	75
N-model	65	66	10	6	48	48
Freibauer and Kaltschmitt (2003)	41	38	58	59	54	55
ALFAM	50	50	58	59	48	51

Note: Base TWS values are from Tables 3, 4 and 5

2.5.3 Concluding remarks

In integrated assessments it is not straightforward which emission estimation methods are the most appropriate for a particular analysis. We propose the approach for the evaluation of emission estimation methods which consists of three steps (1) Comparison, (2) Scoring, and (3) Multi-Criteria Analysis.

The fist step reveals that the ten emission estimation methods differ with respect to the number of sources and compounds included spatial and temporal scale and obviously with application of calculation methods for emission estimate.

From the second step, we observed large quality differences between methods. According to our analysis IPCC Guidelines is a best performing. Second, the evaluation using country specific criteria revealed that most methods are applicable, while only three are flexible enough to account for specific agricultural and environmental condition of the Czech Republic. INITIATOR and the detailed EMEP/CORINAIR methods are feasible. Finally, six types of interrelations served as criteria for assessment. We observed that some types of interrelations are accounted for in all methods, however the degree to which is different. Only the model INITIATOR includes all selected interrelations.

The results of the third step (Multi-Criteria Analysis) support the selection of methods from the pervious two steps. Our analysis suggests that a combination of the IPCC Guidelines, method from INITIATOR the detailed method of EMEP/CORINAIR Guidebook forms a sound basis for a new emission estimation method to be used in integrated assessment of the environmental impact of agriculture in the Czech Republic. Compiling an inventory of agricultural emissions from the Czech Republic, may start by using existing estimates from these methods.

The present study clearly shows that emission factor based methods are transparent and easy to use at the national scale while methods applying regression analyses and process based models are able to consider important interrelations. Thus integrated assessments of the environmental problems associated with the agricultural sector at the national scale preferably combine the best parts of all three types of methods. Obviously, this could be seen as a self evident conclusion, however, in real application this is not the case. There is sill lack of studies applying such combinations, including internationally accepted methods or national/regional models.

Therefore, the importance of this study lays in the fact that it is a first attempt to comprehensively evaluate different emission estimation methods which are usually used in isolation. One can use our evaluation approach to check the quality and test the applicability of the ever increasing number of emission estimation methods available. The large flexibility of our evaluation approach allows for user-defined modifications making it applicable to other economic sectors as well as other countries.

References

Amann, M., Bertok I., Cofala J., Gyarfas F., Heyes C., Klimont Z.,Makowski M., Schopp W., 1998. Cost-effective control of acidification and ground level ozone. Interim Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, http://www.iiasa.ac.at

Amann, M., Bertok, I., Cobala R., Cofala, J., Gyarfas, F., Heyes, C., Klimont, Z., Makowski M., Schopp, Wagner F. 2005. A final set of scenarios for the Clean Air For Europe (CAFE) Programme. CAFE scenario analysis report nr.6 IIASA, Laxenburg, Austria. http://www.iiasa.ac.at/rains/cafe.html

Brown, L., Jarvis S.C., Headon D.A., 2001. Farm-scale basis for predicting nitrous oxide emissions from dairy farms. Nutrient Cycling in Agroecosystems: 60: 149-158

Brown, L., Syed, B., Jarvis, S.C., Sneath, R.W., Phillips, V.R., Goulding, K.W.T, Li, C. 2002 Development and application of mechanistic model to estimate of nitrous oxide form UK agriculture', Atmospheric Environment; 36: 917-928

Brink, J.C., 2003. Modelling Cost-effectiveness of interrelated emission reduction strategies: the case of agriculture in Europe, PhD thesis, Environmental Economics and Nature Recourse Group, Wageningen University, Wageningen, The Netherlands; pp.141

De Vries, W., Kros, H., Oenema, O., 2001. Modeled impact of farming practices and structural agricultural changes on nitrogen fluxes in the Netherlands. In Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Proceedings of the 2nd International Nitrogen Conference on Science and Policy. The Scientific World 1

De Vries, W., Kros, J., Onema, O.,De Klein, J., 2003. Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. Nutrient Cycling in Agroecosystems; 66: 71-102

De Vries, W., Kros, H., Velthof, G., Romkens, P., Gies E., Voogd, J. C., 2004. A decision support system for the integrated evaluation of agricultural management on environmental quality. Proceedings of the 13th Clean Air and Environmental Protection, London, United Kingdom.

De Vries, W., Kros, J., Kuikman, P.J., Velthof, G.L., Voogd, J.C.H.,Wieggers H.J.J., 2005. Use of measurements and models to improve the national IPCC based assessments of soil emissions of nitrous oxide. Environ. Sci; 2: 217-233

De Vries, W., J. Kros, and G.L., Velthof (eds).(in preparation) INITIATOR2: Instrument for an integrated environmental analysis of the changes in agriculture. Calculations of the emissions of ammonia, greenhouse gasses, particles and odour and the accumulation, leaching and runoff, of carbon, nitrogen, phosphorus, bases and heavy metals. Alterra Report, The Netherlands

EEA, 2005. EMEP/CORINAIR Emission Inventory Guidebook –Technical report No 30, Third edition, European Environmental Agency, Copenhagen

EPA, 2004. Compilation of air pollutant emission factors (AP-42).Volume 1: Stationary point and area sources, Fifth Edition: U.S. Environmental Protection Agency. http://www.epa.gov

Erisman, J. W., Schaap, M., 2004. The need for ammonia abatement with respect to secondary PM reduction in Europe', Environmental Pollution; 129:159-163

FAO, 2001. Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land', International Fertilizer Industry Association, Food and Agriculture Organization of the United Nations, Rome. pp.106

Freibauer, A., 2003. A regionalized inventory of biogenic greenhouse gas emissions from European agriculture. European Journal of Agronomy; 19: 135-160

Freibauer, A., Kaltschmitt, M.,2003. Controls and models for estimating direct nitrous oxide emissions from temperate and sub-boreal agricultural mineral soils in Europe. Biogeochemistry; 63: 93-115

Frolking, S.E., Mosier, A.R., Ojima, D.S, Li, C. Parton, W.J., Potter, C.S., Priesack, E., Stenger, R., Haberbosh, C., Dorsh, P., Flesssa, H., Smith K. A., 1998. Comparison of N_2O emissions from soils at three temperate agricultural sites: simulations of year round measurement by four models. Nutrient Cycling in Agroecosystems; 52: 77-105

Foy, B., Sharplay, A., Oenema, O., 2004. Interaction between nitrogen and phosphorus losses at catchments scales. Compromise or conflict? Proceedings of the 4th International Phosphorus Workshop: Critical evaluation of options for reducing phosphorus loss from agriculture, August, Wageningen, The Netherlands

Ignaciuk, A., Kroeze, C., Ierland, E.C. van. ,2002. Models and databases to analyse interactions between emissions of air pollutants in Europe. World Resource Review; 14: 25-53

IPCC, 2001. Good Practice Guidelines and Uncertainty Management in National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, OECD, 2 rue Andre Pascal Paris.

Klaassen, G., 1994. Costs of controlling ammonia emissions in Europe. European Review of Agricultural Economics; 21: 219-240

Klaassen, G., Amann, M., Berglund, C., Cofala, J., Höglund-Isaksson, L., Heyes, C., Mechler, R., Tohka, A., Schöpp,W., Winiwarter,W., 2004. The extension of the RAINS model to greenhouse gases. International Institute for Applied Systems Analysis (IIASA) IR-04-015, Laxenburg, Austria.

Klimont, Z., Cofala, J., Bertok, I., Amann, M, Heyes, C., Gyarfas, F., 2001. Modelling particulate emissions in Europe, a framework to estimate reduction potential and control cost. Interim Report. International Institute for Applied Systems Analysis (IIASA) Laxenburg, Austria

Kroeze, C., 1994. Nitrous oxide and global warming. The Science of the Total Environment; 143: 193-209

Kroeze, C. and Seitzinger, S., 1998. Nitrogen inputs to rivers, estuaries and continental shelves and related nitrous oxide emissions in 1990 and 2050: A global model. Nutrient Cycling in Agroecosystems; 52:195-212

Laegreid, M., Bockman, O., Kaarstad, O., 1999 Agriculture, fertilizers and the environment, CABI publishing in association with Norsk Hydro ASA, Cambridge.

Li C.S., 2000. Modelling trace gas emissions from agricultural ecosystem. Nutrient Cycling in Agroecosystems; 58: 259-276

Mayerhofer, P., Alcamo, J., Posh, M., Van Minnen, J.G. , 2001. Regional air pollution and climate change in Europe: An integrated assessment (AIR-CLIM). Water, Air and Soil Pollution; 130: 1151-1156

Menzi, H., Katz, P.E., Fahrni, M., Nefte, A., Frick, R.A., 1998. Simple empirical model based on regression analysis to estimate ammonia emissions after manure application. Atmospheric Environment; 32: 301-307

MEA, 2003. Millennium Ecosystem Assessment. Ecosystem and human well-being: a framework for assessment. Island Press, Washington DC, USA. pp.138

Monteny, G. J., Groenestein, C. M., Hilhorst, M.A., 2001. Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. Nutrient Cycling in Agroecosystems; 60: 123-132

Neufeldt, H., Schafer, M., Angenendt, E., Li, C.,Kaltschmitt, M., Zeddies, J., 2006. Disaggregated greenhouse gas emissions inventories from agriculture via a coupled economic-ecosystem model. Agric. Ecosyst. Eviron; 112:233-240

ODPM, 2005. Multi-Criteria Analysis manual. Office of the Deputy Prime Ministry UK, pp.145 http://www.odpm.gov.uk

Pinder, R.W., Pekney, N.J. Davidson, C.I., Adams, P.J., 2004. Process-based model of ammonia emissions from dairy cows: improved temporal and spatial resolution. Atmospheric Environment; 38: 1357-1365

Schopp, W; Klimont, Z; Suutari, R; Cofala, J., 2005. Uncertainty analysis of emission estimate in the RAINS integrated assessment model. Environmental Science & Policy; 8: 601-613

Silgram M., Waring, R., Anthony, S., Webb, J., 2001. Intercomparison of national and IPCC methods for estimating N losses from agricultural land. Natur Cycl Agroecosyst; 60: 189-195

Sogaard, H.T., Sommer, S.G., Hutchings, N.J., Huijsmans, J.F.M., Bussink, D.W., Nicholson, F., 2002. Ammonia volatilization from field-applied animal slurry-the ALFAM model. Atmospheric Environment; 36: 3309-3319

Van Aardenne, J.A., 2002. Uncertainties in emission inventories. PhD thesis, Wageningen University, The Netherlands., pp.145

Van Ierland, E.C. Ignaciuk, A., Kroeze, C., Brink, C., Schmieman, E.C, Builtjes, P., Roemer, M., Mayerhofer, P., 2002. Approaches to analyze interactions of climate change, acidification and ozone. Dutch national research programme on global air pollution and climate change. Global Change. Report no.: 410200105, Wageningen University, the Netherlands.

Webb J., 2004. Misselbrook T.H.A. Mass-flow model of ammonia emissions from UK livestock production. Atmospheric Environment; 38: 2163-2176

CHAPTER 3

Environmental and health impact by dairy cattle livestock and manure management in the Czech Republic

Abstract

In this study we evaluate the potential environmental and health impact of dairy cattle livestock and manure management in the Czech Republic. We present a new approach for national assessments of the environmental impact of an agricultural sector. Emission estimates are combined with a country-specific set of indicators to assess the environmental impact in nine regions with specific environmental characteristics. We estimate the contribution of emissions of ammonia (NH_3) and nitrogen oxides (NO) to acidification and terrestrial eutrophication, nitrate (NO_3) and phosphate (PO_4) to aquatic eutrophication, nitrogen oxides (NO_x), particulate matter (PM_{10}) and ($PM_{2.5}$) to human toxicity and methane (CH_4) and nitrous oxide (N_2O) to global warming. We present large regional differences in the environmental and health impact per unit of agricultural production. The regional acidifying, eutrophying and global warming impact of dairy cattle is calculated to be up to three times the national average, depending on the dairy cattle intensity. Aquatic eutrophication is found to be a problem in regions with relatively high eutrophying emissions per hectare of so-called nitrate vulnerable zones. Human toxicity problems caused by dairy cattle livestock and manure management are problematic in regions with a high population density in rural areas. The strength of our approach is the use of country-specific characterisation factors to assess the potential environmental and health impact of agriculture at the sub-national scale. We were able to analyse the potential environmental impact without explicit quantification of specific effects on humans and ecosystems. The results can be used to identify the most polluted areas as well as appropriate targets for emission reduction.

Key words: dairy cattle, environmental impact assessment, site-dependent characterisation factors, Czech Republic

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3.1. Introduction

Agriculture affects the natural environment in many different ways. For example, manure management of dairy cattle is an important source of ammonia emissions causing acidification and eutrophication (Amann et al., 2007) while enteric fermentation of dairy cattle is a significant source of methane responsible for global warming (Crutzen et al., 1986).

In this study we focus on the potential direct environmental and health impact of dairy cattle livestock and manure management. Several studies on the environmental impact of dairy cattle exist. Some of these focus on specific environmental problems. For example, Verge et al. (2007) and Casey and Holden (2005) analysed greenhouse gas emissions. Other studies focus on pollution of specific environmental compartments, such as the atmosphere. Brink et al. (2003) for instance, analysed interactions between conventional air pollutants and greenhouse gases from the agricultural sector including dairy cattle. Some more complete assessments of pollution problems caused by dairy cattle can be found, for instance, in Cederberg and Mattsson (2000) for Sweden, Haas et al. (2001) for Germany and Thomassen et al. (2008) for The Netherlands. These studies differ in system boundaries. However, they all aim for an integrated analysis including an assessment of local (aquatic eutrophication) regional (acidification) and global environmental problems (climate change) caused by dairy cattle.

To our knowledge none of these comprehensive studies focus on the Czech Republic. As one of the Central European countries, the Czech Republic differs from many Western European countries. There are differences in farm structure and production intensity. For the Czech Republic, large scale farming is typical: most of the cattle are kept in large farms with >500 heads (Monteny et al., 2007). The milk yield is relatively low but gradually increasing. In addition, the specific Czech environmental conditions make an assessment of dairy cattle unique. More than 50% of the Czech land is used for agriculture. However, there are substantial differences in types of cultivated lands in the country.

Structural changes in agriculture since the beginning of 1990s ameliorated some environmental problems in the Czech Republic, mainly due to decrease in the number of cattle by about 50% between 1990 and 2005. This led to lower levels of manure application to the land and, consequently, to less environmental damage due to excessive nutrient input. However, the degradation of soil by nutrient replenishment increased substantially (Janosova et al., 2006).

Assessing the direct environmental impact of a complete agricultural sub-sector is not easy because of the complexity of the sector, and the variety of environmental issues at stake. In this paper, we follow up on Chapter 2 (Havlikova and Kroeze, 2006), in which we describe a method to estimate emissions from the Czech agriculture. It builds upon the previous study by adding an assessment of the potential impact of emissions by using characterisations factors. We apply characterisation factors (e.g. acidification potential) describing the relative contribution of emissions to a certain impact category (e.g. acidification).

Two types of characterisation factors can be distinguished: site-generic and site-dependent. Site-generic characterisation factors (e.g. Wenzel et al., 1997) do not take into account spatial characteristics influencing resulted effect of emissions such as structure of sources, background concentration, or sensitivity of receiving ecosystems and human population, while site-dependent characterisation factors to a certain extent do. For acidification and terrestrial eutrophication several site-dependent methods are available (see Potting, 2000; Huijbregts et al., 2000; Hettelingh et al., 2005; Finnveden et al., 2005; Seppälä et al., 2006). This is also the case for aquatic eutrophication (Huijbregts and Seppälä, 2001; Hauschild and Potting, 2003) and for human toxicity (Hauschild and Potting, 2004; Finnveden et al., 2005, Van Zelm et al., 2008).

The purpose of this study is to evaluate the potential environmental and health impact of emissions from dairy cattle livestock and manure management in the Czech Republic at the sub-national level. This is done by applying a site-dependent methodology. However, applying site-dependent characterisation factors at the sub-national level is not straightforward and requires an evaluation of the available characterisation factors, their usefulness, and applicability to our case. In fact, our methodology applies selected characterisation factors while taking into account qualitatively regional differences in terms of agricultural practices and environmental characteristics. The potential environmental and health impact is assessed on the basis of products (milk) and area (ha of agricultural land) for nine study regions in the Czech Republic.

3.2. Method

3.2.1System boundaries

Our analysis includes the emissions of nitrous oxide (N_2O), methane (CH_4), ammonia (NH_3) nitrogen oxides (NO_x), nitrate (NO_3), phosphate (PO_4), particulate matter (PM_{10}) and ($PM_{2.5}$) associated with dairy cattle in the Czech Republic. The system includes processes directly related to the livestock and manure management (Figure 3.1) which can be influenced by farmers itself. Processes related to feed production, fertilizer use and use of diesel and electricity were, therefore, excluded from the analysis. The selected processes are major contributors to the following impact categories: acidification, terrestrial and aquatic eutrophication, human toxicity and global warming. On-farm processes which are included in analysis are: enteric fermentation, manure excretion (stables and pasture) and manure storage. Manure application, and leaching of nitrate and phosphate are off-farm processes that are included as well. The total emissions are calculated per litre of milk produced and per hectare of agricultural land.

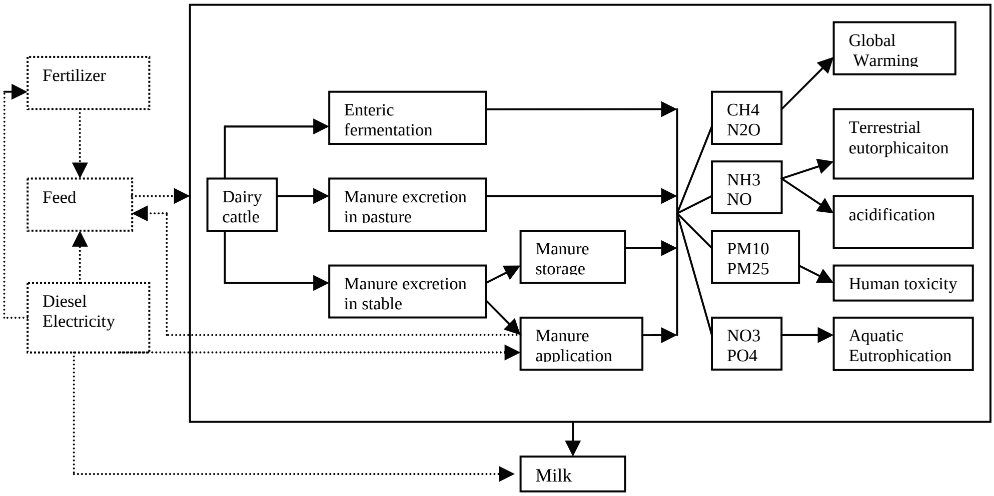


Figure 3.1. Processes, associated emissions and impact categories in dairy cattle livestock and manure management as analysed in the present study. The solid line indicates parts that are included in the present study while dashed lines indicate parts of the system which are excluded.

The processes defined above are used to evaluate the potential environmental and health impact of dairy cattle livestock and manure management in the Czech Republic at the sub-national level. The Czech Republic has a total area of around 79 thousand km^2 of which more then half is agriculture land (CSO, 2006). The country consists of fourteen administrative regions (*Prague, Stredocesky, Jihocesky, Plzen, Karlovarsky, Ustecky, Liberecky, Kralovehradecky, Pardubicky, Vysocina, Jihomoravsky, Olomoucky, Zlinsky, Moravskoslezsky*) (NUTS 3: Nomenclature of Territorial Units for Statistics, level 3). It can, however be, questioned whether administrative regions are the appropriate aggregation level for an assessment of environmental and health impact of agriculture. Important environmental and anthropogenic influencing factors, such as climate, soil characteristics and farming practices typically do not correspond with administrative borders (Bouwman et al., 1996; Finnveden et al., 2005). On the other hand, the data needed for an environmental assessment are usually readily available for administrative regions. The question is, therefore, what the appropriate level of spatial detail is for our study.

Our approach is to classify the fourteen regions based on their specific characteristics. This way, we identify nine study regions. The determining characteristics are (1) dairy farming intensity, (2) sensitivity of terrestrial ecosystems towards acidification and eutrophication, (3) percentage of agriculture land in nitrate vulnerable zones, and (4) population density. These represent parameters on which site-dependent characterisation factors are typically based, as discussed later in this paper. The dairy farming intensity is expressed as the number of dairy cows per 100 hectare of agricultural land. This can be considered as an indicator for the amount of emissions of pollutants. The second characteristic is the sensitivity of terrestrial ecosystems to acidification and eutrophication and is expressed as a critical load for acidity CL (A) and nutrient nitrogen CL N (nut). The third characteristic is defined as the percentage of agriculture land in nitrate vulnerable zones (NVZ). This is an indicator for drained areas with surface and groundwater pollution by nutrients from agricultural sources. The last characteristic is the population density expressed as number of persons per kilometre squared. This can be considered an indicator for the potential exposure of population to air, water and soil pollutants. Table 3.1.A in the Appendix shows how regions in the Czech Republic differ in terms of these environmental characteristics.

The nine study regions are classified as “low ” or “high” for each characteristic according to a general principle: below average = low, and above average = high (Table 3.1, where the average value reflects the average of the 14 administrative regions). The rationale behind the choice of a simple averaged value is that no policy targets are specified in current legislation, except for critical load exceedance (e.g. CLRTAP Gothenburg Protocol). Some of the nine study regions (1, 2, 6, 7) are in fact a group of regions, while the others (3, 4, 5, 8, 9) represent a single region (Figure 3.2).

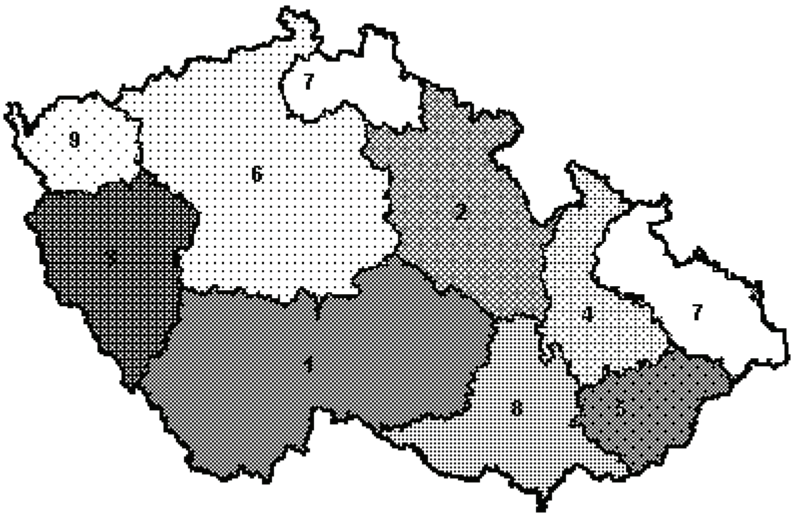


Figure 3.2 Nine study regions (1-9) in the Czech Republic, for detailed explanation see Table 3.1

Table 3.1 Characterisation of study regions based on average values for four environmental indicators

Study region[1]	Dairy farming Intensity[2]	% of agriculture land in nitrate vulnerable zones (NVZ)[3]	Sensitivity to acidification, terrestrial eutrophication[4]	Population Density[5]	Administrative regions
1 (HHHL)	High	High	High	Low	Jihocesky,Vysocina
2 (HHLL)	High	High	Low	Low	Kralovehradecky Pardubicky
3 (HLHL)	High	Low	High	Low	Plzensky
4 (HLLL)	High	Low	Low	Low	Olomoucky
5 (HLLH)	High	Low	Low	High	Zlinsky
6 (LHHH)	Low	High	High	High	Stredocesky Ustecky
7 (LLLH)	Low	Low	Low	High	Liberecky Moravskoslezsky
8 (LHLH)	Low	High	Low	High	Jihomoravsky
9 (LLHL)	Low	Low	High	Low	Karlovarsky

[1] The region identifiers consist of a number and indications (H or L) of the four characteristics presented in this table
[2] High is >10 cows /100 ha agricultural land, Low is <10 cows /100 ha agricultural land
[3] High is > 40% of agricultural land in nitrate vulnerable zones, Low is < 40% of agricultural land in nitrate vulnerable zones
[4] High is CL(A) < 1582 eq/ha*yr, and CL(N) < 515 eq/ha*yr, Low is CL(A) > 1582 eq/ha*yr, and CL(N) > 515 eq/ha*yr
[5] High is >130 persons/km^2, Low is < 130 persons/km^2

3.2.2 Inventory analysis

In our analysis we quantify emissions from dairy cattle livestock and manure management by applying emission estimation methods. In Chapter 2 (Havlikova and Kroeze, 2006), we evaluated emissions estimation methods for an integrated assessment of the agriculture in the Czech Republic. We proposed to combine parts of available emission estimation methods such as the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2001b), the detailed version of EMEP/CORINAIR (2005) Guidebook (EEA,2005) and the model INITIATOR (Integrated Nitrogen Impact Assessment Model On a Regional Scale) (De Vries et al., 2003; De Vries et al., in prep). The approach is a combination of emission factors and simple process based models requiring national specific parameters concerning the number of animals and performance (milk yield, nitrogen and phosphate excretion) and type of housing (solid and liquid systems). For details on these methods we refer to Chapter 2. In line with this, we adopted a GAS_EM model for dairy cattle to derive emission factors (for more details on this model see Dämmgen et al., 2002). GAS_EM requires information about the number of dairy cows and the milk yield per year. These are obtained from the Czech Statistical Office (CSO) for each administrative region see Table 3.2A. The production of manure and the proportion of solid and liquid waste are from the national study by Jelinek et al. (2004). Where input data is not available we use German default values as given by Dämmgen et al. (2002), because the German agricultural situation is comparable to that in the Czech Republic. Emission factors used to estimate emissions are shown in Table 3.2.

We assume that no emission reduction measure is implemented in the Czech Republic in 2004. This basically corresponds with current situation, even though ammonia emissions are regulated through the European Code of Good Agriculture Practice and nitrate leaching by the European Nitrate Directive. However, both have been implemented in the Czech Republic just recently. Therefore, the emission inventory compiled in our study can serve as a baseline for analysis of possible scenarios for implementation of emission reduction measures.

Table 3.2. Overview of processes and related emission factors used in the analysis

Processes	Emission factors kg/ yr/animal								Reference
	NH_3^*	NO	N_2O	CH_4	PM_{10}	$PM_{2.5}$	NO_3	PO_4	
Enteric fermentation				96-111					Dammgen et al.(2006)
Grazing	0.98-1.22		0.08						GAS_EM model
Milking	2.18-2.45								EMEP/ CORINAIR (2006)
Stable	11.02-12.42								
-Solid			0.21		0.70	0.45			IPCC(2001b)
-Liquid			0.46		0.36	0.25			
Storage	8.39-8.66	0.007		30					Dammgen et al.(2006) EMEP/ CORINAIR (2006)
Application	5.62-6.81		0.0125						Dammgen et al.(2006) IPCC (2001b)
Indirect			0.025						IPCC(2001b)
Leaching							0.3	0.1	IPPC(2001b), EDIP2003

* For each study region a specific emissions factor were used, ranges indicate lowest and highest values between study regions

3.2.3 Impact assessment

We use impact factors, or so-called characterisation factors, to assess the potential contribution of emissions to acidification, terrestrial and aquatic eutrophication, human toxicity and global warming. Several sets of characterisation factors exist, some of which are specific for the Czech Republic.

Characterisation factors from EDIP2003 are used for aquatic eutrophication by NO_3^- and PO_4^{-3} and human toxicity by $PM_{2.5}$, PM_{10} and NO_x. This is the only available set of site-dependent characterisation factors specific for the Czech Republic. For global warming by N_2O and CH_4 the IPCC (2001a) Global Warming Potentials for a time horizon of 100 years are used, in line with EDIP2003 (Hauschild and Potting, 2004).

For acidification and terrestrial eutrophication by NH_3 and NO_x several sets of site-dependent characterisation factors for the Czech Republic are available in the literature: e.g.

in Huijbregts et al., (2000), EDIP2003 (Hauschild and Potting, 2004), Hettelingh et al. (2005) and Seppälä et al. (2006).

Table 3.3 present s four sets of characterisation factors for acidification and three for terrestrial eutrophication which are available for the Czech Republic (Huijbregts et al., 2000, Hauschild and Potting, 2004, Hettelingh et al.,2005 and Seppälä et al., 2006). These were developed by applying different modelling approaches and input data (e.g. reference years for the emissions, atmospheric transport models used and assumed sensitivity of ecosystems).

An important difference between these characterisation factors is the category indicators used to quantify the environmental and health problems associated with acidification and eutrophication. As a result, the characterisation factors need to be interpreted in different ways. For instance, the Hazard Index (HI) developed by Huijbregts (2001) is basically referring to changes in the potential risk of ecosystem acidification and eutrophication due to changes in emissions. This HI approach could be classified as an *above and below the critical load (AB) approach*. Alternatively, Seppälä et al (2006) use Accumulated Exceedance (AE) to indicate the amount of emissions causing exceedance of the critical capacity of ecosystems. It can, therefore, be classified as a *only above the critical load (OA)* approach. EDIP2003's Unprotected Ecosystem (UA) indicator, refers to the area where deposition rates are at the critical capacity of the ecosystem. This category indicator can therefore be considered as an *around the critical load (A)* approach. In the following we analysed which of these environmental indicator can suits for the environmental situation in the Czech Republic best.

Table 3.3. Overview of selected characterisation methods for acidification and terrestrial eutrophication available for the Czech Republic, including approaches for calculation used, category indicators selected, temporal and spatial scale

Impact category	Characterisation methods	Approach for calculation	Category indicator	Temporal scale	Spatial Scale
Terrestrial Eutrophication	Huijbregts et al (2000)	RAINS [1]	HI (hazard index)	1990, 1995,2010	National
	EDIP2003[3]	RAINS[1]	UA (unprotected ecosystem)	1990, 2010	National
	Seppälä a et al. (2006)	EMEP/Emission CL database[2]	AE (accumulated exceedance)	2000, 2010	National
Acidification	Huijbregts et al (2000)	RAINS[1]	HI (hazard index)	1990, 1995,2010	National
	EDIP2003[3]	RAINS[1]	UA (unprotected ecosystem)	1990, 2010	National
	Hettelingh et al. (2004)	EMEP/Emission CL database[2]	UA (unprotected ecosystem)	2000, 2010	National
	Seppälä et al. (2006)	EMEP/Emission CL database[2]	AE (accumulated exceedance)	2000, 2010	National

[1]Amann et al., 1998; [2] EMEP (1998); [3] Haushild and Potting (2004)

NH_3 : NO_x ratios

It is interesting to compare differences between the characterisation factors for acidification and terrestrial eutrophication in terms of NH_3: NO_x ratios (Table 3.4). This ratio reveals the relative importance of these two compounds in acidification and eutrophication. If, for instance, a characterisation factor for NH_3 was twice as high as for NO_x, the calculated potential environmental impact of NH_3 emissions would be double that of a similar amount of NO_x emissions.

For acidification the relative differences between characterisation factors for NH_3 and NO_x are a factor of 5 to 6 in the studies of Hettelingh et al. (2005) and Seppälä et al. (2006). For the EDIP2003 characterisation factors the difference is a factor of 2. The reason for the variation could be the choice of emission change, the modelling approaches and input data. Huijbregts et al. (2000) developed characterisation factors for 1990 and 1995 based on areas with exceeded critical load, so called *only above* critical load approach (OA) and also developed characterisation factors for ecosystems *above and below* their critical loads (AB). These NH_3: NO_x ratios indicate differences ranging between a factor of 3 and 6. The highest is for the year 1995 and compares well with other studies such as Hettelingh et al. (2005) and Seppälä et al. (2006), while the lowest is for the AB case. For terrestrial eutrophication, a comparison of NH_3: NO_x ratios lead to similar observations as for acidification. We may conclude that the characterisation factors for terrestrial eutrophication from Seppälä et al. (2006) and Huijbregts et al. (2000) are generally in good agreement.

Our analysis shows that for both acidification and terrestrial eutrophication, the differences between the NH_3: NO_x ratios are within a factor of 2 for characterisation factors from Huijbregts et al. (2000), Seppälä et al. (2006), and Hettelingh et al. (2005). This indicates that these characterisation factors are rather robust and their application will not lead to large differences in results.

Table 3.4 Ratios of NH_3: NO_x characterisation factors for acidification and terrestrial eutrophication for the Czech Republic as available from the literature (see Table 3.3)

Impact category (c)	EDIP 2003 Haushild and Potting, 2004 UA	Hettelingh et al. (2004) UA	Huijbregts et al. (2000) HI			Seppälä et al.(2006) AE
	A1990	A2000	AB	OA1990	OA1995	OA2002
Acidification	2 : 1	6 : 1	3 : 1	5 : 1	6 : 1	5 : 1
Terrestrial Eutrophication	2 : 1	NA	3 : 1	4 : 1	4 : 1	4 : 1

Note: AE –accumulated exceedance, UA-area of unprotected ecosystems and HI- hazard index, A-around the critical load, OA-only above critical load, AB–above and below critical load, NA-not available. See section 2.3 for more details.

Here, we adopt site-dependent characterisation factors from Seppälä et al. (2006) for several reasons. First, they include separate characterisation factors for both acidification and terrestrial eutrophication and therefore the potential impact can be calculated consistently. Second, the study provides the most recent set of characterisation factors, which were derived from national emission estimates, transfer matrices, deposition and critical loads corresponding with national submissions to international bodies such as CLRTAP (Convention on Long Range Transboundary Air Pollution). And finally, the relative difference between their characterisation factors for NH_3 and NO_x is comparable to that for characterisation factors from Hettelingh et al. (2005) and Huijbregts et al. (2000), indicating that there is general agreement among these studies about the relative importance of NH_3 and NO_x in acidification and terrestrial eutrophication. .

Tables 3.5a and 3.5b summarise the characterisation factors that we consider most appropriate for an integrated environmental assessment of the agriculture sector in the Czech Republic. Basically it is a combination of the characterisation factors from Seppälä et al. (2006) and EDIP2003 (Hauschild and Potting, 2004).

These characterisation factors can be used to estimate the potential impact (P_c) for impact category c by multiplying the amount of emissions (E) of given compounds (x) emitted in a study region (n) by characterisation factors (CFc) and sum these impact scores over all compounds (Table 3.5a, b).

$$P_c = \sum E_{x,n} \times CF_c$$

Table 3.5a Characterisation Factors (CF_c) for environmental problems as used for the assessment of the environmental impact of dairy cattle livestock and manure management in the Czech Republic in this study

Impact category (c)	Compound (x)	Characterisation Factor (CF)	Reference
Acidification	NH_3 NO_x	3.65 keq/t 0.73 keq/t	Seppälä et al. (2006)
Terrestrial Eutrophication	NH_3 NOx	10.33 keq/t 2.52 keq/t	Seppälä et al. (2006)
Aquatic* Eutrophication	NO_3^- PO_4^{-3}	0.64 g NO_3 eq/g 0.73 g NO_3eq/g	EDIP 2003 (Haushild and Potting, 2004)
Global Warming	N_2O CH_4	296 g CO_2 eq 23 g CO_2 eq	IPCC(2001a)

Explanation of abbreviation:
Keq/t - kiloequivalents of H^+ per tons of emissions, eq/g – equivalents of nitrate per gram of nutrients released
*Site-dependent characterisation factors (CF) for aquatic eutrophication are calculated from site-dependent exposure factors for eutrophication of inland waters (IEF) adjusted for a factor (F) relating the emission of compounds (x) to nitrate (modified form EDIP2003): $CF = IEF * F$. Factor (F) is for phosphate 10.45 g NO_3 eq/g and for nitrate 1 gNO_3 eq/g

Table 3.5b Characterisation Factors (CF_c) as used for the assessment of the human health problems caused by dairy cattle livestock and manure management in the Czech Republic in this study

Impact category (c)	Compound (x)	Characterisation Factor (CF)*			Reference
		F (m^3air/g)	REF (person/µg/m3/g)	LEF (person µg/m3/g)	EDIP2003
Human toxicity	$PM_{2.5}$	0.0002	50000	122	(Haushild
	PM_{10}	0.0006	50000	122	and Potting,
	NO_x	0.008	3115	47	2004)

Explanation of abbreviation:
*Site-dependent characterisation factors (CF) are calculated from regional (REF) and local (LEF) exposure factors adjusted for population density (D) and a factor (F) relating the emission of compounds (x) to the impact from exposure as follows (modified form EDIP2003: $CF = (REF + D \times LEF) * F$.

Site-dependent characterization factors developed for European countries (e.g. Seppälä et al., 2006) do not taken into account regional differences at sub-national level. They do not consider changes in impact indicators (e.g. accumulated exceedance of critical load) within study regions caused by unit changes of emissions from dairy cattle livestock and manure management in the study regions. We therefore combine site-dependent characterization factors with qualitative information on environmental indicators for each impact category (see Table 3.1 and Table 3.1A). The study regions presented in Table 3.1 are characterized for indicators of potential risk with regard to particular environmental problems. This qualitative information is then used for further interpretation of the severity of the estimated potential impact (P_c).

3.3. Results

We present the estimated potential environmental and health impact of dairy cattle livestock and manure management in the nine study regions. Figures 3.3A-E presents the sub-national impacts per year, per hectare and litre milk production and the contribution of selected pollutants to the various impacts. The impact per hectare of agriculture land indicates the land intensity of dairy cattle in each study region. The indicator based on a litre of milk produced per cow reflects cattle performance (milk yield). For human toxicity, the indicator on a per capita basis is added to show potential exposure of humans to pollution by dairy cattle.

Figure 3.3A-E indicates that ammonia is the main cause of acidification (responsible for 98%) and terrestrial eutrophication (92%) while nitrogen oxides contribute 2% and 7%, respectively. Nitrate accounts to more than 90% of the terrestrial and aquatic eutrophication in all study regions. Human toxicity problems are largely associated with nitrogen oxides (87-92%), while the contributions of PM_{10} and $PM_{2.5}$ are around 10% and 2%, respectively. For global warming, emissions of methane are the most important (70%) while nitrous oxides contribute by 30%.

Acidification and terrestrial eutrophication

In Figure 3.3 A-B, acidifying and eutrophying emissions are expressed in kilo equivalents of averaged accumulated exceedance of critical loads per litre of milk produced per cow and per ha of agriculture in each study region. The average of the nine values for the study regions in the Czech Republic is 0.8 keq per litre of milk per cow and 0.01 keq per ha of agriculture land for acidification and 2.5 keq per litre of milk per cow and 0.03 keq per ha of agriculture land for eutrophication. Clearly, the terrestrial eutrophication impact is dominating over acidification. On a milk production basis, the largest impact is calculated for study regions 1(HHHL), 2(HHLL) and 6(LHHH) where the indicator value is 1.5 to 3 times the national average. These study regions include six administrative regions: *Jihocesky*,*Vysocina*, *Kralovehradecky*, *Pardubicky*, *Stredocesky*, *Ustecky*. These study regions have the highest milk yield and high number of dairy cattle. This may indicates relation between emissions emitted and increasing cattle performance. In addition it is interesting to note that for study regions 1 and 6 there is a clear relation between the calculated impact and the sensitivity of the regions for acidification and terrestrial eutrophication. The critical load indicator is relatively low for acidity and nutrient nitrogen (Table 1A). This indicates that both ecosystems are potentially sensitive to acidification and terrestrial entrophication here. Actually, the pollution by ammonia emissions from dairy cattle in these study regions may be one of the important driving forces for these two environmental problems. In addition study region 1, 2 and 6 are neighbouring regions and it is likely that there is relatively high net transport of ammonia between them. On an area basis, the largest impact is again calculated for study regions 1and 2, but also for study region 3(HLHL) which includes the region *Plzeňský*. This may indicates that dairy farming is relatively land intensive in these three regions.

Aquatic eutrophication

Eutrophying emissions of nitrate and phosphate are expressed in t NO_3^- equivalents per year. The average of the nine indicator values for the different regions is 0.1 t NO_3^- per litre of milk produced per cow and 0.0025 t NO_3 per hectare of agriculture land. The results indicate that aquatic eutrophication is particularly a problem in study regions with intensive dairy cattle livestock and manure management: 1(HHHL), 6(LLLH) and 2(HHLL). Their indicator values are 1.5-2.8 times the national average (Figure 3C). Regions 1 and 2 are classified as sensitive to nutrient pollution because relatively large areas (around 50%) of agriculture land are located in nitrate vulnerable zones. In addition, the potential impact for aquatic eutrophicaton is expressed per hectares of agriculture land in nitrate vulnerable zones. The average value for this indicator is 0.008 t NO_3^- per ha of agriculture land in nitrate vulnerable zones. For this indicator, study region 5(HLHL) has the highest value (about twice the national average). Despite the fact that this study region as a whole is classified as relatively insensitive to aquatic eutrophication (ranked as last in Figure 3.3C), the potential for aquatic eutrophication is relatively high.

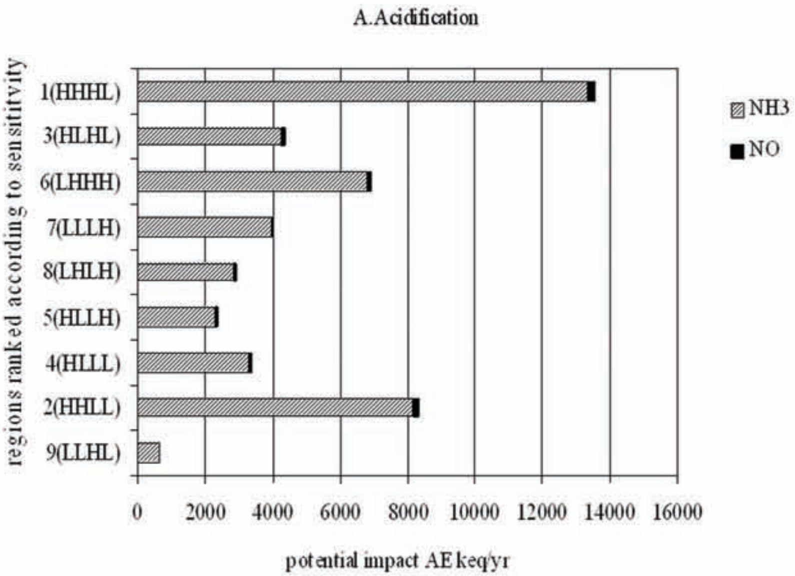
Human toxicity

The average of the nine regional indicator values for human toxicity potential (Hta) is 0.12 Hta per litre of milk and 0.002 Hta per hectare of agriculture land. Study regions 1 (HHHL) and 2(HHLL) have the highest potential for toxicity problems, with indicator values that are

1.5-2.5 times the national average (Figure 3D). The potential for human toxicity problems depends, amongst others, on population density: the more people live in an area, the larger the potential impact. The characterisation factor used here is therefore a function of population density (see Table 5b). However, Figure 3D indicates that the regions 1 and 2, for which we calculate high potentials for human toxicity problems, have relatively low population densities. This may be explained by the fact that not all people have an equal chance to be exposed to toxic compounds emitted from dairy farms. People living in rural areas may have a higher risk of exposure than urban population, because most of the dairy cattle farms are located in rural areas. Therefore, we used as an additional indicator the potential human toxicity per person living in *rural* areas (Figure 3.3D). The national average is 0.002 Hta per person in rural areas. The highest potential health impact for population living in rural areas is calculated for areas 1(HHHL) and 3(HLHL). In these two study regions a relatively large number of people live in rural areas. These are potentially affected by emissions from dairy cattle causing human toxicity problems.

Global Warming

The average of the nine regional indicator values is 0.03 kt CO_2 equivalents per litre of milk and 0.0004 kt CO_2 equivalents per hectare of agriculture land. Areas 1(HHHL) and 2(HHLL) have the highest emissions per litre of milk (2.7-1.7 times the national average). Emissions per hectare of agriculture land are highest in area 3 (HLHL), where intensive dairy farming takes place on a relatively small agricultural area (Figure 3E).



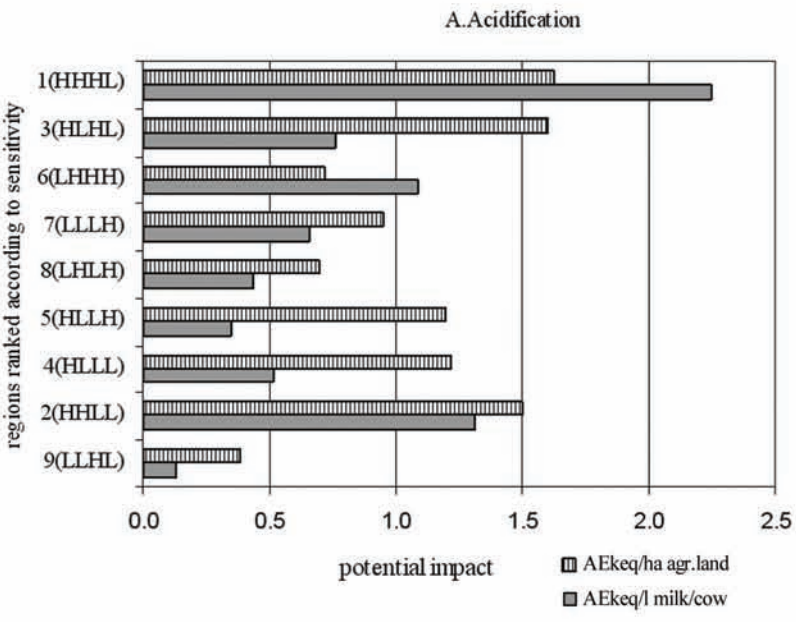
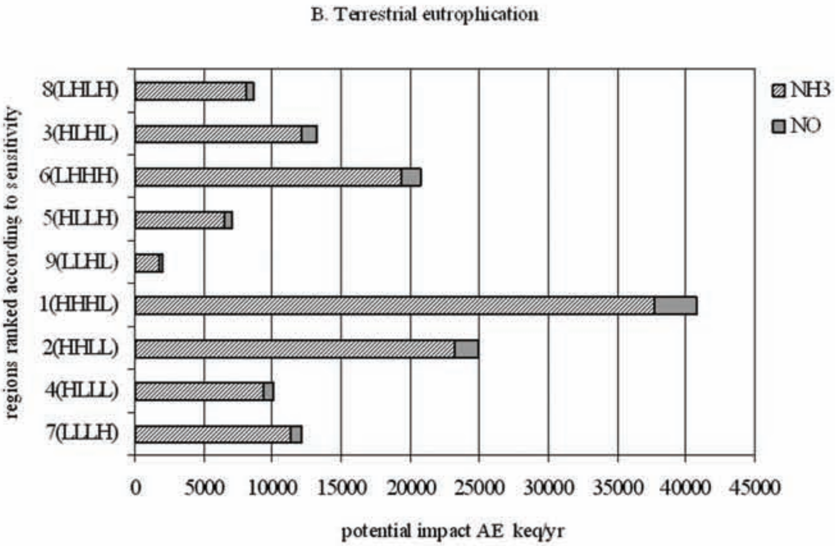


Figure 3.3A Potential environmental and health impact of dairy cattle in nine study regions in 2004. **A up:** Acidification; regions on the y axis are ranked according to sensitivity to acidification, from the least sensitive region 9(LLHL) to most sensitive region 1(HHHL). **A down:** acidification per hectare and per litre of milk produced per cow.

Note: the values of indicators per hectare of agriculture basis are multiplied by 100.



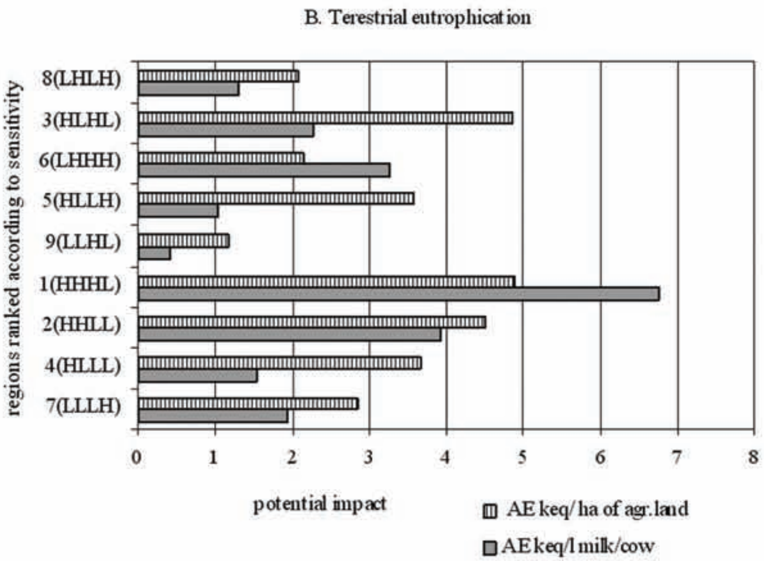
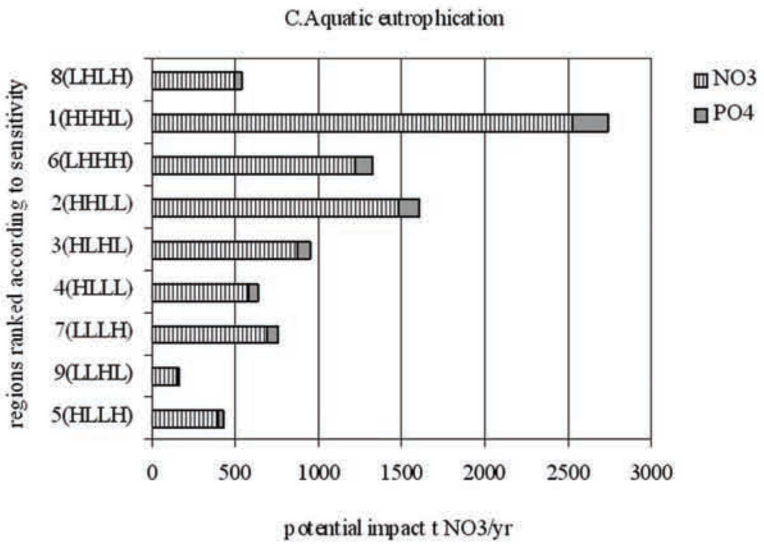


Figure 3.3B Potential environmental and health impact of dairy cattle in nine study regions in 2004. **B up:** Terrestrial Eutrophication; regions on the y axis are ranked according to sensitivity towards terrestrial eutrophication, from the least sensitive region 7(LLLH) to most sensitive 8(LHLH). **B down:** terrestrial eutrophication per hectare and per litre of milk produced per cow

Note: the values of indicators per hectare of agriculture basis are multiplied by 100.



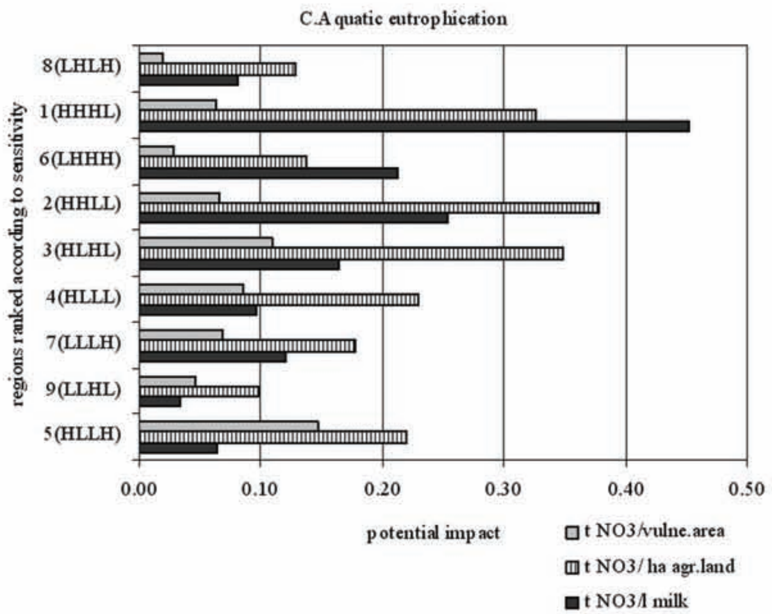
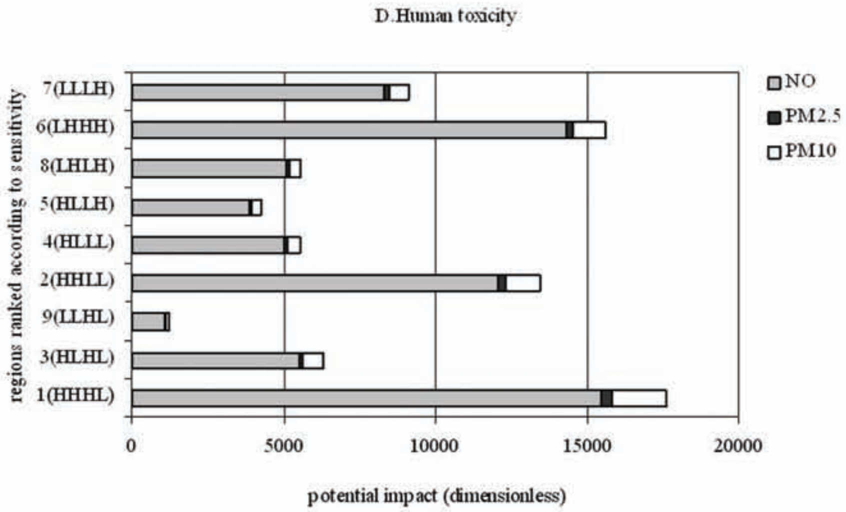


Figure 3.3C Potential environmental and health impact of dairy cattle in nine study regions in 2004. **C up:** Aquatic Eutrophication; regions on the y axis are ranked according to % arable land in vulnerable areas, from the lowest % in region 4(HLLH) to highest in region 8(LHLH). **C down:** Aquatic eutrophication by dairy cattle per hectare of agriculture land, per hectare of agricultural land located in nitrate vulnerable zones and per litre of milk produced per cow.

Note: the values of indicators per hectare of agriculture basis are multiplied by 100. The values of indicators per hectare of agriculture land in vulnerable areas by 10.



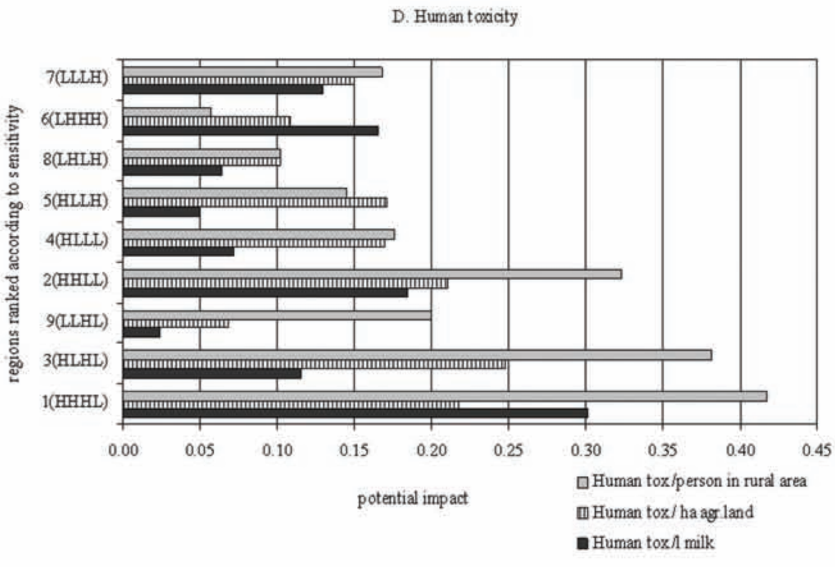
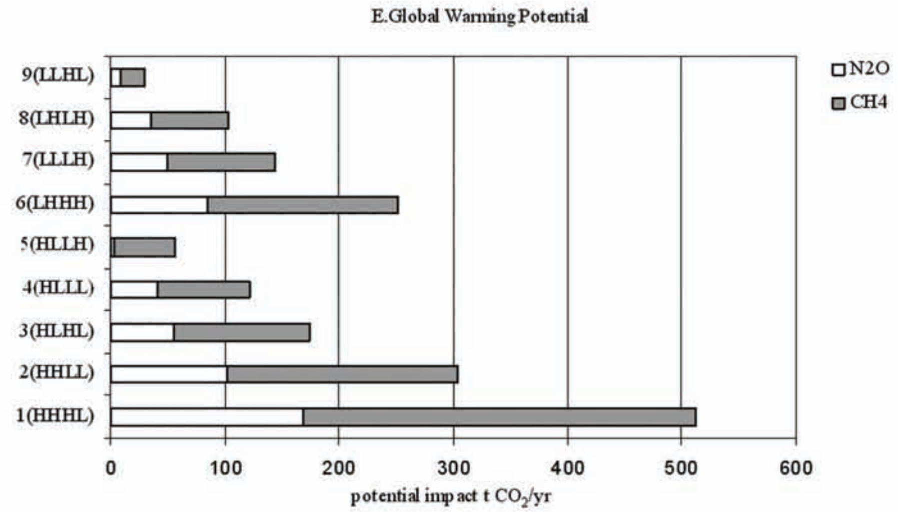


Figure 3.3D Potential environmental and health impact of dairy cattle in nine study regions in 2004. **D up:** Human toxicity; regions on y axis are ranked according to population density, from the most populated 7(LLLH) to the least populated 1(HHHL). **D down:** human toxicity problem per hectare of agriculture land, per litre of milk produced per cow and per person living in rural areas

Note: the values of indicators per hectare of agriculture basis are multiplied by 100. The values of indicators per person living in rural areas are multiplied by 10.



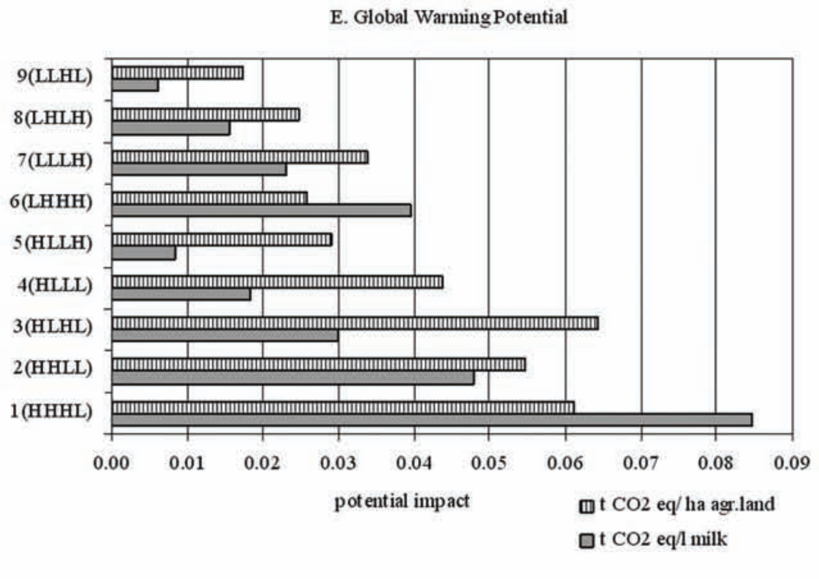


Figure 3.3E Potential environmental and health impact of dairy cattle in nine study regions in 2004. **E up:** Global warming (no ranking). **E down:** global warming per hectare and per litre of milk produced per cow.

Note: the values of indicators per hectare of agriculture basis are multiplied by 100.

3.4. Discussion

In this paper we evaluate the potential environmental and health impact of dairy cattle livestock and manure management in the Czech Republic on a sub-national basis. For this purpose, Czech-specific characterization factors were combined with region-specific data. Several methodological choices were required in our calculations which can affect the results of our assessment. In our analysis each study region is treated as a single unit. However, in reality a variety of farm types exist within the regions. More detailed farm data would probably result in a more appropriate assessment than the limited statistical information for administrative regions. This would be an interesting topic for further analysis and uncertainty reduction. The Czech statistics provide information on emissions of NH_3 from dairy cattle livestock and manure management at the national level and for administrative regions. Emissions of N_2O, CH_4 and PM are provided at the national level only, while no information is available for NO_x, NO_3 and PO_4. In our study we applied a process-based model to estimate NH_3, N_2O, CH_4 and NO_x. When comparing emission factors for ammonia one can observe that our emission factors are 16% higher then those used for national emissions inventory (Budankova, 2005). The main reason for this deviation is that we applied more detailed methodology here, which defines emission factors based on cattle performance in each study region. The national emission inventory is based on fixed emission factors which do not reflect differences between study regions.

The sensitivity of terrestrial and aquatic ecosystems and human population vary not only between countries but also within countries. One can argue that site-dependent characterisation factors should be therefore developed at the level of the sub-national regions or even environmental areas within the country. This further reduces model uncertainties involved. Our approach could be considered as a step towards these sub-national factors. In further analysis, the application of sub-national source-receptor matrices, at least for the most polluted areas with sensitive ecosystems, is an interesting additional step forward.

We concluded that, for our case, the most appropriate set of characterisation factors is a selection of factors from Seppälä et al. (2006) and EDIP2003. One of the main strengths of this combination is that the characterisation factors are based on the most recent input data (emission inventory and projections, deposition, critical loads) and best available scientific models. A weakness of the combination may be potential internal inconsistency, in particular due to application of various calculation approaches and input data for each environmental and health theme separately. Most of the environmental and health problems are caused by similar sources and emissions and one may assume that characterisation factors should take this into account. However, so far no European modelling system exists for spatially explicit assessments of air, water and soil pollutants simultaneously. The development of new consistent characterisation factors is outside the scope of this study. Nevertheless, it is highly recommended to be a subject of further environmental research. Despite of these potential inconsistencies, we argue that for the purpose of our case study the selected set of characterisation factors is appropriate.

Taking into account methodological constraints we compared our results with outcomes of selected studies dealing with environmental assessment of dairy cattle livestock and manure management in various countries. These include a Dutch study by Thomassen et al (2008), German by Haas et al. (2001), Irish by Casey and Holden .(2005), and Canadian by Verge et al. (2007) and Swedish by Cederberg and Mattson (2000). Indeed the comparison is not straightforward because none of these studies applied the site-dependent characterisation factors for acidification, terrestrial and aquatic eutrophication and human toxicity. For global warming all studies applied the characterisation factors given in IPCC (2001). In addition, each study applied different system boundaries. It is important to note that most of the studies present a result for conventional and organic type of farming. In the Czech Republic we consider only conventional farm, according to a recent statistics only 7% of agriculture land is used for organic farms.

The comparison is done on the product basis for acidification and terrestrial eutrophication and climate change. The aquatic eutrophication and human toxicity were not compared. Human toxicity was calculated for instance by Haas et al., (2000) but they indicate that the impact was very low and Thomassen et al. (2008) did not include human toxicity in the assessment.

Acidification and terrestrial eutrophication

The ammonia emissions as a dominant source of acidification were recognized by Thomassen et al. (2008), Haas et al. (2001) Cederberg and Mattson, 2000. However, these studies do not consider the important role of ammonia also in terrestrial eutrophication. To be able to compare our results with outcomes of these studies we transform their estimated emissions of ammonia by site-dependent characterisation factor by Seppälä et al. (2006). Focus only on ammonia emissions is justified by the fact that the most of the ammonia emissions in the milk's life cycle take place at the farm level in close connection with the farmyard manure (Cederberg and Mattson, 2000) and this correspond with the system boundary of present study. The results of our comparison should be treated as an illustrative; more studies applying site-dependent characterisation factors would be much desirable.

Table 3.6 indicates that that contribution of ammonia emission to acidification as estimated by site-dependent characterisation factors is only slightly different as in case of site-generic characterisation factors. Indeed ecosystems may be more sensitive to acidification in Nordic and Western European countries (Sweden, Netherlands) compared to central Europe (Czech Republic, Germany). For terrestrial eutrophication the difference is much more visible, indicating that ecosystems in central Europe may be more sensitive. This simple comparison shows the importance to take into account country specific environmental differences. In addition, it is important to consider that the difference is also driven by different amount of ammonia emissions estimate in selected case studies.

Table 3.6 Comparison of potential impact of acidification and terrestrial eutrophication per milk produced calculated by site-generic characterisation factors (in SO_2-eq) and by site-dependent characterisation factors (AE) for the Czech Republic, Germany, The Netherlands and Sweden.

Country (reference)	Acidification SO_2-eq/ t milk	Acidification AE/ t milk	Terrestrial eutrophication AE/ t milk
Czech Republic (present study)	9	0.02	0.05
Germany (Haas et al.,2001)	19	0.04	0.13
The Netherlands (Thomassen et al.,2007)	10	0.02	0.04
Sweden (Cederberg and Mattson, 2000)	18	0.04	0.07

Global warming

For global warming we did not used site-dependent characterisation factors, nevertheless it is interesting to discuss some of our results. The emission intensity per tonne of milk produced is the lowest in comparison to selected studies 590 kg CO_2-eq/t milk. Tomassen et al (2008) presented estimates 1400 kg CO_2-eq/t milk for Dutch conventional intensive dairy production system, while Haas et al. (2001) give a value of 1300 kg CO_2-eq/t milk in German and Casey and Holden (2005) report a 1500 kg CO_2-eq/t milk, for Canadian dairy cattle a value of 1002 kg CO_2-eq/t milk is estimated by Verge et al. (2007). From above one can observe relatively good agreement between selected studies while there is a large difference with our study. The main reason is a different systems boundary employed in our study. While we consider only greenhouse gas emissions directly related to dairy cattle like enteric fermentation and manure management, the other studies consider on the top of this also emissions related to the synthetic fertilizers, electricity, concentrates, use of diesel and gas. Another reason of a difference is that the Czech dairy cattle have lower milk yield per cow in comparison to Dutch, German of Canadian situation.

Concluding remarks

Our analysis indicates that nitrogen compounds are important contributors to all analysed environmental problems, except for global warming. Ammonia is largely causing acidification and terrestrial eutrophication, while nitrates drives aquatic eutrophication, nitrogen oxides give rise to human toxicity and methane to global warming. In addition the results indicate where the most polluted areas are located and could be used as a basis to set emission reduction targets within the country.

The present study can provide useful information for assessing the effect of implementation of CAP (Common agriculture policy) reform in the Czech Republic. CAP should lead to a decrease of dairy cattle numbers and increase specialisation in the sector with increased milk yield production. The results from our study exactly show which region within the Czech Republic is an appropriate for dairy cattle production from environmental point of view. Therefore they form a good basis for development of agriculture and environmental policy.

Our study indicates that selected characterisation factors combined with information on study regions are useful in an assessment of the environmental and health impact of dairy cattle livestock and manure management in the Czech Republic. As such, it may serve as an example for analyses of other sectors or other countries. In addition, the results of this analysis are relevant as a baseline for further analyses of emission reduction strategies and their implementation costs in the most polluted areas, while for the less polluted areas the results can be instrumental to pollution prevention planning.

Appendix 3.A

Table 3.1.A Number of dairy cows, density of dairy cows, percentages of agriculture land in nitrate vulnerable zones (NVZ), critical load of acidity and nutrient nitrogen and population density for fourteen administrative regions in the Czech Republic for the year 2004

	Cows/100ha Agric.Land[1]	% of agriculture land in nitrate vulnerable zones (NVZ)[2]	Critical load (CL)[3]		(Persons/km^2)[1]
			CL(N)nut	CL (A)	
Středočeský + Prague	8	55	452	1547	201
Jihočeský	12	55	516	1323	62
Plzeňský	12	32	478	1320	73
Karlovarský	6	21	502	1839	92
Ústecký	4	42	504	1520	154
Liberecký	8	24	675	1505	134
Královehradecký	13	42	546	1953	115
Pardubický	15	46	519	1546	112
Vysočina	17	49	503	1245	75
Jihomoravský	7	64	459	1656	159
Olomoucký	11	27	555	1727	123
Zlínský	11	15	495	1712	149
Moravskoslezský	9	29	502	1674	227

Source: [1]CSO (Czech Statistical Office), [2]Budankova et al.(2003), EC(1991) [3]Skorepova (personal communication , 2006)

Table 3.A.2 General parameters (number of dairy cattle, milk yield, area of agriculture and number of rural population) for each study region in 2004)

	Parameter			
Study region	Dairy cattle (1000 heads)	Milk yield (litre/animal/yr)	Agriculture land (1000ha)	Rural population (1000 people)
1(HHHL)	131.3	6043	837	436
2(HHLL)	77.4	6340	554	361
3(HLHL)	45.4	5744	271	175
4(HLLL)	30.5	6588	277	267
5(HLLH)	20.7	6741	196	230
6(LHHH)	63.6	6350	468	1849
7(LLLH)	36.2	6241	426	379
8(LHLH)	25.9	6656	418	416
9(LLHL)	8.0	4903	171	58

References

Amann, M., Asman, W.,Bertok, I., Cofala, J., Heyes, C., Klimont, Z.,Schöpp, W.,Wagner, F., 2007.Cost-effective Emission Reductions to meet the Environmental Targets of the Thematic Strategy on Air Pollution under Different Greenhouse Gas Constraints.NEC Scenario analysis report Nr.5. Inistiute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Amann, M., Bertok, I., Cofala ,J., Gyarfas, F., Heyes, C., Klimont, Z.,Makowski, M., Schopp, W., 1998. Cost-effective control of acidification and ground level ozone. Interim Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Bouwman, A.F., 1996. Approaches to scaling a trace gas fluxes in ecosystems. Development in atmospheric science 24.Elsevier, Amsterdam

Budankova, M., (eds), 2003. Situation and prospective report –soil. Ministry of Agriculture of the Czech Republic, IBSN 80-7084-292-x (in Czech)

Brink C., 2003. Modelling cost-effectiveness of interrelated emission reduction strategies, the case of agriculture in the Czech Republic. PhD thesis Wageningen University, The Netherlands

Casey, J.W., and Holden, N.M., 2005 Analysis of greenhouse gas emissions from the average Irish milk production system. Agriculture Systems; 86:97-114

Cederberg, C., and Mattsson, B., 2000. Life cycle assessment of milk production- a comparison of conventional and organic farming. Journal of Cleaner Production; 8:49-60

CSO, 2006. Czech Statistical Office, http://www2.czso.cz/csu/edicniplan.nsf/publ/2002-05-(1999___2004) October2nd , 2006

CSO, 2007 Czech Statistical Office. http//www2.czso.cz

CHMU, 2006. Air Pollution in the Czech Republic in 2005. Czech Hydrometeorological Institute, Air Quality Protection Division. IBSN 80-86690-37-7

Crutzen, P.J., Aselman, I., Seiler, W., 1986. Methane production by domestic animals, wild ruminants, other herbivores fauna and humans. Tellus; 38B, 271-284

EEA, 2007. EMEP/CORINAIR Emission Inventory Guidebook-2007, technical report No. 30, Third edition, European Environmental Agency, Kopenhagen

EMEP,1998. Transboundary acidifying air pollution in Europe. EMEP/MSC-W, report 1/98, Norwegian Meteorological Institute, Oslo, Norway

Dämmgen, U., Luttich, M., Dohler, H., Eurich-Menden, B., Osterburg, B. 2002 GAS-EM a procedure to calculate gaseous emissions from agriculture. Landbauforshung Volkenrode; 52:19-42

De Vries, W., Kros, J., Oenema, O. and de Klein, J., 2003. Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. Nutrient Cycling in Agroecosystems; 66: 71-102.

De Vries W., Kros, H., Velthof, (in preparation). INITIATOR2 (Integrated Nitrogen Impact Assessment Model On a Regional Scale): Instrument for an integrated environmetnal analysis of the changes in agriculture. Calculations of emissions of ammonia, greenhouse gases, paticles and oudour and accumlation, leaching and runoff of carbon, nitrogen, phosphorus, bases and heavy metals. Alterra Report, The Netherlands.

Finnveden, G., Nilsson, M., 2005. Site-dependent life-cycle impact assessment in Sweden. Int. J.LCA; 10: 235-239

Haas, G., Wetterich, F., Kopke, U., 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems & Environment; 83: 43-53.

Havlikova, M., Kroeze, C., 2006 Evaluation of methods for quantifying emissions of air, water and soil pollutants. The Science of the Total Environment; 372: 133-147.

Haushild, M., and Potting, J.M.B., (Eds), 2004. Spatial differentiation in life cycle impact assessment the EDIP2003 Methodology; Guidelines from the Danish Environmental Protection Agency: Copenhagen

Hettelingh, J-P., Posch, M., Potting, J., 2005. Country-dependent characterisation factors for acidification in Europe. A critical evaluation. Int. J LCA; 3: 177-183

Huijbregts, M.A.J, Schöpp, W, Verkuijlen, E, Heijungs, R, Reijnders, L., 2000. Spatially Explicit Characterization of Acidifying and Eutrophying Air Pollution in Life-Cycle Assessment. Journal of Industrial Ecology; 3: 75-92

Huijbregts, M.A.J., and Seppala, J., 2001. Life-cycle impact assessment of pollutants causing aquatic eutrophication. Int.J.LCA; 6:339-343

IPCC, 2001a. Climate Change. The scientific basis contribution of working group I to the third assessment report of Intergovernamental Panel on Climate Change. Houghton, J.T., Y.Ding, D.J.,Griggs, M. Noguer, P.J. Van der Linden, X. Dai, K. Maskell, C.A. Johnson, (Eds), Cambridge University Press, Cambridge, UK

IPCC, 2001b. Good practice guidelines and uncertainty management in National Greenhouse Gas Inventories. Intergovernmental panel on climate change, OECD, 2rue Andre Pascal Paris

Janosova, B., Miklankova, J., Hlavinek, P., Wintgens, T., 2006 Drivers for wastewater reuse: regional analysis in the Czech Republic. Desalination; 187:103-114

Jelinek, A., Dedina, M., 2004. Emissions of Ammonia from intensive farming. Research Institute for agriculture techniques, The Czech Republic

Monteny, G.J., Witzke, H.P., Oudendag, D.A., 2007. Impact assessment of possible modification of the IPCC Directive. Interim report under European Comission. Servise Contract NO:070501/2005/422822/MAR/C1. Alterra, Wageningen, The Netherlands.

Potting, J.M.B., 2000. Spatial differentiation in life cycle impact assessment. A framework and site-dependent factors to assess acidification and human exposure. PhD thesis, Faculty of Chemistry, Utrecht, The Netherlands

Seppällä,J., Posch, M., Johanson, M., Hettelingh, J-P., 2006. Country Dependent Characterisation Factors for Acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. Int. J LCA; 6: 403-416

Schroder, J.J., Aaats, H.F.M., Van Middelkoop, J.C., Schils, R.L.M.,Velthof, G.L.,Fraters, B.,Willems, W.J., 2007. Permissible manure and fertilizer use in dairy farming systems on sandy soils in The Netherlands to comply with the Nitrate Directive target. European J. Agronomy; 27:102-114.

Thomassen, M.A., Calker, Van K.J, Smits, M.C., Iepema, G.L., De Boer, I.J.M., 2008 Life-Cycle assessment of conventional and organic milk production in the Netherlands. Agriculture, Systems; 96: 95-107

Verge, X.P.C., Dyer, J.A., Desjardins, R.L.,Worth, D., 2007. Greenhouse gas emissions from the Canadian dairy industry in 2001. Agriculture Systems; 94: 683-693

Van Zelm R., Huibregts, M.A.J., Den Hollander, H.A., Van Jaarsveld, H.A., Sauter, F.J. Stuijs, J.Wijnen, Van H.J., Van de Meent D. 2008. European charaterisation factors for human health damage of PM10 and ozone in life-cycle impact assessment. Atmospheric Environment; 42:441-453.

Wenzel, H, Hauschild, M, Alting, L., 1997. Environmental Assessment of Products. Vol. 1-Methodology, tools and case studies in product development. First edition. Chapman&Hall, United Kingdom, Kluwer Academic Publishers, Hingham, MA.USA IBSN 0412 80800 5

CHAPTER 4

Cost-effective reduction of environmental impact of dairy cattle in the Czech Republic

Abstract

The objective of this study is to analyse the cost-effectiveness of policy measures to reduce environmental impact of dairy cattle in the Czech Republic for the current situation and to explore future trends up to 2020 by applying a linear optimisation model. The model combines process-based and emission factor approaches to calculate emissions, and site-dependent characterisation factors to assess their contribution to acidification, terrestrial and aquatic eutrophication, global warming and human toxicity. In addition, a so-called overall environmental impact (OEI) indicator is used to assess the environmental performance of dairy cattle. The analysis shows that the potential environmental and health impact has been decreasing over time as a result of reduced cattle numbers. In 2005 the impact was considerably lower than in 1990. In a scenario, which assumes no emission control, the 2020 environmental impact is again 9% lower than in 2005, mainly as a result of continued reduction in cattle numbers. We study the possibilities to further reduce these 2020 uncontrolled emissions. Technical measures aimed at reducing ammonia emissions may reduce the 2020 uncontrolled OEI levels by 10%. Implementation of all technical measures considered would reduce the 2020 OEI levels by 30% at the national level. In optimised scenarios, the OEI in 2020 is 1-30% lower than in the No Control scenario, while the costs range between 0.2 and 16 MEuro. We show that targets for OEI close to maximum feasible reduction can be realized at about one-third of the costs of non-optimised scenarios. In such cost-effective scenarios the model tends to select measures to reduce aquatic eutrophication and climate change first, which is in contrast to current policies aiming at acidification and terrestrial eutrophication. Cost-optimal solutions at the national level are not always the cheapest solutions at the regional level. It is a political decision how to balance environmental problems. Indeed our study can serve as a starting point to establish a more sophisticated approach for emission target setting at the national and sub-national level, and help policy makers to understand the importance to solve environmental and health problems simultaneously.

Key words: dairy cattle, emissions, environmental impact, cost-effectiveness, optimisation, Czech Republic

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Havlikova M., Kroeze C. Cost-effective reduction of environmental impact of dairy cattle in the Czech Republic. Submitted to Environmental Management

4.1. Introduction

Agriculture is an important source of water, air and soil pollution, and contributes to problems at the local (human toxicity), national (aquatic eutrophication), continental (acidification, terrestrial eutrophication) and global (global warming) scale. A recent analysis indicates that agricultural emissions are likely to increasingly affect European ecosystems in the next decades (Amann et al., 2005).

Many technical measures are available to reduce emissions of pollutants. However, some of these may have unintended side-effect on other pollutants. For example, Brink (2003) reports that measures to reduce emissions of ammonia (NH_3) may increase nitrous oxide emissions (N_2O) and decrease methane emissions (CH_4). Likewise, interrelations exist between these compounds and other agriculture emissions such nitrogen oxide (NO) particulate matter (PM) or nitrate (NO_3).

From the above may be clear that consideration of environmental and health problems in isolation may not lead to optimal solutions. Indeed, studies that do take into account interrelations between pollutants indicate that solving environmental problems simultaneously is often more cost-effective than policy aimed at individual pollutants (e.g. Brink, 2003, Amann et al., 2007). However, only very few studies take into account such interrelations. Rather, the possible side-effects of measures to reduce emissions are ignored in analyses of policy measures. Cost-effective analyses typically focus on the reduction of one compound, or a group of compounds contributing to a single environmental problem (Webb et. al., 2005). Moreover, these analyses are often limited to an evaluation of technical measures to reduce emissions and typically ignore non-technical measures which affect emissions indirectly through the changes in the level of activities. Non-technical measures may offer potential for further reduction at very low or negative costs (Van Vuuren et al., 2006). Clearly, there is a need for more complete analyses of optimal strategies to reduce the environmental impact of agricultural activities.

Analyses of the costs and environmental effectiveness of technical and non-technical reduction measures and their optimal allocation may require Integrated Assessment modelling. The Regional Air Pollution and Simulation Model (RAINS) is one of the best known and widely used models used to identify cost-effective reduction strategies for air pollutants and greenhouse gas emission control in Europe. Brink (2003) built on RAINS and developed an alternative model to assess cost-effective reduction of simultaneous reduction of ammonia, nitrous oxide and methane emissions from European agriculture, while considering interrelations between these emissions. This work was later implemented in RAINS (now called GAINS, including greenhouse gases). Both, RAINS/GAINS model and Brink (2003) focus on technical measures to reduce agriculture emissions. Moreover, they include air pollutants and greenhouse gases and focus on regional scale rather than on national or sub- national. An interesting alternative is the model INITIATOR2, which was developed for the Netherlands and to analyse cost-effective reduction of air, water and soil pollution from agriculture at landscape level (De Vries et al., 2003).

To our knowledge no model exists to analyse cost optimal allocation of emission reduction measures for the agricultural sector with a complete coverage of all relevant environmental and health issues, and with a focus on both technical and non-technical measures. Moreover, most studies do not consider the sub-national level. So the question how to implement control strategies within a country is not addressed. In this paper we aim to advance the development of such approaches.

We will take dairy production in the Czech Republic as an example. For the Czech Republic no model exists to evaluate environmental policies for agriculture. The Czech Republic is one of the Central European countries which went through rapid economical changes during the last decade, leading to a sharp decrease in numbers of cattle, pigs and poultry, as well as in use of fertilizers. Recently, the Czech Republic adopted emission control obligations as set by international legislation, including Directives of the European Commissions (EC) and Protocols under the Convention on Long range Transboundary Air Pollution (CLRTAP).

In Chapter 2 (Havlikova and Kroeze, 2006) we developed a method to estimate agricultural emissions of pollutants to air, water and soil, which takes into account interrelations between sources, emissions and their potential environmental impacts. In Chapter 3 (Havlikova et al., 2008) we also developed a method to assess the potential environmental and health impact of these emissions using site-dependent impact factors adopted form Life-Cycle Impact Assessment (LCIA). Here we will integrate these approaches in an innovative framework to assess environmental policy measures for agriculture.

The purpose of this study is therefore to describe a linear optimisation model to analyse the cost-effectiveness of policy measures to reduce environmental impact of dairy cattle in the Czech Republic for the current situation and to explore future trends up to 2020. The model focuses on simultaneous reduction of emissions of ammonia (NH_3), nitrogen oxide (NO_x) nitrous oxide (N_2O), methane (CH_4), particulate matter (PM_{10}, $PM_{2.5}$) and nitrate (NO_3) from dairy cattle.

4.2. Methodology

4.2.1 Model description

Inspired by Brink (2003) we developed a new static optimisation model (DAIRY). This model can be used to analyze the cost-effectiveness of policies for the simultaneous abatement of acidification, terrestrial and aquatic eutrophication, human toxicity and global warming caused by dairy production in the Czech Republic. More specifically, the model minimizes total costs of realizing environmental targets. These environmental targets can be defined at the national, and at the sub-national level, and either refers to emissions or to environmental impacts.

DAIRY considers seven pollutants (NH_3, N_2O, NO_x, CH_4, $PM_{2.5}$, PM_{10} and NO_3), contributing to acidification, eutrophication, global warming and human health problems. The model distinguishes between nine study areas which differ in cattle intensity, environmental sensitivity and population density (Chapter 3, Havlikova et al., 2008). We estimate emissions by combining emission factors with a simple-process based approach (see section 4.2.2). The potential environmental and health impact of selected pollutants is assessed based on impact factors so called characterisation factors adopted form Life Cycle Impact Assessment (LCA) (see section 4.2.3). A package of technical and non-technical emission reduction measures and their possible combinations is considered largely on the RAINS/GAINS model developed in IIASA Amann et al. (2007) Brink (2003), Oenema et al. (2007) Van Pul et al. (2004) (see section 4.2.4). The applicability of emission reduction measures, their reduction potentials and implementation costs are based on national sources such national legislation (in our case Czech legislation) on air quality and the Action Plan on the Nitrate Directive. The model is implemented in the GAMS programming language (General Algebraic Modelling Systems) and uses the CONOPT3 solver (Brooke et al., 1998).

DAIRY builds on the model of Brink (2003) but includes a number of novel features. First, DAIRY performs optimisation analyses at the sub-national level, while Brink (2003) focused on the European scale. DAIRY is therefore a better tool to assist national decision makers in identifying optimal allocation of reduction measures over regions within a country. Second, Brink (2003) included only three pollutants in his model (NH_3, N_2O and CH_4) while DAIRY includes seven. This implies a more complete assessment of the environmental impact of dairy production. Third, DAIRY applies a unique set of characterisation factors to quantify the five different environmental and health impact categories to which dairy cattle contribute, while Brink (2003) accounted for three categories (acidification, terrestrial eutrophication and global warming). As a result, DAIRY cannot only be used to optimize emission reduction strategies, but also to identify optimal strategies to reduce the environmental impact. On the other hand, DAIRY focuses on only part of the agricultural sector (dairy cattle) as a one of the most important sub-sector of agriculture systems in many European countries. However, the model is flexible enough to include other sub-sectors as well. In the following, we describe the model in more detail (see also Box 4.1).

Box 4.1. Indices used in DAIRY

sa = study region
p = source of emissions
i = sub-sources of emissions
e = impact category
n = reduction measures (see table 1-3A)

Study regions (sa):
1 (HHHL) Jihocesky, Vysocina
2 (HHLL) Kralovehradecky, Pardubicky
3 (HLHL) Plzensky
4 (HLLL) Olomoucky
5 (HLLH) Zlinsky
6 (LHHH) Stredocesky, Ustecky
7 (LLLH) Liberecky, Moravskoslezsky
8 (LHLH) Jihomoravsky
9 (LLHL) Karlovarsky

Sources (p):
- Dairy cattle solid system
- Dairy cattle liquid system

Sub-sources (i):
- grazing
- milking
- housing -solid
- housing - liquid
- storage - liquid
- storage -solid
- application-liquid
- application-solid
- indirect emissions
- leaching

Impact categories (e):
AC Acidification
TE Terrestrial eutrophication
AE Aquatic eutrophication
HT Human toxicity
CC Climate change

Model Variables

The decision variables in the model are application rates (a) of emission reduction measures (n) at source (p). The model identifies optimal application rates for each abatement measure in order to achieve environmental targets in the most cost-effective way (following Brink, 2003). Equations 1-4 summarize how (C), emissions (E) costs, and environmental impact (I and OEI) are calculated.

$$C_{sa,p} = \sum_{n \in N} a_{p,n,sa} \times c_{p,n} \times A_{p,sa} \qquad (1)$$

Where C = costs of emission reduction for study region (sa) and source (p). Costs are a function of application rate (a) of reduction measures, unit costs, and activity rates (cattle numbers).

$$E_{p,x,sa} = \sum_{i \in I} ef_{p,i,x,sa} \times A_{p,sa} \times \left(1 - \sum_{n \in N} a_{p,n,sa} \times r_{p,i,n,x} \right) \qquad (2)$$

Where E= emissions of pollutants (x) from sub-source (i) of source (p) in study region (sa). Emissions are a function of emission factors (ef), activities (A), application rate (a) and reduction potential (r) of the emission reduction measure (n)

$$I_{e,sa} = \sum_{p \in P} \sum_{x \in X} E_{p,x,sa} \times CF_e \qquad (3)$$

Where I = potential environmental and health impact (I) for impact category (e) in study region (sa). The impact is a function of emissions (E) of pollutants (x) from source (p) and characterisation factors (CF) for environmental impact category (e). CF is region specific for: human toxicity, country- specific for acidification, terrestrial and aquatic eutrophication and world wide for global warming (Table 4.1a and Table 4.1b)

$$OEI_{sa} = \sum_{e \in E} \frac{I_{e,sa}}{N_e} \times W_e \qquad (4)$$

Were OEI = overall potential impact (OEI) in study region (sa). This OEI is the sum of the normalized environmental and health impacts for impact category (e) in study are (sa) multiplied with valuation factors (W). For normalization, the potential environmental and health impact at European level (N) is used. Valuation factors reflect the relative importance of environmental problems for decision making. Valuation factors are by definition subjective and should be defined by decision makers or other users of DAIRY. Here, we include one set of possible valuation factors for illustrative purposes.

Objective function and restrictions

The objective function is to minimize costs (C) of emission control per study region (sa) and source (p):

$$\text{Min} \sum_{sa}\sum_{p} \mathbf{C}_{\mathbf{sa.p}}(\mathbf{v}_{\mathbf{sa,p}}) \text{ with } v_{sa,p} \text{ as vector with elements } a_{sa,p,n} \quad (5)$$

The model minimizes total costs (C) of abatement to achieve constraints on either emissions (E), the potential impact (I) or the overall environmental impact (OEI).

In case of restrictions on emissions (E), these may not exceed level $\overline{E}$

$$\sum E_{p,x,sa} \leq \overline{E}_{p,s,sa} \quad (6)$$

In case of restrictions on the potential environmental and health impact (I) of specific impact category (e), this may not exceed level $\overline{I}$.

$$\sum I_e \leq \overline{I}_e \quad . \quad (7)$$

In case of restrictions on the overall environmental impact (OEI) per study region (sa) or at national level, this may not exceed level $\overline{OEI}$

$$\sum OEI_{sa} \leq \overline{OEI}_{sa} \quad (8)$$

$$\sum OEI \leq \overline{OEI} \quad . \quad (9)$$

In addition, there are technology specific constraints for application rate (a) which can not be lower than 0 and larger than 1.

$$\sum a_{p,n} \leq 1 \quad (10)$$

$$\sum a_{p,n} \geq 0 \quad . \quad (11)$$

4.2.2. Emission estimation method

The emissions are quantified in such way that effects of changes in animal numbers, their productivity (e.g. milk production) and effects of emission reduction measures are properly reflected. The emissions are estimated following Chapter 2 (Havlikova and Kroeze, 2006). We combine so called emission factor approaches with simple process based models.

Emission factor approaches are used to estimate emissions of methane (CH_4) and particulate matter (PM_{10}, $PM_{2.5}$). In many national inventories of ammonia (NH_3) and other N-related emissions process-based models are used, for example in the UK (Webb et al, 2004a), Germany (Dämmgen et al., 2002), and Switzerland (Menzi et al., 2003). None of these have been applied to the Czech agriculture. Here, we apply one of these models as a first step towards a more process based oriented emission inventory. We chose to use the GAS_EM model developed by Dämmgen et al. (2002) for estimating agricultural emissions from Germany. The German agriculture is in many ways comparable to the Czech. Thus adopting GAS_EM parameter values for an analysis of the Czech agricultural system seems appropriate in cases where Czech specific information is not available.

The emission factors derived from process-based modelling are a function of animal performance (annual milk yield, weights), time spent in pastures, milking and in stables, and of type of housing (share of liquid/solid system). For our case study focusing on dairy production, input data is required such as number of dairy cows and milk yield for the year 1990 and 2005. These were obtained from the Czech Statistical Office (CSO, 2007) for each administrative region and converted to the level of study regions (Table 4.1). The share of liquid and solid systems in dairy waste management was adopted form Jelinek (2004) (Table 4.1). Emissions of nitrogen-compounds are related to the amount of nitrogen excretion (Nex) which in turn is calculated as a function of milk yield (following Klimont and Brink, 2004). The annual variation in milk yield is considerable in the period 1990-2005 in the Czech Republic. The average milk yield in 1990 was 3905 kg/year, while in 2005 it was 6000 kg/year. As a consequence the calculated N excretion is calculated to have increased over this time period, as well as N-related emissions (Table 4.1A).

The model (DAIRY) includes a static linear optimisation model. The process-based model GAS_EM, on the other hand, includes several non-linearity (see Dämmgen et al., 2002 or Dämmgen et al., 2006 for details). When combining the approaches we defined endogenous variables in DAIRY describing emissions as a function of nitrogen flows. These nitrogen flows (in grazing, milking, housing, storage and manure application) in the study regions are output of the GAS_EM model as applied to the Czech agriculture. We therefore use soft-link between GAS-EM and DAIRY in order to avoid unnecessary complexity of the optimisation analysis.

4.2.3. Potential impact assessment method

The potential environmental and health impact (I) of agriculture emissions is estimated by applying impact factors so called characterisation factors (CF) adopted from Life-Cycle Assessment (LCA). These express the amount of environmental and health impact per quantity of emitted substance. In Chapter 3 (Havlikova et al., 2008) we selected characterization factors to be used for integrated environmental assessment of agriculture in the Czech Republic. Characterisation factors used by present study are presented in Table 4.1a a Table 4.1b and are based on EDIP2003 (Haushilds and Potting, 2004) and Seppälä et al. (2006). The potential impact of substances is normalized by applying normalization factors (N) using per capita equivalents as recommended by Stranddorf et al. (2005). This results in a unit “impact potential *per person* per year” for each individual impact category (e). The importance between environmental and health impact categories is differentiated by using valuation factors (W). There are several methods to derive at valuation factors (ODPM, 2004). Here, we use as a reference equal valuation factors for all impact categories, reflecting a perspective in which all environmental problems are considered equally important. The potential impact is calculated for nine study regions that differ in (1) dairy farming intensity, (2) sensitivity of terrestrial ecosystems towards acidification and eutrophication, (3) percentage of arable land in vulnerable areas, and (4) population density. The nine study regions are classified as "low " or "high" for each characteristic according to a general principle: below average = low, and above average = high. For more details see Chapter 3 (Havlikova et al., 2008).

Table 4.1a Characterization factors (CFe), normalization factors (N_e), and valuation factors (W_e) as used here for each impact category (e)

Impact category (e)	Indicator	Characterisation Factor (CFe)[3]	Normalization (N_e)[4]	Valuation factor (W_e)
			unit/ person/year	dimensionless
Acidification	AAE[1]			
NH_3		3.65 keq/t	0.016 keq	1
NO_x		0.73 keq/t		
Terrestrial eutrophication	AAE			
NH_3		10.33 keq/t	0.055 keq	1
NO_x		2.52 keq/t		
Aquatic eutrophication	NO_3 -eq			
NO_3		0.64 g eq/g	47000 g NO_3-eq	1
Global Warming	CO_2-eq			
CH_4		23 kg CO_2 eq	8200 kg CO_2-eq	1
N_2O		296 kg CO_2 eq		
Human toxicity				
NO, PM_{10}, $PM_{2.5}$	HTP[2]	See Table 4.1b	$1.7*10^8$	1

[1] accumulated exceedance of critical load
[2] human toxicity potential
[3] based on EDIP2003 (Haushilds and Potting, 2004) and Seppälä et al. (2006)
[4] Stranddorf et al. (2005)

Table 4.1b Region specific characterisation Factors (CF_c) for human toxicity

Study regions	Administrative regions	Characterisation factor (CFe)		
		NO	PM_{10}	$PM_{2.5}$
1 (HHHL)	Jihocesky,Vysocina	50.5	34.5	12
2 (HHLL)	Kralovehradecky Pardubicky	68	38	13
3 (HLHL)	Plzensky	53	35	12
4 (HLLL)	Olomoucky	72	41	13
5 (HLLH)	Zlinsky	81	39	14
6 (LHHH)	Stredocesky Ustecky	92	42.5	14.5
7 (LLLH)	Liberecky Moravskoslezsky	92	43	14.5
8 (LHLH)	Jihomoravsky	85	41	14
9 (LLHL)	Karlovarsky	60	37	12

4.2.4. Emission reduction measures

Several types of emission reduction measures exist. For example Amann et al., (2006) distinguish between three groups: (1) *behavioral changes,* (2) *structural changes* and (3) *technical measures*. Dellink (2003) considers next to the *technical measures* also *emission prevention measures* which include good housekeeping, *process-integrated measures* which represent input substitution in production process, basically these corresponds with structural changes as defined by Amann et al. (2006*) and reduction of economic activity* which can be related to behavioral changes.

We build on the abovementioned studies and distinguish between technical and non-technical measures. We define technical emission reduction measures (TM) as those which reduce emissions by changing the input (e.g. low nitrogen feed) or add-on abatement techniques (e.g. covering manure storage). These lead to reductions of emissions per unit of product or activity. For this type of measure estimates of reduction potentials, application rates and costs are often readily available. However, an important disadvantage of technical measures is that they may give rise to unwanted side-effects (Brink, 2003).

The second type is non-technical measures (NTM) which reduce emissions indirectly through changes in activity rates (e.g. decreasing number of cattle due to low demand for milk). Barret (2005) discusses several advantages and disadvantages of NTM. Advantages include their effective and fast reducing effect on emissions. They can have low or net negative costs. A disadvantage of NTM is that they typically require changes in human behavior and possible may have side-effects on other emissions.

For the present study we selected technical and non-technical measures which may be used for emission reduction in dairy cattle, based on data availability on reduction potential, side-effects on other pollutants, application rates and costs (Table 4.2A, 4.3A, 4.4A).

Ammonia

For ammonia emissions the reduction measures are adopted from the RAINS/GAINS model (Klimont and Brink, 2004). These include low nitrogen feed, stable adaptation, covered storage, and low ammonia application. Information on the possible side effects on emissions of methane and nitrogen oxide is taken from Brink (2003), while their impact on nitrate emissions is derived from Oenema et al. (2007). If possible we applied country or region specific data. Reduction potentials are specified according to Czech national legislation and the information on applicability of emission reduction measures at regional level is based on database of application of Code of Good Agriculture Practice.

Nitrous oxide and methane

Three reduction measures to reduce nitrous oxide from manure are included: improved timing of manure application, grazing restrictions and manure efficiency improvements. Four reduction measures for methane are considered, including propionate precursors, daily spread of manure and two types of anaerobic digestion (small scale and centralized). The reduction potentials, side-effect and costs are from Brink (2003), while possible side-effects on nitrate are derived from Oenema et al. (2007). Effects on particulate emissions are tentative, following estimated changes in productivity of dairy cattle by Brink (2003) for nitrous oxide and methane.

Nitrate

Manure efficiency improvements and manure application with minimum risk on leaching are the two measures considered to reduce emissions of nitrate. Manure efficiency improvement includes a package of measures such as a limitation of manure application in the winter and wet period, limitation of application of manure on the sloping ground, maximum manure application standards and appropriate application technique. Information on reduction potentials, side-effects and costs are derived from Brink (2003) and Oenema et al. (2007). In addition, Velthof et al. (2006) assume that application of nitrate emission reduction measures in areas with more then 25% agriculture land in vulnerable areas may have a significant effect on nitrogen related emissions. In the Czech Republic, three of the nine study regions have less than 25% of their agricultural land located in so-called vulnerable areas. In our study we therefore also examine the effects of nitrate emission reduction measures in less sensitive regions.

Non technical measures

One of the most effective non-technical measures is closure of dairy farms. This leads to decreasing numbers of animals, and as a result in a reduction of all emissions. This measure is simulated exogenously in the model through assumed changes in cattle numbers. Reduction potentials and costs are not available and difficult to estimate. The costs were set arbitrarily based on estimates by Van Pul et al. (2004) for average farms (Table 4.4A in Appendix). The average size of a Czech dairy farm is estimated to be 400 dairy cattle. Van

Pul et al. (2004) analysed also other non-technical measure such as relocation of the farm and restriction on farming in selected areas. These two are, however, related to the sensitivity of ecosystems to environmental pollution. We assume that relocation of the farm will not lead to decrease of emissions. Rather, it results in lower emissions in sensitive ecosystems close to farms. The current version of DAIRY does not take into account such local effects. Therefore, we do not consider this type of measure in our analysis.

4.3. Evaluation of effectiveness of environmental policy for dairy production

4.3.1 Scenario description

We define eight scenarios for the year 2020 in order to analyze the environmental effectiveness and costs of technical and non-technical reduction measures (see Tables 4.2A, 4.3A and 4.4A in Appendix for an overview of reduction measures). For reasons of comparison, emissions and their potential environmental and health impact are also calculated for 1990 and 2005.

We analyze two types of scenarios (Table 4.2). First, we define a set of non-optimised scenarios illustrating future consequences of policy plans for the environment and the associated costs. This part of our analysis does not include cost minimization. Thus for our non-optimised scenarios no environmental targets are defined. Rather, they serve as a benchmark. The second group of scenarios include cost minimization (equation 5), and are therefore optimised scenarios. For this part of our analysis, we defined environmental targets for emissions or the environmental impact at the level of study regions or at the national level. The model is used to indentify policy measures to be taken at the regional level, in order to minimize total abatement cost at the national level.

In the following, we describe the four non-optimised, and four optimised scenarios for 2020 analyzed in this study. All scenarios assume a 10% reduction in dairy cattle between 2005 and 2020, based on official national projections.

Non- optimised scenarios for 2020

NOC: The *No Control* scenario assumes no implementation of technical or non-technical measures in dairy cattle. It should be noted that this is a hypothetical case, since some of the emission reduction measures are already included in current policy plans, and being implemented. Emission reductions in the NOC 2020 scenario as compared to 2005 are entirely the result of reducing cattle numbers. The NOC scenario is used as a benchmark here, used to analyze the effects of current legislation as well alternative allocation of measures.

MAX_1: The *Maximum Feasible Technical Reduction scenario 1* focuses on ammonia reduction. It assumes maximum reduction of ammonia emissions by technical measures specifically designed to reduce ammonia (i.e. the measures included in Table 4.3A). This corresponds with the current environmental policy for agriculture (dairy production) in the Czech Republic, which is based on Gothenburg Protocol of the Convention on Long Range Transboundary Air Pollution (CLRTAP). This scenario is another hypothetical case, because it assumes implementation of the most effective options regardless of their costs.

MAX_2: The *Maximum Feasible Technical Reduction scenario 2* also focuses on ammonia, but not only includes technical reduction measures listed in Table 4.2A, but also technical reduction measures designed for reducing other emissions that, as a side-effect, also reduce ammonia (as listed in Table 3A). This scenario represents an important benchmark indicating the potential to reduce ammonia emissions considering all technical measures included in the model.

MAX_3: The *Maximum Feasible Technical Reduction Scenario 3* assumes implementation of the most effective measures to reduce the overall environmental impact (OEI) by all pollutants considered here. It reflects the largest possible simultaneous reduction of this impact by NH_3, N_2O, CH_4, NO_x, NO_3, PM_{10}, and $PM_{2.5}$ emissions by technical measures included in the model.

Optimised scenarios for 2020

CZECHPLAN: In the *Current Policy to reduce Ammonia (NH_3)* scenario, the model is used to analyze the most cost- effective strategy to reduce ammonia emissions. The scenario reflects the current environmental policy for agriculture (dairy production) in the Czech Republic, which primarily aims at reduction ammonia emission by technical measures as specified in the Gothenburg Protocol. There is no specific target for NH_3 set by the government for 2020. For the CZECHPLAN scenario we set a 15% emission reduction target for ammonia for each study region, relative to 2005. We use the model to identify the set of policy measures to realize this target at the lowest national abatement costs.

EUPLAN: In the *EUPLAN* scenario we also define specific reduction targets for ammonia for each of the nine study regions for 2020. These region-specific targets are based on the Thematic Strategy on Air Pollution (TSAP) of the European Commission (Amann et al., 2007). For each region we use for 2020 a 30% reduction target for ammonia emissions from dairy cattle, relative to 2005. We use the model for total abatement cost minimization at the national level.

IMPACT: The *IMPACT* scenario aims at identifying strategies to reduce the overall environmental impact (OEI) in 2020 by 30% at the national level relative to 2005 at least costs. We use the model for total abatement cost minimization at the national level.

CATTLECUT: The *CATTLECUT* scenario starts with the assumption that dairy cattle numbers are by 2020 reduced by an additional 10% relative to 2005 (a non-technical measure; see Table 4.4A). This is on top of the already assumed 10% reduction in the other scenarios. Then, a cost minimization analysis is performed, aimed at reducing the OEI by 10% at the national level relative to 2005. We use the model for total abatement cost minimization at the national level.

Table 4.2 Overview of non-optimised and optimised scenarios used by present study

Scenario	Reduction measures	Summary of analysis
NOC	No emission control; no measures	None
MAX_1	Only technical measures for ammonia	Maximizing reduction in total NH_3 emissions in the Czech Republic
MAX_2	All technical measures in the model	Maximizing reduction in total NH_3 emissions in the Czech Republic
MAX_3	All technical measures in the model	Maximizing reduction in total OEI in the Czech Republic
CZECHPLAN	Technical measure for ammonia	Minimizing total reduction costs in the Czech Republic to reduce NH_3 emissions by 15% relative to 2005 in each study region
EUPLAN	All technical measure in the model	Minimizing total reduction costs in the Czech Republic to reduce NH_3 emissions by 30% relative to 2005 in each study regions
IMPACT	All technical and non-technical measures in the model	Minimizing total reduction costs in the Czech Republic to reduce the OEI emissions by 30% relative to 2005 at the national level
CATTLECUT	Additional 10% reduction of cattle relative to No Control 2020; All technical measures in the model	Minimizing total reduction costs in the Czech Republic to reduce the OEI emissions by 10% relative to 2005 at the national level

4.3.2 Results

Baseline: Analysis for 1990 and 2005 and the 2020 No Control scenario

The potential environmental and health impact in 2005 is considerably lower than in 1990 (Table 4.3); the 2005 OEI is only one-third of the level in 1990. This is mainly caused by structural changes in the Czech agriculture sector. During this period the number of dairy cattle decreased by 65%. A moderate further reduction of 9% is calculated between 2005 and 2020 for the scenario assuming no emission reduction measures (NOC scenario). Again, this is the effect of envisaged decreasing dairy cattle numbers.

Maximum feasible reduction

Technical measures alone are calculated to reduce the overall environmental impact (OEI) by 9% in scenario MAX_1, by 10% in scenario MAX_2 and by 26% in scenario MAX_3 relative to 2020 No Control scenario. The costs of emission reduction range between 40 and 102 MEuro in these scenarios. Scenarios MAX_1 and MAX_2, focus on measures reducing ammonia emissions, and therefore show reductions in the calculated potential acidification and eutrophication relative to 2005. In both scenarios also the potential global warming is reduced, as a side-effect of implementation of measures to reduce ammonia. For scenario MAX_1 this side-effect is relatively small, because it also includes measures which, as a side effect, increase greenhouse emissions (stable adaptation and low ammonia application; Brink, 2003). In scenario MAX_2 all available emission reduction measures affecting NH_3

are applied. This not only result in lower NH_3 emissions, but also in an additional 15% reduction of greenhouse gases compared to MAX_1 and in slightly lower terrestrial and aquatic eutrophication and human health impacts. Scenario MAX_3, aims at maximum reduction of all pollutants and results in additional reduction of aquatic eutrophication and climate change. However, the total reduction costs of this scenario are extremely high (102 MEuro).

Optimised scenarios

We analyze cost-optimal allocation of emission reduction measures to either reduce emissions, or the overall environmental impact (OEI). Table 4.3 allows for the following observations. First, we observe that the OEI in 2020 in the optimised scenarios are 1-30% lower than in the No Control scenario, while the costs range between 0.2-16 MEuro. The scenarios differ considerably in their cost-effectiveness.

The CZECHPLAN and EUPLAN scenarios, reflecting current Czech policies, are the least effective of the optimised scenarios with regards to overall environmental impact (OEI). The EUPLAN scenario, reflecting European policies, is the most expensive of the optimised scenarios. We therefore conclude that setting targets for ammonia alone (as in the CZECHPLAN and EUPLAN scenario) is not a cost effective strategy to reduce the overall environmental impact of dairy cattle in the Czech Republic. However, both scenarios are the most cost-effective with regards to reduction of ammonia emissions at regional level. On the other hand the IMPACT scenario is relatively cost-effective compared to the scenarios focusing on technical measures only. It reduces the OEI to levels close to those of the three non-optimised MAX scenarios, but at about one-third of the costs (12 MEuro instead of 40-102 MEuro). This indicates the importance of aiming at cost-minimization as opposed to reducing emission reduction maximization.

We analysed an extra scenario that is not included in Table 4.3. This is the IMPACT-EUPLAN scenario, in which we use the model to find the optimal strategy to limit the OEI to $7.49\ 10^5$ PE, which is the OEI level reached in the EUPLAN scenario. It is interesting to compare the costs of the EUPLAN scenario (16 MEuro) and those of the IMPACT-EUPLAN scenario (0.2 MEuro), realising that the overall environmental impact of these two scenarios is equal. This clearly demonstrates that setting a target for overall environmental impact at national is cheaper than defining policies for single pollutants at regional level.

Our analysis can also be used to set priorities for environmental policies. In the relatively cost-effective IMPACT scenario the model tends to select measures to reduce aquatic eutrophication and climate change first. This is in contrast with current policies, which tend to focus on acidification and terrestrial eutrophication. In fact, our model prefers a selection of reduction measures leading to an increase in emissions of NH_3 and NOx relative to the No Control scenario, causing acidification and terrestrial eutrophication and human health impacts (Table 4.3, Figure 4.1). This is not the case in the CZECHPLAN and EUPLAN scenarios which primarily aim at ammonia emission reduction.

Table 4.3 Potential environmental impact, overall environmental impact and total reduction cost for optimised and non-optimised scenarios in year 1990, 2005 and 2020

Scenario	Environmental impact (I_e)					OEI	Total reduction cost (C)	Cost-effectiveness*	
	AC	TE	AE	CC	HT			Cost (M€) / Avoided OEI (%)	Cost (M€) / Avoided NH_3 (%)
	keq	keq	kt NO_3eq	kt CO_2eq	–	PE (10^5)	M€		
Non-optimised scenarios									
Baseline 1990	0.11	0.32	83	4912	266	23.8	n.a	n.a	n.a
Baseline 2005	0.04	0.11	30	1811	92	8.42	n.a	n.a	n.a
NOC 2020	0.03	0.10	26	1646	83	7.74	0	n.a	n.a
MAX_1	0.02	0.07	24	1576	61	7.11	40	5	16
MAX_2	0.02	0.07	24	1514	61	7.04	47	5	16
MAX_3	0.03	0.08	19	1400	66	5.76	102	4	65
Optimised scenarios with technical measures									
CZECHPLAN	0.03	0.08	26	1581	69	7.67	11	12	7
EUPLAN	0.03	0.08	26	1558	64	7.49	16	5	8
IMPACT	0.04	0.11	20	1552	88	6.12	12	0.6	-7
IMPACT-EUPLAN	0.04	0.10	25	1618	85	7.49	0.2	0.1	-0.1
Optimised scenarios with non-technical measures (10% reduction of dairy cattle)									
CATTLECUT	0.04	0.11	19	1444	84	5.89	2**	n.a	n.a

Note: AC-acidification, **TE**-terrestrial eutrophication, **AE**-aquatic eutrophication, **CC**-climate change, **HT**-human toxicity, **OEI**-overall environmental impact
PE normalized the potential impact expressed in Person Equivalents

* $\dfrac{\text{Total reduction cost (M€)}}{(OEI_{NOC2020} - OEI_{scenario} / OEI_{NOC2020}) \times 100}$ $\dfrac{\text{Total reduction cost (M€)}}{(NH3_{NOC2020} - NH3_{scenario} / NH3_{NOC2020}) \times 100}$

** Only costs of technical measures; excluding costs of closing farms, which we tentatively estimate to range between 16 and 50 M€ (Van Pul, 2004)

In the CATTLECUT scenario we also investigated the effect of non-technical measures such as a closure of farms. Our results indicate that closing farms may be more cost effective than some technical measures. We investigate the effect of closing 10% of farms in each study region, and then performed an optimisation analysis aimed at reducing the OEI as in the IMPACT scenario. Closing down the farms alone resulted in a reduction of overall environmental impact by 10% relative to the No Control scenario. To achieve the environmental target as in the IMPACT scenario, additional technical measures were selected by the model at costs of 2 MEuro. The combined result is a reduction in OEI comparable to that in the MAX_3 scenario, while the total reduction costs (including tentative estimates for closure of farms) are half of those of the MAX_3 scenario

Emissions changes

Figure 4.1 presents the calculated changes in national emissions for two optimised scenarios (EUPLAN, IMPACT,) and one of the maximum feasible technical reduction scenarios (MAX_3) relative to the No Control scenario for 2020. The comparison demonstrates the extent to which emissions can be reduced by technical measures alone.

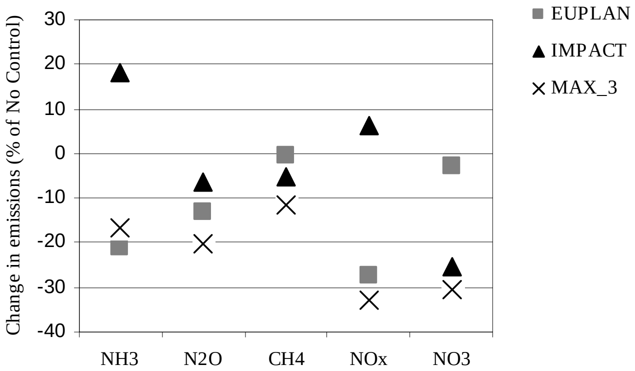

Figure 4.1 Change in emissions (NH_3, N_2O, CH_4, NO_x, NO_3) relative to the No Control 2020 emissions for two optimised scenarios (EUPLAN, IMPACT) and for one of the maximum feasible reduction scenario (MAX_3). See Table 4.2 for a description of the scenarios.

Ammonia emissions are almost 20% lower than No Control levels in the EUPLAN scenario, and 20% higher in the IMPACT scenario. In the MAX_3 scenario the ammonia emissions are not as low as in scenario EUPLAN. This is because the EUPLAN scenario is specifically focused on ammonia, while in the MAX_3 scenario the reduction target is to reduce the overall environmental impact.

Nitrous oxide emissions are reduced by almost 20% in MAX_3, and by 10-15% in the optimised scenarios. Reductions in emissions of methane range from 0% in the scenario EUPLAN to more than 8% in the IMPACT scenario, while the maximum potential is 12%

(scenario MAX_3). The largest potential reduction is calculated for nitrogen oxides (34% for scenario MAX_3). The optimised scenario reflecting EU policy to reduce ammonia (EUPLAN) is close to this maximum (30%), while no NOx reduction is realized in the IMPACT scenario. For emissions of nitrate the maximum reduction is around 30% and optimised IMPACT scenario results in a 27% reduction.

Total reduction costs and reduction of overall environmental impact in study regions

Next, we analyze results for the nine study regions. Region-specific costs of measures selected to achieve environmental targets in the three optimised scenarios (CZECHPLAN, EUPLAN, and IMPACT) are shown in Figure 4.2, while Figure 4.3 presents the reduction in overall environmental impact (OEI) relative to the No Control scenario.

The reduction costs differ considerably between study regions (0.1-3.3 MEuro; Fig. 2). The regional costs depend on dairy production intensity, the environmental target and the control measures selected for each study region. The highest reduction costs are calculated for study regions 1(HHHL), 2(HHHL), 4(HLLL) and 5(HLLH) which can be classified as very intensive dairy production regions. However, despite these relatively high costs (1.7-2.5 MEuro), the effect on OEI is negligible in the CZECHPLAN scenario. This is caused by application of ammonia abatement measures which increase emissions of methane and nitrate. The reduction of NH_3 emissions is counter balanced by increased greenhouse gas emissions. This effect is less pronounced in study regions that are classified as a less intensive. In these areas reduction measures for ammonia are applied to a lower extent and consequently a negative side effect is avoided, the reduction of OEI is up to 8%.

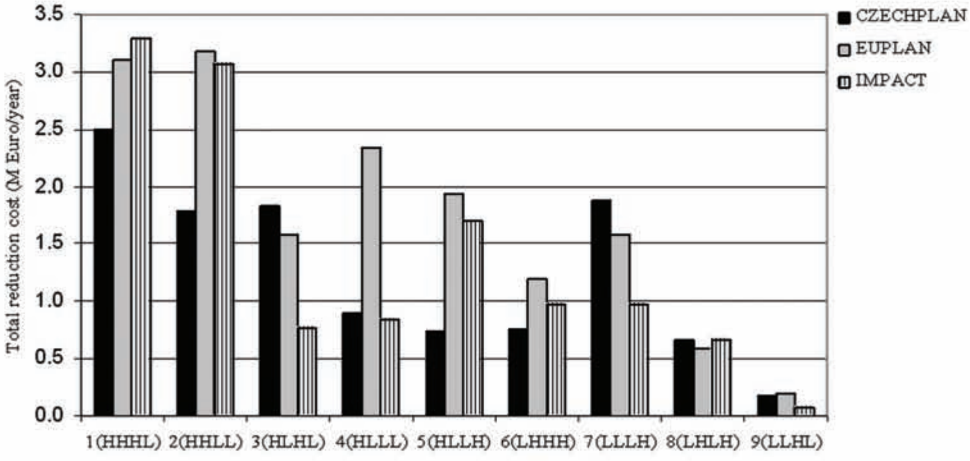

Figure 4.2 The total reduction cost (MEuro/year) for three optimised scenarios (CZECHPLAN, EUPLAN, IMPACT) by nine study regions.

For the scenario EUPLAN reductions in OEI are calculated that range from 1% in study regions 1(HHHL) and 2(HHLL) to 13% in study region 5(HLLH). Also for study regions 4(HLLL) the model selects a combination of measures leading to relatively large reductions. Both regions 4(HLLL) and 5(HLLH) are characterised high productive dairy cattle with high N excretion (Table 1A). The analysis indicates that cost-optimal solutions at the national level are not always the cheapest solutions at the regional level. For instance, the IMPACT scenario is the most cost-effective at the national level (Table 3), but not the cheapest for specific regions. Likewise, the reduction costs for the Czech Republic as a whole is highest for the EUPLAN scenario, however for some study regions the costs of the IMPACT and CZECHPLAN scenarios are the highest. The regional differences in IMPACT scenario are not as large as for the other two scenarios. The calculated reduction of OEI ranges from 18% 7(LLLH) up to 25% in study region 9 (LLHL).

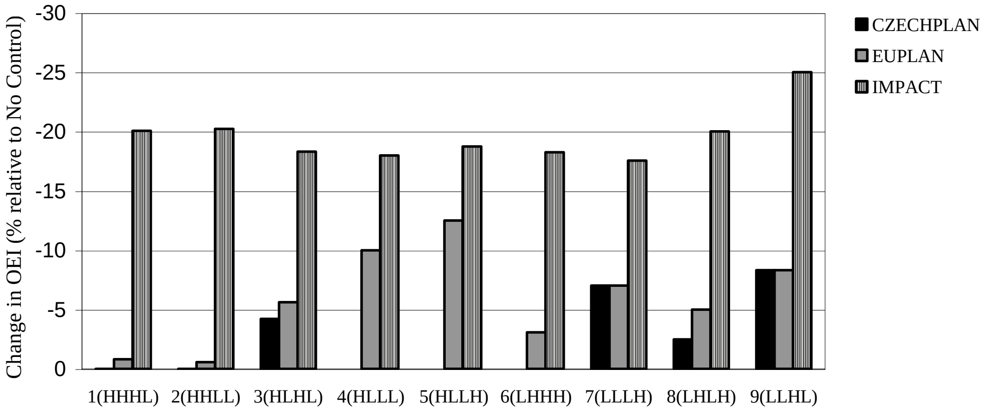

Figure 4.3 The overall environmental impact (OEI) for three scenarios (CZECHPLAN, EUPLAN, IMPACT) by nine study regions presented as a relative change to the No Control scenario

Emission reduction measures

The optimisation analysis allows us to explore the reduction measures selected by the model in the cost effective solutions (Table 4.4). Our analysis indicates that the cheapest way to realize current policy target for ammonia (as reflected in the CZECHPLAN scenario) is by stable adaptations application in all study regions. For study regions 3(HLHL) and 7(LLLH) the model also selects low nitrogen feed and covered manure storage to realize the CZECHPLAN targets.

The European ammonia targets (as defined in the EUPLAN scenario) cannot be realized by applying ammonia reduction measures alone. The reduction potential of these measures is limited and they are relatively costly and thus less attractive. In scenario EUPLAN the target is nevertheless met, because the model can also select measures aimed at the reduction of other pollutants that as a side-effect also reduce ammonia. Among the selected measures are manure efficiency improvement, stable adaptations and low nitrogen feed. For study areas 4(HLLL) and 5(HLLH) also propionate and covered manure storage with low ammonia application are selected by the model. For the IMPACT scenario (with a target for the overall environmental impact OEI), the model indicates that it is cost-effective to reduce nitrate and greenhouse gases first. The associated selected measures include alternative timing of manure application, manure efficiency improvement and stable adaptations. However, changes in timing of manure application increases ammonia and nitrogen oxide emissions as a side-effect, due to larger storage times.

Table 4.4 The three most frequently selected emission reduction measures in optimised scenarios (in order of frequency in the modelled optimal solutions)

Scenario	Emission reduction measures (ranking according to frequency of application to A_p)		
	1	2	3
CZECHPLAN	Stable adaptation	Low nitrogen feed	Covered manure storage
EUPLAN	Manure efficiency improvement	Stable adaptation	Low nitrogen feed
IMPACT	Manure timing application	Manure efficiency improvement	Stable adaptation

4.4 Discussion and conclusion

We analysed the cost-effectiveness of policy measures to minimize the environmental and health impact by dairy production in the Czech Republic. The results of this study indicate that simultaneous reduction of environmental problems at the national level is more cost-effective than reduction of problems one by one at the regional level.

The application of an overall environmental impact (OEI) indicator as an optimisation target for cost-effectiveness analysis of emission reduction measures has several advantages. It identifies which environmental problem should be reduced first. Second it provides insight in the relative contribution of different environmental problems to the overall environmental impact. Third it may help to policy makers to identify optimal strategies to reduce emissions of multiply pollutants simultaneously.

In addition our approach illustrates how different types of emission estimation methods can serve as a basis for linear optimisation models. Our model combines emission factors approaches and process-model based emission estimates for nitrogen related emissions. Next, we use site-dependent characterisation factors to calculate the potential environmental and health impact. Site-dependent characterisation factors for environmental problems take into account site-specific characteristics of a country in assessing acidification, terrestrial and aquatic eutrophication and regional differences for human toxicity problems. Many environmental assessment models use site-generic impact factors, ignoring regional variability. By including normalization and weighting of the potential environmental and health impact we were able to assess the environmental and health impact in one aggregated environmental indicator, reflecting overall environmental performance of dairy production. In future analyses it would be interesting to use different valuation factors reflecting different views and priorities of decision makers and to investigate how this would affect the selection of emission reduction measures in optimised scenarios.

The policy implications of our results refer to the situation in which the different environmental problems are equally important. The impact of dairy cattle in 2005 is only one-third of that in 1990. And between 2005 and 2020 an additional 9% reduction is calculated as a result of reductions in dairy cattle numbers. Technical measures are calculated to have a limited reduction potential (10-30% reduction of OEI). Non-technical measures (e.g. closure of farms) are needed for further reductions in OEI. We investigated the effects of closure of farms (CATTLECUT scenario). Our results indicate that this may be more cost effective than some of the “traditional” technical measures. Non-technical measures may therefore be considered important in strategies to reduce the environmental impact of agriculture.

The optimised scenarios illustrate how environmental targets can be reached at lowest costs. The overall environmental impact (OEI) in 2020 is 1-30% lower in the optimised scenarios than in the No Control scenario, while the costs range between 0.2-16 MEuro. Setting a target for OEI as done in the IMPACT scenario may have similar effect as maximum feasible reduction scenarios (MAX), but at about one-third of the costs.

Measures to reduce aquatic eutrophication and climate change are first selected in relatively cost-effective scenarios. This is in contrast with current policies, which tend to focus on acidification and terrestrial eutrophication. The European ammonia targets (as defined in the EUPLAN scenario) cannot be achieved by applying ammonia reduction measures alone.

At the level of nine study region the reduction costs differ considerably (0.1-3.3 MEuro). Cost-optimal solutions at the national level are not always the cheapest solutions at the regional level. For instance, the IMPACT scenario is the most cost-effective at the national level but not the cheapest for specific regions.

The results of this study can be used for discussions on target setting procedures within the country and help policy makers to understand the importance to solve environmental and health problems simultaneously.

Acknowledgments

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Appendix 4A:

Table 4.1A Number of dairy cattle (in 1000 heads) kept in solid system (DS) and dairy cattle kept in liquid system (DL) in 1990 and 2005 (taken from CSO, 2007) and nitrogen excretion in 2005 (GAS_EM model).

Study regions	Administrative regions	1990		2005		Nitrogen excretion (Nex)
		DS	DL	DS	DL	kg/year
1 (HHHL)	Jihocesky,Vysocina	299	37	105	13	104
2 (HHLL)	Kralovehradecky Pardubicky	258	32	91	11	108
3 (HLHL)	Plzensky	102	13	36	4	88
4 (HLLL)	Olomoucky	69	9	24	3	112
5 (HLLH)	Zlinsky	67	8	23	3	114
6 (LHHH)	Stredocesky Ustecky	146	18	21	5	110
7 (LLLH)	Liberecky Moravskoslezsky	82	10	28	3	110
8 (LHLH)	Jihomoravsky	59	7	20	2	114
9 (LLHL)	Karlovarsky	18	2	6	1	84

Table 4.2A Reduction factors (r), applicability (a) and annual costs (c) of emission reduction measures (n) primarily aimed at NH_3 emissions from dairy cattle in the Czech Republic. Based on Klimont and Brink (2004), Brink (2003) and Oenema et al. (2007).

Reduction measure (n)	Process (i)	Reduction factor % (r)							Applicability % (a)		Cost-Euro/per animal (c)	
		NH_3	NO	N_2O	CH_4	PM_{10}	PM_{25}	NO_3	Liquid	Solid	Liquid	Solid
Low nitrogen feed	Housing	-15			n.e	n.e	ne		75	75	29	29
	Storage	-15	-15	-15								
	Application	-15		-15								
	Grazing	-20		-15								
	Deposition			-15								
	Leaching			-15				-15				
Stable adaptation	Housing				n.e	n.e	n.e		50	50	79	79
	- liquid	-35										
	- solid	-50										
	Storage	-70										
	Application		12	12								
	Deposition			- 16								
	Leaching			4				4				
Covered outdoor store (high efficiency)	Storage-liquid	-80	-10	-10	10	n.e.	n.e	n.e	50	50	11	
	Application			1								
	Deposition			-1								
	Leaching											
Covered outdoor store (low efficiency)	Storage-liquid	-40	-10	-10	10	n.e	n.e	n.e	50	50	4	
	Application			1								
	Deposition			-1								
	Leaching											
Low nitrogen application (high efficiency)	Application				n.e	n.e	n.e		20	30	58	59
	- solid	-40	100	100								
	- liquid	-70	100	100								
	Deposition											
	- solid			-32								
	- liquid			-21								
	Leaching							3				
	- solid			7								
	-liquid			5								
Low nitrogen application (low efficiency)	Application				n.e	n.e	n.e		20	30	58	47
	- solid	-20	60	60								
	- liquid	-35	60	60								
	Deposition			-10								
	Leaching			3				3				

Note: n.e. means no effect

Table 4.3A Reduction factors (r), applicability (a) and unit costs (c) of emission reduction measures primarily aimed at N_2O, CH_4, and NO_3 from dairy cattle in the Czech Republic. Based on Brink (2003) and Oenema et al. (2007)

Reduction measure (n)	Process (i)	Reduction factor % (r)							Applicability % (a)		Cost -Euro/animal (c)	
		NH_3	NO	N_2O	CH_4	PM_{10}	PM_{25}	NO_3	Liquid	Solid	Liquid	Solid
Timing of manure application	Storage Leaching	20	20	20 -15	20	n.e	n.e	-15	100	100	1.8	1.8
Propionate precursors	Housing Storage Application	-5	-5	-5	-25	-5	-5	-5	75	75	25-60	25-60
Probiotics	Grazing Deposition Leaching	-7.5	-7.5	-7.5	-7.5	-7.5	-7.5	-7.5	50	50	35	35
Daily spreads	Storage Application Leaching	-50 10	80	80 80	-90	n.e	n.e	80	100	100	8-75	8-75
Anaerobic digestion small scale	Storage Application Leaching	n.e.	n.e	5	-50	n.e	n.e	5	30	n.e	11-155	11-155
Anaerobic digestion centralized	Storage Application Leaching	n.e	n.e	5	-50	n.e	n.e	5	30	n.e	3-26	3-26
Manure efficiency improvement	Application Leaching	-5	-5	-5 -5	n.e	n.e	n.e	-5	50	50	5	5
Storage with minimum leaching	Leaching	n.e.	n.e	-10	n.e	n.e	n.e	-10	30	30	55	55

Note: n.e. means no effect

Table 4.4A Applicability and cost of measures which directly affect input parameters (number of cattle)

Reduction measure (n)	Applicability % (a)	Cost in Euro (c)
Restriction on grazing	100	1 Euro/ton manure stored
Closure of farms	100	150 000-450 000 Euro per farm

References

Amann, M., Bertok, I., Cobala R., Cofala, J., Gyarfas, F., Heyes, C., Klimont, Z., Makowski M., Schopp, Wagner F., 2005. A final set of scenarios for the clean air for Europe (CAFÉ) Programme. Cafe scenario analysis report nr.6 IIASA, Laxenburg, Austria

Amann, M., Asman, W., Bertok, I., Cofala, J., Heyes, C., Klimont, Z., Schöpp, W. and Wagner, F., 2006. Emission control scenarios that meet the environmental objective of Thematic Strategy on Air Pollution. NEC Scenario Analysis Report Nr.2. IIASA, Laxenburg, Austria

Amann, M., Asman, W., Bertok, I., Cofala, J., Heyes, C., Klimont, Z., Schöpp, W. and Wagner, F., 2007 Updated Baseline Projections for the Revision of theEmission Ceilings Directive of the European Union. NEC Scenario AnalysisReport #4. International Institute for Applied Systems Analysis (IIASA),Laxenburg, Austria.

Barret, M., 2005. Including non-technical measures for reducing air pollution in Integrated Assessment Modelling. Workshop Gotheborg 7-8 December 2005. Asta Sweeden

Brink, J.C., 2003. Modelling cost-effectiveness of interrelated emission reduction strategies, the case of agriculture in Europe. PhD thesis. Wageningen University. The Netherlands

Brooke, A., Kendrick, A., Meeraus, R., Raman, R.E., Rosenthal, 1998. GAMS: a user's guide. GAMS Development Corporation, Washington D.C. http://www.gams.com

CSO, 2007. Czech Statistical Office. http//www2.czso.cz

Cofala, J., Amann, M., Gyarfas, F., Schoepp, W., Boudri J.C., Hordijk L., Kroeze C., Junfeng Li., Dai Lin, Panwar, T.S.,Gupa S., 2004. Cost-effective control of SO_2 emissions in Asia. Journal of Environmental Management; 72: 149-161.

Dämmgen, U., Luttich, M., Dohler, H., Eurich-Menden, B., Osterburg, B., 2002. GAS-EM a procedure to calculate gaseous emissions from agriculture. Landbauforshung Volkenrode; 52: 19-42

Dämmgen, U.,Lüttich M., Döhler H., Eurich-Menden B., Osterburg B., 2006. Calculations of emissions from German agriculture-national Emission Inventory Report (NIR)2006 for 2004. Part 3: Methods and Data (GAS_EM). Landbouforschung Volkenrode; Special Issue 291:47-221

Dellink, R.B., 2003. Economic impacts of pollution and abatement: A dynamic empirical modelling assessments. PhD thesis. Vrije Universiteit, Amsterdam. The Nederlands

De Vries, W., Kros, J., Oenema, O., and de Klein, J., 2003. Uncertainties in the fate of nitrogen II: A quantitative assessment of the uncertainties in major nitrogen fluxes in the Netherlands. Nutrient Cycling in Agroecosystems; 66: 71-102

Havlikova, M., Kroeze, C., 2006 Evaluation of methods for quantifying emissions of air, water and soil pollutants. The Science of the Total Environment; 372: 133-147.

Havlikova, M., Kroeze, C., Huijbregts, M., A. J., 2008 Environmental and health impact by dairy production in the Czech Republic. The Science of the Total Environment; 396:121-131.

Klimont, Z., and Brink, C., 2004. Modelling of Emissions of Air Pollutants and Greenhouse Gases from Agricultural Sources in Europe**.** Interim Report IR-04-048, IIASA

Menzi, H., Rüttimann L., Reidy B., 2003. DYNAMO: A new calculation model for dynamic emission inventories for ammonia, in: International symposium on gaseous and odour emissions from animal production facilities,1-4 June, Horsena, Denmark, pp.378-381

ODPM, 2005. 'Multi-Criteria Analysis manual', Office of the Deputy Prime Ministry UK, pp.145 http://www.odpm.gov.uk

Oenema, O., Oudendag D.A. Witzke H.P., Monteny G.J., Velthof G.L., Pietrzak S., Pinto M., Britz W. Schwaiger E., Erisman J.W. De Wries W., Van Grinsven J.J.M, Sutton M., 2007. Integrated measures in agriculture to reduce ammonia emissions, final summary report. Alterra, Wageningen University and Research Centre.

Haushilds, M., and Potting, J.M.B. (Eds), 2004. Spatial differentiation in life cycle impact assessment the EDIP2003 Methodology; Guidelines from the Danish Environmental Protection Agency: Copenhagen

Seppala, J., Posch, M., Johanson, M., Hettelingh, J-P., 2006. Country Dependent Characterisation Factors for Acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. Int. J LCA; 6: 403-416

Stranddorf, H.K, Hoffmann L., Schmidt A., 2005. Update on impact categories, normalization and weighting in LCA. Selected EDIP-97data. Environmental project nr.995 2005. Miljoprojekt. Danish Ministry of the Environment.Copenhagen, Denmark: Environmental Protection Agency; 290pp.

Van Pul, W.A.J., B.J. de Haan, J.D. van Dam, M.M., van Eerdt, J.F., de Ruiter, A. van Hinsberg, H.J., Westhoek, 2004. Cost-effectiveness of generic and locally applied ammonia abatement measures. RIVM report: 500033001/2004, RIVM. The Netherlands. In Dutch

Velthof, G.L., Oudendag, D.A., Oenema, O., 2007. Development and application of the integrated nitrogen model MITTERA-EUROPE. Ammonia service contract "Integrated measures in agriculture to reduce ammonia emissions" Contract number:070501/2005/422822/MAR/C1

Van Vuuren, D.P., Cofala, J., Eerens, H.E., Oostenrijk, R., Heyes, C., Klimont, Z., Den Elzen, M.G.J., Amann, M., 2006. Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. Energy Policy; 34: 444-460.

Webb, J., Misselbrook, T.H.A., 2004a. Mass-Flow Model of Ammonia Emissions from UK Livestock Production, Atmospheric Environment; 38: 2163-2176

Webb, J., Chadwick, D. and Ellis, S., 2004b. Emissions of ammonia and nitrous oxide following incorporation into the soil of farmyard manures stored at different densities. Nutrient Cycling in Agroecosystems; 70:64-76.

Webb, J. H., Menzi, B.F., Pain, T.H., Misselbrook, U., Dämmgen, H., Hendriks, H., Dohler H., 2005. Managing ammonia emissions from livestock production in Europe. Environmental Pollution; 135: 399–406.

CHAPTER 5

Exploring future environmental impact by dairy cattle in the Czech Republic

Abstract

In this paper we explore possible reduction of the future environmental impact by dairy cattle in the Czech Republic. We use an optimisation model combined with Multi-Criteria Analysis (the DAIRY model). First, two reference scenarios are analysed: one assuming no emission control and a policy scenario aiming at cost-effective reduction of the overall environmental impact (OEI). These reference scenarios indicate that the OEI by dairy cattle is mainly associated with global warming and aquatic eutrophication, while leaching and housing are the two most contributing processes. The costs to reduce OEI by 20% are 12 MEuro. The most cost-effective combination of measures to achieve this target are manure efficiency improvement and improved timing of manure application. Next, we explore how these calculated trends change as result of different assumption on (i) views of hypothetical model users on the relative importance of environmental problems, (ii) projected cattle numbers and animal management, and (iii) application of emission reduction measures. The results suggest that, regardless of model users views, global warming and aquatic eutrophication are the most important environmental problems. However, the relative shares of these two in OEI depend on the valuation of the environmental impact categories. This, in turn, has an impact on the costs of reducing OEI, because it is cheaper to reduce emissions of nitrate than emissions of greenhouse gases. The second case shows that dairy cattle kept in slurry-based systems have a better environmental performance than dairy cattle kept in straw-based system. Cattle numbers are found to influence the OEI and reduction costs more than changes in milk yield. The third case indicates that taking into account unintended side-effects of emission reduction on the environment as a criterion for selection of measures, increases the reduction costs considerably.

Keywords: dairy cattle; future trends, Multi-Criteria Analysis; environmental impact; costs

This chapter has been submitted:
Havlikova M., Kroeze C. Exploring future environmental impact by dairy cattle in the Czech Republic. Submitted to the journal of Agriculture Systems

5.1 Introduction

Dairy cattle production is contributing to a number air, water and soil pollution problems. These environmental problems are associated with for example, emissions of greenhouse gases such as methane from enteric fermentation, nitrous oxide from application of manure. In addition, manure management gives arise to emissions of ammonia, particulate matter and nitrate. Environmental policy to reduce the emissions from dairy cattle is still relatively new in European countries including the Czech Republic.

Dairy cattle production is an important and traditional agricultural sector in the Czech Republic. This study focuses on the future environmental impact of dairy cattle in the Czech Republic. In Chapter 4 (Havlikova and Kroeze, submitted), we developed a model to identify cost-effective measures to reduce emissions from dairy cattle in the Czech Republic (DAIRY). The model is based on a study by Brink (2003) who extended the widely used integrated assessment model RAINS (Regional Acidification Information and Simulation model) (Amann et al., 2004) with methane and nitrous oxide from European agriculture.

The DAIRY model is a static optimization model and combines linear programming with Multi-Criteria Analysis (MCA). The model minimises the costs of simultaneously reducing abatement of acidification, terrestrial and aquatic eutrophication, human toxicity, global warming by dairy cattle. The model includes sixteen emission reduction measures. Emissions are calculated using emission factors derived either from international guidebooks or from the process-based model GAS_EM (Dämmgen et al., 2006). The potential environmental impact of emissions is based on so-called site-generic and site-dependent characterisation factors (Chapter 3, Havlikova et al., 2008).

Environmental models like DAIRY are surrounded with uncertainties there we discuss three sources of uncertainty and how they may affect the output. Several elements may be considered to affect the model output. First, the valuation of different environmental and health problems in one aggregated environmental indicator is considered as one of the most controversial steps because valuation process is subjective and it is classified as strongly subjective. Many different valuation factors are available see for example overview in Lindeijer et al. (1996). Indeed, valuation should be done by model user and not model builders. Several studies indicate that different valuation factors may lead to different model outputs (Pluimers et al., 2001, Engrstrom et al., 2007, Zhou et al., 2007).

As Van Asselt and Rotmans (1996) state the future is uncertain and images of the future are subjective and perspective dependent. For a model like DAIRY it is therefore important to critically evaluate the assumptions on future trends in economic activities since these largely affect the model output. The allocation of measures to reduce emissions from dairy cattle depends on the projected livestock numbers and assumptions on animal management. Several assumptions on future development of dairy cattle numbers and animal management are reasonable. One could assume that current trends will continue. Alternatively, Common Agriculture Policy (CAP) of the European Commission proposes to further specialise dairy cattle farms which will lead to higher milk yield.

Third, the procedure by which the DAIRY model selects emission reduction measures is worthwhile to mention. It is based on cost-effectiveness analysis, which is the most often used criterion for current policy making (Amann et al., 2007). However, a number of other criteria are also important in the final selection of the measures, for example, the practicality of measure for farmers, acceptance by the public and farmers, the possibility to monitor the effects of measures as well as the environmental condition of the farm. In addition, one may wants to take into account unintended side-effect of measures. For example, low ammonia application technique may increase nitrous oxide emissions and leaching of nitrate (Brink, 2003). These side-effects are usually not well known and therefore usually not considered.

The objective of this study is to explore the future environmental impact by dairy cattle in the Czech Republic. First, future trends are analysed for 2020 while assuming no implementation of environmental policy measures. Next, the DAIRY model is used to identify cost-optimal way to reduce overall environmental impact of dairy cattle in 2020 by 20% relative to a No Control scenario. These two scenarios are used as reference and reveal the most important environmental problems and underlying emission processes by dairy cattle. Finally, we analyse how the model output is affected by changes in assumptions on (i) views of model users on the importance of environmental problems, (ii) projected cattle numbers and animal management and (iii) the application of emission reduction measures. These three cases are analysed in terms of the overall environmental impact (OEI) by dairy cattle, total costs of emission reduction and the selection of the cost-effective measures to achieve 20% reduction in OEI.

The paper is structured as follows. Section 5.2 includes a brief description of the model DAIRY, while Section 5.3 shows the model output for the two reference scenarios. In Section 5.4 the three alternative cases are explored. Section 5.5 includes the result of analysis. A summary of the results, a discussion and final conclusions are given in the last section.

5.2. Model description

We developed a static optimisation model (DAIRY) for the Czech Republic, which is based on a European model by Brink (2003). For a detailed description we refer to the Appendix 5.B of this Chapter or to Chapter 4 (Havlikova and Kroeze, submitted). Here we summarise the main features of the model. The main aim of the model is to analyse the cost-effectiveness of policies for the simultaneous abatement of acidification, terrestrial and aquatic eutrophication, human toxicity and global warming caused by dairy cattle in the Czech Republic.

The model minimises total costs of realising environmental targets at the national, and at the sub-national level. The targets are either for emissions or for environmental impacts. DAIRY considers seven pollutants: ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), particulate matter ($PM_{2.5}$, PM_{10}) and nitrate (NO_3) emitted from two sources: dairy cattle kept in solid systems and dairy cattle kept in slurry systems. Several processes give rise to emissions: grazing, milking, housing, storage, application, indirect emissions and leaching. The model distinguishes between nine study regions within the Czech Republic which differ in cattle intensity, environmental sensitivity and population density. The environmental indicators used to distinguish study regions are presented in Table 1A in the Appendix. In addition, more detailed information regarding study regions is provided in Chapter 3 (Havlikova et al., 2008).

The model includes fifteen emission reduction measures to abate the above mentioned emissions, from which six are primarily aimed at reducing of ammonia, five at reducing greenhouse gas emissions such as nitrous oxide and methane, and four at reducing nitrate. In addition, the model considers unintended side-effect of the measures on other pollutants.

Emissions are calculated by study region based on emission factor approaches as described in Chapter 2 (Havlikova and Kroeze, 2006). Emission factors of different pollutants are derived from the literature or from process-based model GAS_EM (Dämmgen et al., 2006). In GAS_EM model emission factors are calculated as a function of dairy cattle performance (milk yield) and actual feed composition. The DAIRY model includes number of reduction factors expressing the amount of emission reduced by a given measure, and the applicability of measures expressing the fraction of application of the given measures at a source.

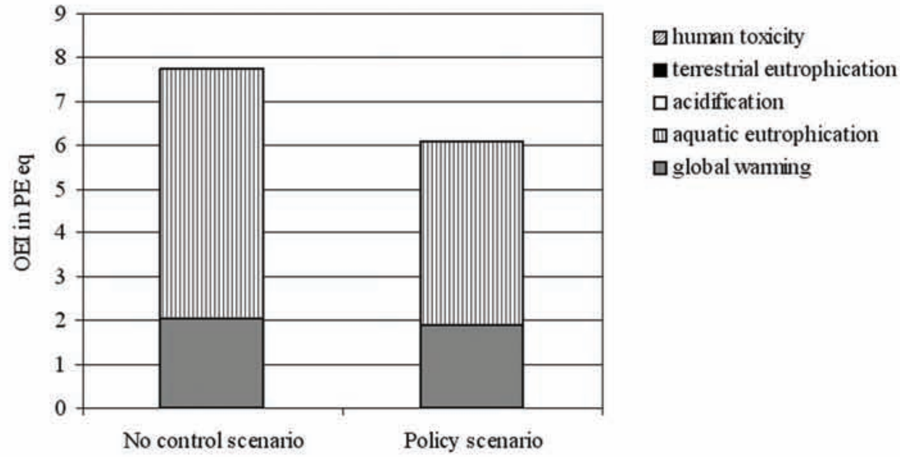
The potential environmental impact is calculated using so-called characterisation factors, which are region specific for human toxicity EDIP2003 (Hauschild and Potting, 2004), country specific for acidification, terrestrial eutrohication (Sepällä et al., 2006) and aquatic eutrophication EDIP2003 (Hauschild and Potting, 2004) and generic for global warming (IPCC, 2000). The individual impact categories are aggregated into an overall environmental impact (OEI) indicator by means of normalization and valuation as usual in Multi-Criteria Analysis (MCA). OEI as a single indicator is used to determine the environmental performance of dairy cattle at the regional and national scale.

5.3. Two reference scenarios for 2020

The overall environmental impact was estimated for dairy cattle in the Czech Republic in 2020 for two reference scenarios. First, the so-called No Control scenario presents a hypothetical case in which no emission reduction measures are considered to be implemented and serves as a benchmark for further comparison. The second reference scenario is a Policy scenario in which we impose a target to reduce the overall environmental impact by 20% relative to the No Control scenario. The DAIRY model is used to minimise total abatement costs at the national level to reach this target.

Both scenarios assume a 10% reduction in dairy cattle number between 2005 and 2020, based on official national projections. We assume that the majority of dairy cattle are housed in straw-based systems (90%) while the rest are slurry-based (10%). In addition, 70% of dairy cattle are kept indoor the whole day while 20% are kept outdoor only. The remaining 10% are grazing part of the day. Figure 5.1 clearly shows that in both scenarios aquatic eutrophication and global warming are the most important environmental problems caused by dairy cattle in the Czech Republic in 2020.

A. Overall environmental impact by impact category



B. Overall environmental impact by process

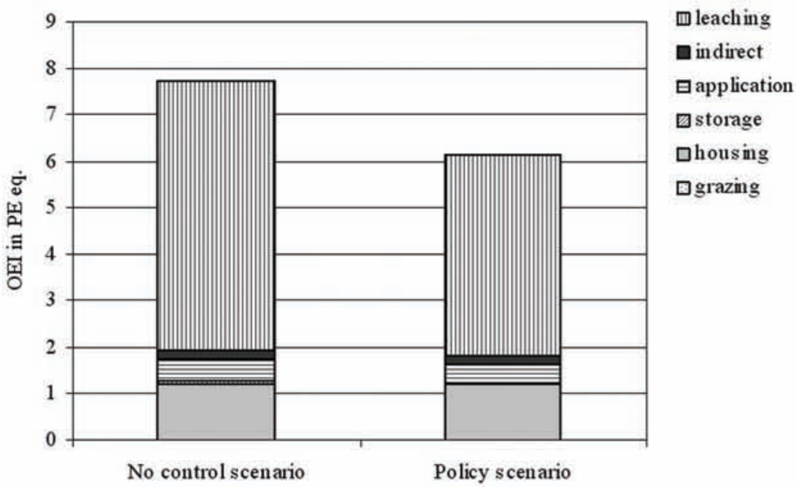


Figure 5.1 Overall environmental impact (OEI) by Czech dairy cattle in 2020 for a No Control scenario and Policy scenario per impact category (A) and process (B).

Note: PE eq. Normalised the potential impact expressed in PE eq. person equivalents

These problems are largely caused by leaching and housing including enteric fermentation. A 20% reduction in the overall environmental impact in the Policy scenario is achieved by improved timing of manure application and by measures leading to a more efficient use of manure further referred as manure efficiency improvement (e.g. balanced manure application, the maximum manure application standard and limiting manure application in sloping grounds). These measures aim to reduce aquatic eutrophication and global warming first. Total reduction costs of achieving the target are 12 MEuro.

5.4. Alternative case descriptions

Case 1: Valuation factors

The overall environmental impact (OEI) combines information on individual environmental problems into one aggregated indicator based on valuation factors. This indicator reflects the total environmental performance of dairy cattle in the country. In the reference scenarios the valuation factors for all environmental problems are equal to one, assuming that all environmental problems are equally important to the model users (Fig. 5.1). This, in fact, may not be the case in reality. Model users may perceive the environmental problems differently and this, in turn, may influence the contribution of these problems to the overall environmental impact.

Therefore, four alternative sets of valuation factors are used here and compared to the reference scenario with “Equal’’ factors. The alternative approaches includes: (1) Distance to Target (DTT1) by Stranddorf et al (2005), (2) Distance to Target (DTT2) by Goedekoop (1995), (3) Ecotax by (Finnveden et al., 2006) and (4) Ecotax_region. These methods are described below and presented in Table 5.1a and 5.1b.

Different Distance to Target (DTT) valuation methods exist (see for instance Lindeijer et al., 1996 for an overview). Here we select the Distance to Target method (DTT1) by Stranddorf et al. (2005) which is based on political reduction targets used in the Czech Republic for individual substances. The valuation factors represent the ratio of actual emissions (year 2005) to target emissions in the year 2020 as set, for instance, by the European Commissions and/or UNFCCC (United Nation Framework on Climate Change). The second type of Distance to Target (DTT2) is based on an analysis of damage to ecosystems and human health caused by European pollutants. These valuation factors express the amount by which the emissions should be reduced to achieve ecosystem protection (Goedkoop, 1995).

The next valuation method is the so called Ecotax method. Taxes and fees for pollutants are directly used as valuation factors (Finnveden et al., 2006). In the Czech Republic, large and medium sources of pollutants are charged for emitting emissions of air pollutants including ammonia, nitrogen oxide and particulate matter. The information on fees for these pollutants in 2005 is taken from the environmental statistics of the Czech Republic (Cenia, 2006). It is difficult to estimate how much of this fee can be assigned to acidification, terrestrial eutrophication and human toxicity separately. Therefore, the fee for ammonia is considered here to be half for acidification and half for terrestrial eutrophication. Likewise, for nitrogen oxide the fee is equally divided between acidification, terrestrial eutrophication and human toxicity. For greenhouse gas emissions the tax for carbon dioxide is used. For emissions of nitrate no tax or fees are used in the Czech Republic. Therefore, we used a tax on application of nitrogen fertilizer from Ericsson, (2004).

Table 5.1a Valuation factors (We) as used in Case I: Equal, Distance to target (DTT1), (DTT2) and Ecotax

Environmental problem (e)	W_e	Rank	Target basis and/or reference
Equal targets			
Acidification	1	n.r	-
Terrestrial eutrophication	1	n.r	-
Aquatic eutrophication	1	n.r	-
Human toxicity	1	n.r	-
Global warming	1	n.r	-
Distance to target: DTT1 (Stranddorf et al., 2005)			
Acidification	1.59	2	Thematic strategy on air pollution (EC, 2005)
Terrestrial eutrophication	1.34	3	Thematic strategy on air pollution (EC, 2005)
Aquatic eutrophication	1.11	5	10% reduction up to 2020 (arbitrary target)
Human toxicity	1.73	1	4th National Communication UNFCCC (2005)
Global warming	1.24	4	Thematic strategy on air pollution (EC, 2005)
Distance to target: DTT2 (Goodekoep et al., 1995)			
Acidification	10	1	5% of terrestrial ecosystem impairment
Terrestrial eutrophication	5	2	5% of terrestrial ecosystem impairment
Aquatic eutrophication	5	2	5% of aquatic ecosystems impairment
Human toxicity	10	1	Probability of 1 death / year /million people*
Global warming	2.5	3	0.1ºC per decade, 5% impairment
Ecotax : Taxes and fees in the Czech Republic			
Acidification	0.1€/kg AE	5	35 €/ t NH_3, 25 €/ t NO_x (Cenia, 2006)
Terrestrial eutrophication	0.2€/kg AE	4	35 €/ t NH_3, 25 €/ t NO_x (Cenia, 2006)
Aquatic eutrophication	1.2€/kg N	3	N in fertilizer 1.2 € / kg N (Finveden, 2006)
Human toxicity	3.2 kg Ht.eq	2	100 €/ t PM (Cenia,2006)
Global warming	3.8€/kg CO_2-eq	1	CO_2 price 12 €/ t CO_2 (Amann et al., 2006)

Explanation of Abbreviation: n.r means no ranking
* Valuation factors taken for carcinogenic substances

Table 5.1b Assumptions on region specific valuation factors (We) based on environmental indicators (EI) as used in Ecotax_region. For details see also Table 1A and 2A (Appendix).

Ecotax _region: region - specific taxes and fees		
Impact category	Environmental Indicator (EI)	Valuation factor (We)
Acidification	$EI_{cr} > EI_{region}$	$W_{e,region}$ = +50% $W_{e,cr}$
Terrestrial eutrophication	$EI_{cr} < EI_{region}$	$W_{e,region}$ = -50% $W_{e,cr}$
	$EI_{cr} = EI_{region}$	$W_{e,region} = W_{e,cr}$
Aquatic eutrophication	$EI_{cr} < EI_{region}$	$W_{e,region}$ = +50% $W_{e,cr}$
Human toxicity	$EI_{cr} > EI_{region}$	$W_{e,region}$ = -50% $W_{e,cr}$
Global warming	$EI_{cr} = EI_{region}$	$W_{e,region} = W_{e,cr}$

*Note: Environmental indicator (EI) for impact categories:
Acidification and terrestrial eutrophication: critical load for acidity and nitrogen
Aquatic eutrophication: area of agriculture land in nitrate vulnerable zones
Human toxicity: population density
Global warming: dairy cattle intensity
Abbreviations: cr – Czech Republic, region – one of the nine study regions, e-impact category

The Ecotax approach ignores regional differences because it is based on national taxes. Ideally, the tax rates would differ by study region because of differences in environmental conditions. Farmers contributing most to environmental problems would then pay more than farmers contributing less. However, emissions (e.g. ammonia emissions) are transported over long distances and farmers in one region may influence environmental conditions in another. As a result, a 'farm-to-farm' differentiation of taxes seems to be unfeasible. Therefore we define study specific valuation factors for each of the nine study regions based on the sensitivity of their ecosystems as indicated in Table 5.1A in the Appendix. This regionally differentiated Ecotax method is referred as "Ecotax-region'' and the valuation factors for the nine study regions are presented in Table 5.1b and Table 5.2A in the Appendix. Here we briefly summarise the underlying assumptions. For acidification and terrestrial eutrophication it is assumed that if the level of the environmental indicator (EI) such as critical load for acidity and nitrogen within a region is lower than the national average the valuation factor is 50% higher than the national Ecotax valuation factor (Table 5.1a) and vice versa. For aquatic eutrophication, human toxicity and global warming the assumptions are opposite: if the environmental indicator (area of agriculture land in vulnerable zones, population density and dairy cattle intensity) within a region is lower than the national average the valuation factor is 50% lower than national Ecotax and vice versa.

Case II: Animal management

Several assumptions related to animal management, dairy cattle numbers and milk yield are underlying two reference scenarios presented in the section 5.3. These are based on official projections of dairy cattle numbers and on current animal management in the Czech Republic. The two reference scenario indicates that leaching and housing are the two most important contributors to environmental problems by dairy cattle. In these reference scenarios it is assumed that in the future most of the dairy cattle are housed in straw-based system. However, other animal management systems exist with different environmental impact (see for instance Oenema et al., 2001, Mosquera et al., 2006). Slurry-based system is currently applied on 10% of the farms in the Czech Republic. This is opposite to many Western European countries where intensive dairy cattle production is typical (e.g. Germany and The Netherlands). A comparison of the environmental performance of the traditional straw-based systems with slurry-based systems may therefore, be interesting.

Moreover, the reference scenarios assume that the number of dairy cattle will decrease over time and that milk yield, influencing nitrogen excretion and consequently N related emissions, do not change. One could question what model output will be if the dairy production further intensifies, or animal number may decrease by more then 10% as an effect of competition with production of bio-energy.

As an alternative to a reference it is assumed in Case II that the farmers will switch to slurry-based systems so that the ratio of straw-based to slurry-based housing system becomes opposite to the current situation: 90% slurry-based system and 10% straw-based system. Next, we assumed different number of dairy cattle in the calculation by arbitrarily increasing and decreasing the numbers by 50% from 2005. This is further combined with an increased milk yield by 50%. We do not assume that milk yield will decrease. Rather it may stabilise at the 2005 level. In total the model is ran for six cases: (1) reference No Control and Policy scenario scenarios, (2) decrease in cattle number and increase in milk yield (3) no change in cattle number and increase in milk yield, (4) increase in cattle number and increase in milk yield (5) increase in cattle number and no change in milk yield (6) decrease in cattle number and no change in milk yield. All six cases are run for both straw-based and slurry-based housing. Total are 24 different alternative cases. Overview of analysis of Case II is presented in Table 5.2.

Table 5.2 Overview of Case II analysis

Parameter	Assumptions
Housing	90% straw-based and 10% slurry- based (Straw) 10% straw-based and 90% slurry-based (Slurry)
Cattle numbers	50% higher than reference (HC) 50% Lower than reference (LC) No change in cattle numbers (NC)
Milk yield	50% higher than reference (HM) 50% lower than reference (LM) No change in milk yield (NM)
Model run	Not optimised (NOC) Optimised with 20% reduction in OEI (POL)

Case III: Region-specific applicability of emission reduction measures

The emissions are not only determined by activity data (e.g. number of cattle), emission factors (e.g. nitrogen excretion) and efficiency of emission reduction measures but also by assumed applicability of reduction measures (i.e. extent to which a measure can be applied to a source). In our reference scenarios applicability of all fifteen emissions reduction measures are defined at the national level because no region-specific information was available. In original version of DAIRY model, the maximum applicability ranges from 20% - 100% reflecting penetration of different emission reduction measures in the Czech Republic in 2020. This applicability is presented in Table 5.3A in the Appendix. National allocation of emission reduction measures may seem not be a reality but can serve as starting point. There we analyse how the applicability of emission reduction measures may be influenced by environmental condition and the extent to which emission reduction measures increase or decrease other emissions (as unintended side-effect).

The original version of the DAIRY model does not explicitly calculate atmospheric deposition acidifying and eutrophying compounds. Rather, the potential sensitivities of regions are defined on the basis of qualitative information on environmental characteristics such as critical loads for acidity and nutrient nitrogen, the area of agricultural land located in nitrate vulnerable zones, population density, and dairy cattle density per hectare of agricultural land. These environmental characteristics are presented in Table 5.1A in the Appendix.

We combine these environmental characteristics with the environmental side-effects of emission reduction measures as analysed by Brink (2003). This forms the basis for the assumed region-specific applicability of measures in the Czech Republic. The underlying assumptions to come to our region-specific applicability factors are as follows. The applicability of a reduction measure in a region is lowered if that measure is, an increasing emissions of a pollutants in that region, while ecosystems in that region are potentially sensitive to that pollutant. In principle, we lower or increased the applicability of measures by 25% or 50% if the measure is increasing emissions by less than 10% or more than 10% respectively depending on sensitivity of regions. For some measures, the region-specific applicability factors are based on other consideration. For instance, probiotics and propionate are considered to be fully applicable (100%) in all study regions because side-effect is unknown. Manure efficiency improvements have a 50% applicability because to autonomous trends in efficiency improvement. Low nitrogen feed is considered not applicable in regions with very low milk yield, because further changes in diet of cattle may lead to decrease in productivity. Anaerobic digestion is assumed to be less applicable (by 50%) in less intensive regions. Storage of manure with minimum leaching is assumed to be 50% applicable in regions less sensitive to aquatic eutrophication.

5.5. Alternative cases: Results

5.5.1 Case I: Valuation factors

Relative contribution of different impact categories

The relative contribution of the impact categories by dairy cattle to the overall environmental impact (OEI) was analysed by using five different valuation factors (see Table 5.1a and 5.1b) and assuming that there are no emission reduction measures implemented in year 2020. The result of the Equal method presented in the Figure 5.2 is identical to No Control reference scenario. The results clearly indicate that global warming and aquatic eutrophication are the most important environmental problems regardless of the valuation factors used. This is a robust conclusion. However, which of these problems two is the most important is depending on the valuation factors used. Aquatic eutrophication is dominant when using DTT1, DTT2 and Equal valuation factors while global warming is dominant when using Ecotax valuation factors.

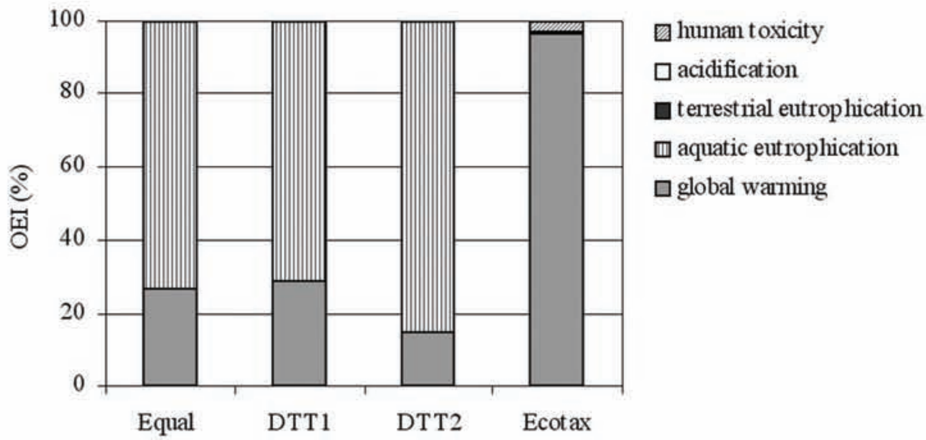
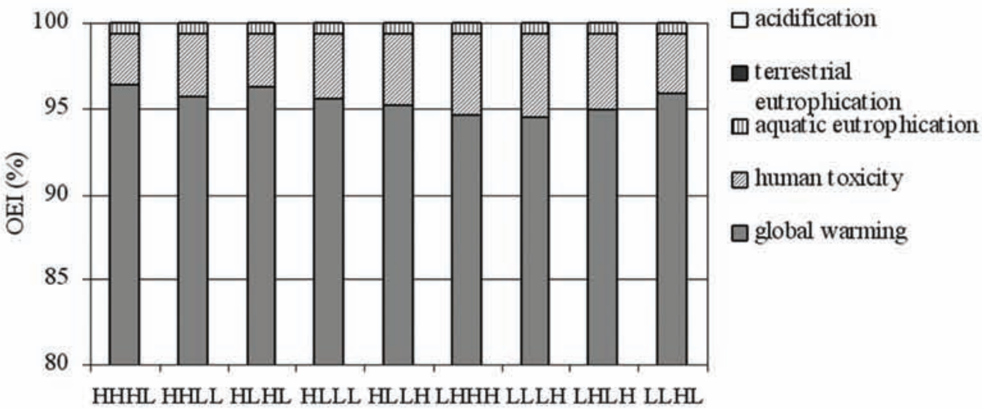


Figure 5.2 The relative contribution of different impact categories to the overall environmental impact (OEI) based on four valuation factors: Equal (= No Control reference scenario), Distance to target (DTT1, DTT2) and Ecotax.

To reflect also regional difference in the analysis we applied region-specific valuation factors derived from hypothetical regional taxes: "Ecotax_region" factors (for details see Table 5.2A in the Appendix). Figure 5.2A compares the differences between Ecotax_region and Ecotax approach for the nine study regions. Clearly, global warming is still the most important environmental problem in all study regions contributing by more than 90% to the OEI. However, by using the Ecotax_regions valuation factors the relative contribution of impact categories may change. The human toxicity is more important in study regions 6(LHHH) and 8(LHLH) with relatively high population density, in all cases < 2%.

A. Ecotax



B. Ecotax_region

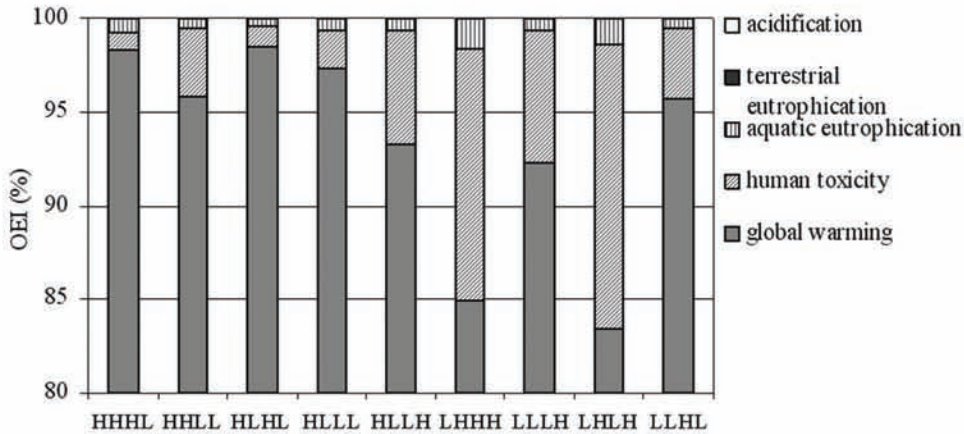


Figure 5.3 The relative contribution of different impact categories to the overall environmental impact for nine study regions using two valuation methods: A. Ecotax_regions , B. Ecotax.

Impact on reduction costs and selection of the cost-effective measures

The effect of different valuation factors on the total reduction costs and selection of cost-effective emission reduction measures was analysed for the reference Policy scenario aiming at 20% reduction in the overall environmental impact (OEI) by dairy cattle in the Czech Republic, relative to the No Control scenario in 2020.

The total reduction costs at the national level differ per valuation method. In the reference Policy scenario using Equal valuation factors the costs of reducing OEI by 20% are 12 MEuro. The lowest reduction costs are found when using DTT2 valuation factors (7 MEuro) while the highest costs are for the Ecotax and Ecotax_region valuation factors (29 MEuro). The high costs for the Ecotax and Ecotax_region methods can be explained by the fact that these value global warming as the most important environmental problem. Therefore, the model selects measures aiming at reduction of greenhouse gases which are relatively expensive. When using Equal and Distance To Target valuation factors the human toxicity and acidification are valued as relatively important. However, the contribution of these impact categories to OEI is small (see Figure 5.1) and therefore increasing their importance does not have a significant impact on the total reduction costs. DTT2 ranks aquatic eutrophication and human toxicity as most important problems, which results in lower costs compared to the reference scenario.

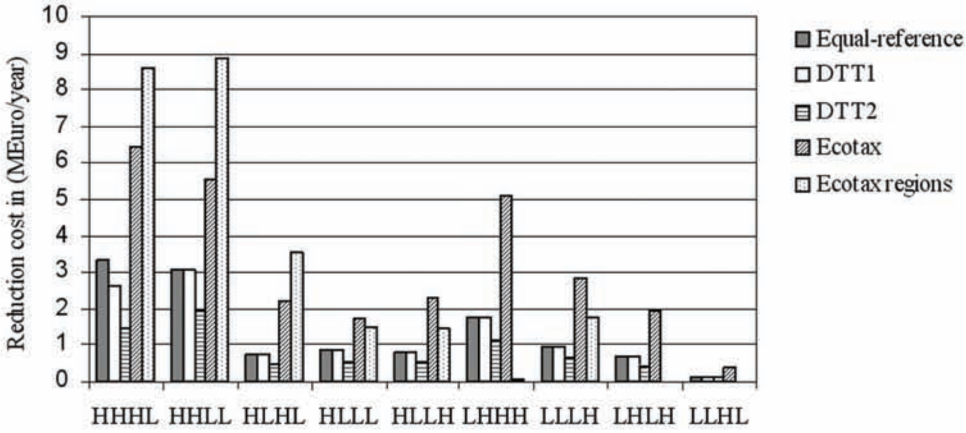


Figure 5.4 Regional costs of reducing the overall environmental impact (OEI) by dairy cattle in the Czech Republic by 20% relative to the No Control Scenario as calculated by different valuation factors: Equal method (= reference Policy scenario), Distance to target (DTT1 and DTT2), Ecotax and Ecotax-region.

At the regional level the costs also depend on the valuation factors used. Figure 5.4 shows that for the Ecotax_region approach costs are highest for the regions with high dairy cattle intensities (HHHL, HHLL, HLHL) while for low intensive regions the costs are lower. In fact high intensive regions have high taxes for global warming, since the environmental indicators used for this problem is directly related to dairy cattle numbers. In all study regions the lowest costs are found for DTT 2.

The selection of emission reduction measures differs per valuation factor. In comparison to the reference Policy scenario (Equal method) we can conclude that there are measures which are selected for all valuation factors (Table 3). These are manure efficiency improvement, grazing restriction and to a less extent manure timing application. As discussed above, reducing the OEI while using the Ecotax and Ecotax_regions valuation factors requires selection of measures reducing greenhouse gases (mainly methane as the main contributor to global warming). These measures reduce methane either directly or as a side-effect, and include propionate, stable adaptation; low nitrogen feed and covered manure storage.

Table 5.3 Ranking of measures according to frequency of selection in cost-optimal combinations to measures in reduce OEI by 20% calculated by the DAIRY model.

Measures	Ranking in cost-optimal combinations			
	Reference	DTT1+DTT2	Ecotax	Ecotax_region
Low nitrogen feed	3	3	-	7
Stable adaptation	-	-	4	5
Covered manure storage	-	-	6	6
Manure timing application	1	1	5	4
Manure efficiency improvement	1	1	1	1
Grazing restriction	2	2	2	2
Propionate	-	-	3	3

Note: 1 means the measure is selected most frequently in combinations of measures to reduce OEI by 20%;
7 indicates least frequent selection
(-) means that measures is not selected.

5.5.2 Case II: Animal management

In Case II we explore how different assumptions on animal management, cattle number and milk yield affect the result of the DAIRY model. First, two animal management practices for dairy cattle are compared: a straw and slurry-based housing system. The contribution to emissions of NH_3, NO, N_2O, CH_4, PM_{10}, $PM_{2.5}$ and NO_3 from these two housing systems differ considerably. In the comparison to reference scenarios (90% straw-based), a change to 90% slurry-based systems would lead to 30% higher emissions of ammonia. However, NO_3 losses are 23% lower and emissions of PM_{10} and $PM_{2.5}$ 40% lower. These changes in emissions influence the overall environmental impact. The overall environmental impact in the reference scenarios with 90% straw-based systems is 18% higher than when assuming that 90% of the dairy cattle are kept in slurry-based systems (NOC-straw and POL-slurry) (Fig.5.5). Global warming and aquatic eutrophication remain the most important environmental problems for both animal management systems.

For Case II we also define five alternative cases with different dairy cattle numbers and milk yield (see Section 5.4). These cases are compared with the reference scenarios: No Control and Policy scenario. All are analysed for straw-based and slurry-based systems. Figure 5.5 shows that straw-based systems cause a larger overall environmental impact than slurry-based systems, regardless of the assumed number of cattle and milk yield. The lowest level of OEI is achieved when assuming decreasing number of cattle, while milk yield is not changing (LC-NM). The largest overall environmental impact is calculated when assuming increasing number of dairy cattle kept in straw-based system with high milk yield (HC-HM). In addition, Figure 5.5 indicates that the results are more sensitive to changes in number of cattle than to changes in milk yield.

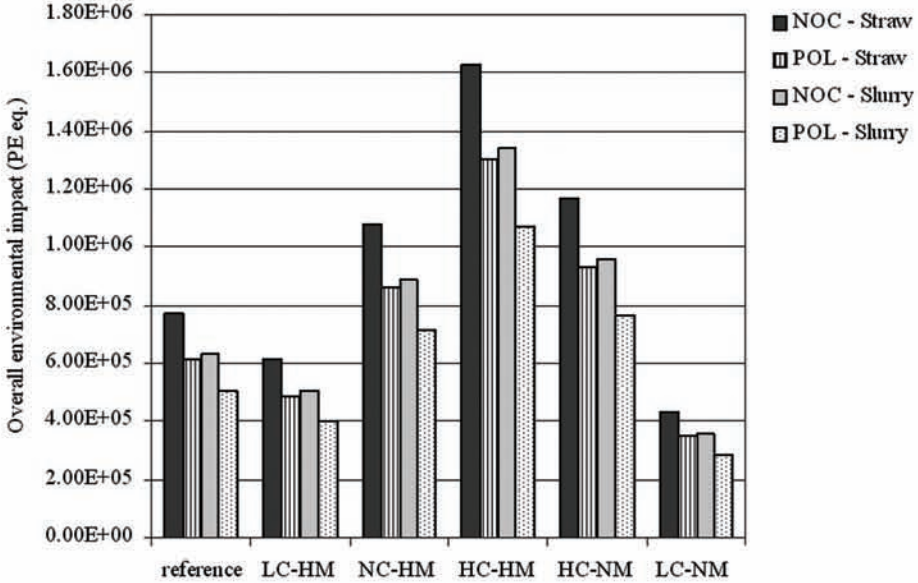
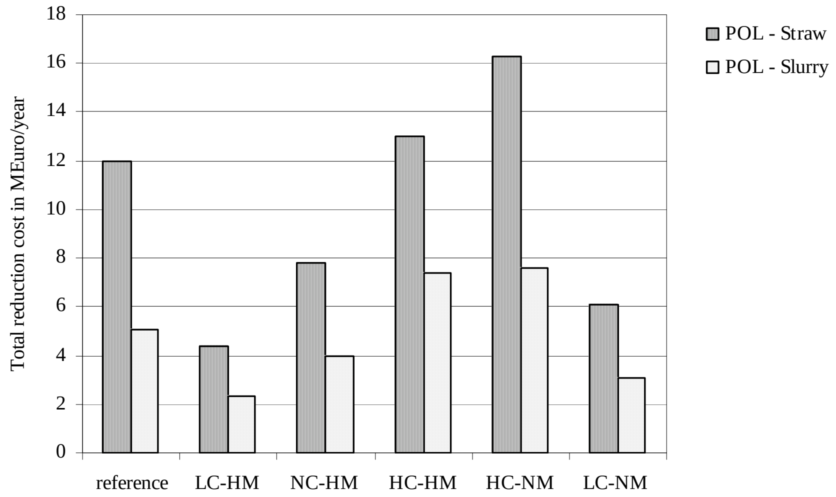


Figure 5.5 Overall environmental impacts by dairy cattle in the Czech Republic in 2020 for Case II. Results for reference scenarios: No Control (NOC) and Policy (POL) compared to alternative cases. **Note: LC-HM:** low number of cattle, high milk yield, **NC-HM**: no change in cattle, high milk yield, **HC-HM:** high number of cattle, high milk yield, **HC-NM:** high number of cattle, no change in milk yield, **LC-NM:** low number of cattle, no change in milk yield. All analyses are presented for 90% straw-based or 90% slurry-based systems.

The reduction costs to achieve a 20% reduction in OEI relative to the uncontrolled scenarios (NOC) are shown in Figure 5.6. Total costs to reduce OEI by 20% relative in reference scenario are 12 MEuro (POL - straw) which is 0.005 MEuro per kiloton of milk produced. The calculated costs are 13 MEuro for the cases assuming increasing number of dairy cattle and milk yield (HC-HM) which equals to 0.002 MEuro per kiloton of milk, 17 MEuro when only cattle numbers increase (HC-NC) which is around 0.005 MEuro per kiloton of milk. When assuming that cattle are kept in slurry-based systems, the costs are considerably lower (2.3 to 7.6 MEuro) in comparison to straw-based system in all cases. The lowest costs are calculated for cases assuming reduced cattle numbers with increased milk yield. In LC-HM slurry-based case, the costs are 2.3 MEuro which is 0.001 kiloton of milk. It should be noted that these costs do not include the costs of closing down farms which is needed to reduce cattle numbers, or the costs of changing from straw-based to slurry-based, or increasing milk yield of cattle.

A. Total costs per year



B. Total costs per milk produced

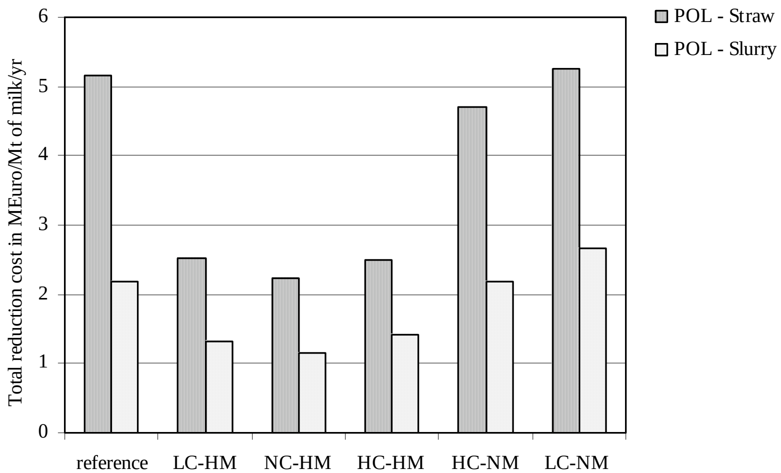


Figure 5.6 Total costs to reduce overall environmental impact (OEI) by 20% in 2020 relative to the No Control scenario for the case at stake (for case descriptions see Table 5.2 and Figure 5.5). **A:** Total costs per year, **B:** Total costs per kiloton of milk produced

5.3. Case III: Region-specific applicability of emission reduction measures

To analyse the effect of region-specific applicability (RSA) of emission reduction measures on the total reduction costs of emission reduction within the regions as well as at the national level, two alternative cases are analysed here. These are compared with the reference Policy scenario using Equal valuation factors aiming at 20% reduction of OEI relative to the No Control scenario. In the first alternative the region-specific applicability is combined with a valuation method considering all environmental problems equally important (RSA_Equal) and second, region-specific applicability is combined the Ecotax_region valuation factor (RSA_Ecotax_region) (See Case I).

Figure 5.7 indicates that in the reference Policy scenario the reduction costs is highest in regions with high dairy cattle production intensity (HHHL, HHLL) but also in region with a low intensive region LLLH. The restriction on application of reduction measures while considering all environmental problems equally important cause an increase in costs at national level from 12 MEuro to 50 MEuro. At the regional level the increase in costs is ranging between 39% in study region HLLH and LHLH and by more than 900% in study region LHLH in comparison to the reference Policy scenario.The relatively high reduction cost in low intensive region LLLH is caused by lesser restriction on applicability of emission reduction measures due to low sensitivity of regions to acidification, terrestrial and aquatic eutrophication.

In second alternative case the restriction on the application of measures is combined with Ecotax_region valuation factors. This reduces the increase in cost in comparison to RSA_Equal case. Total costs are calculated to be 24 MEuro. At the regional level, the total reduction costs are lower than in RSA_Equal case, except a region HHLL where the cost is amongst highest. The reason is that manure timing application is applied to larger extend then in other regions because of low sensitivity to acidification and terrestrial eutrophication (see Table 5.2A in the Appendix).

Clearly, the changes in reduction costs are driven by the selection of emission reduction measures by DAIRY model in cost-optimal combinations (Table 5.2). Some of the most costs-effective measures used in the reference Policy scenario are classified to cause unintended side-effects on other emissions and as a result, their applicability was in some regions changed (for details see section 5.3 and Table 5.3A). This is the case for improved timing of manure application, for which the applicability was reduced in study regions with ecosystems potentially sensitive to acidification and terrestrial eutrophication. Consequently, other emission reduction measures were selected by the DAIRY model, which are more expensive. It is, however, interesting to note that manure efficiency improvement is the most frequently selected measures applied not only in reference Policy scenario, but also in both alternatives. In addition in reference Policy sceanario and “RSA_Equal” case also low nitrogen feed and grazing restriction are selected. In “RSA_Equal” a more wide diversity of measures is selected. These include stable adaptation, covered manure storage, probiotics and storage with minimum leaching. Selection of these measures leads to increased reduction costs. In the RSA_Ecotax_region case propionate is most frequently used, because as discussed in Section 5.4 global warming is considered the most important environmental problem in this case and, therefore, the model selects mainly measures to reduce emissions of methane.

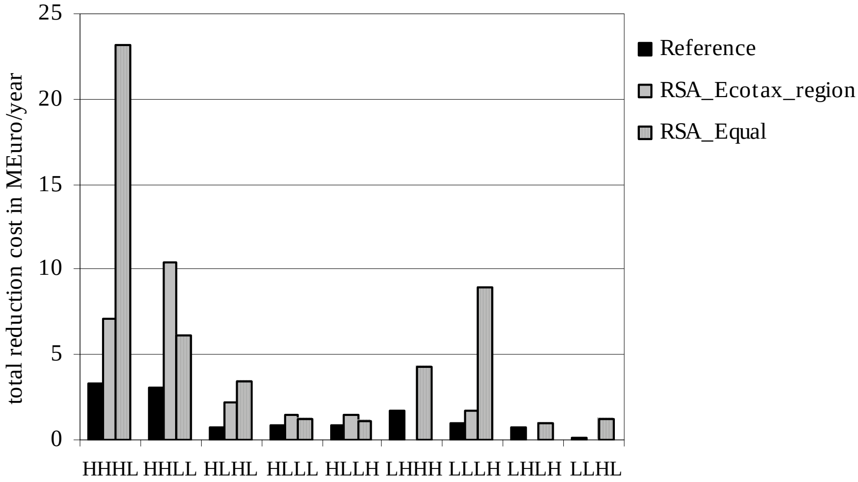


Figure 5.7 Total costs to reduce OEI by 20% in 2020 for the reference policy scenario and two alternatives assuming region-specific applicability (RSA) combined with Equal and Ecotax_region valuation factors.

Table 5.3 Ranking of measures according to frequency of selection in cost-optimal combinations to measures in reduce OEI by 20% calculated by the DAIRY model.

Measures	Reference	RSA_Equal	RSA_Ecotax
Low nitrogen feed	3	2	-
Stable adaptation	-	8	5
Covered manure storage	-	9	-
Manure timing application	1	4	4
Manure efficiency improvement	1	1	1
Grazing restriction	2	3	3
Propionate	-	5	2
Probiotics	-	7	-
Storage with minimum leaching	-	6	-

Note: 1 means the measure is selected most frequently in the optimal combination of measure to reduce OEI by 20%, 7 indicates least frequent selection (-) means that measures is not applied

5.6. Discussion and conclusions

We explored possible future trends in environmental impact by dairy cattle in the Czech Republic up to 2020. To this end we used a linear optimisation model DAIRY, and analysed how the model output is affected by (I) different views of hypothetical model users on the importance of environmental problems, (II) changes in projected dairy cattle numbers, animal management, and (III) changes in application of emission reduction measures.

We analysed two reference scenarios: a No Control and a Policy scenario. The results indicate that the overall environmental impact of dairy cattle is mainly associated with global warming and aquatic eutrophication. These two environmental problems account for more than 95% of the overall environmental impact. The main compounds responsible for these impacts are methane and nitrate. In addition, our analysis indicates that 90% of the overall environmental impact by dairy cattle comes from leaching and housing including enteric fermentation of dairy cattle. The costs of reducing the overall environmental impact by 20% relative to the No Control scenario are 12 MEuro. To achieve this target, the DAIRY model selects manure efficiency improvement and manure timing application in the most cost effective combinations of measures. In the following we summarise how the results of the reference scenarios change as a result of changes in selected model parameters (Table 5.4a,b,c).

The results of Case I (Table 5.4a) indicate that the DAIRY model is relatively robust in the identification of the most important environmental problems. Global warming and aquatic eutrophication were identified to have largest share in the overall environmental impact regardless of valuation factors used. However, as indicated in Table 4a their relative contribution may change when using different valuation factors. Global warming is responsible for about 26% of the OEI in 2020 in the reference No Control scenario using Equal valuation factors. When other valuation factors are used the share of global warming in OEI may change to 26% - 97%. Aquatic eutrophication accounts for about three quarter of OEI in 2020 in reference No Control Scenario. This share may change to 0.1% -85% when using other valuation factors (Table 5.1a). Also the costs depend on valuation factors used. Reduction costs range from 7 MEuro when using DTT2 valuation factors to 28 MEuro when using Ecotax valuation factors. Our analysis indicates that the DAIRY model is robust in terms of measures selected to reduce OEI by 20%. Manure efficiency improvement and grazing restriction are among the selected measures regardless of the valuation factors used. Improvement of the timing of manure application is selected mainly when using Distance To Target valuation factors while propionate is selected when using Ecotax valuation factors.

Table 5.4a Case I (alternative valuation factors): changes in the relative contribution of the environmental problems (GW) global warming and (AE) aquatic eutrophication to 2020 OEI and, costs of reducing OEI in 2020 by 20% compared to cost calculated by reference Policy scenario.

Alternative Cases*	Relative contribution to OEI		Total reduction costs (MEuro/year)
	GW	AE	
Reference/Equal	26%	73%	12
DTT 1	27%	71%	12
DTT 2	14%	85%	7
Ecotax	97%	0.1%	28
Ecotax_region	93%	0.8%	26

* See Table 1a

Case II explores how changes animal management may influence the model results. Variation in dairy cattle number, their milk yield and animal management considerably change the calculated overall environmental impact and reduction costs (Table 5.4b). Changing dairy cattle numbers affects the total overall environmental impact and the reduction costs more than changes in milk yield. The combined effect of changing animal numbers and milk yield may decrease OEI by up to 53% or increase OEI by up to 112% compared to reference straw-based Policy scenario. The reduction of overall environmental impact of dairy cattle kept in straw-based system is found to be more expensive than in slurry-based system. The reduction costs range from 2 MEuro (slurry-based system: LC-HM) to 16 MEuro (straw-based system: HC-NM) and on a product basis from 0.0011 MEuro per kt of milk produced (slurry-based system: NC-HM) to 0.0053 MEuro per kt of milk produced (straw-based system: LC-NM). Therefore it can be concluded that current practice in the Czech Republic, which is mainly straw-based, is not preferred from environmental or economical point of view.

Table 5.4b Case II (alternative animal management): relative change in overall environmental impact and costs of reducing OEI in the 2020 Case II cases, compared to OEI and costs calculated for the reference: straw-based Policy scenario.

Alternative case	Change in OEI*		Total reduction cost M Euro/yr		Total cost M Euro/ kt milk	
	Straw	Slurry	Straw	Slurry	Straw	Slurry
Reference POL	0%	-17%	12	5	0.0052	0.0022
LC-HM	-20%	-34%	4	2	0.0025	0.0013
NC-HM	+41%	+16%	8	4	0.0022	0.0011
HC-HM	+112%	+75%	13	7	0.0025	0.0014
HC-NM	+53%	+25%	16	8	0.0047	0.0022
LC-NM	-43%	-53%	6	3	0.0053	0.0027

*Compared to the reference POL-straw

In Case III the model is changed such that it includes region-specific assumptions for allocation of reduction measures as compared to national maxima used in the reference Policy scenario. The results indicate that this makes reaching a 20% reduction in OEI more expensive. The region-specific restrictions on applicability of emission reduction measures were related to possible side-effects of these measures on the environment (Table 5.4c). The costs may increase to 50 MEuro when using equal valuation factors which is a more thatn four times the cost as calculated for the reference policy scenario. When using Ecotax_region valuation factors global warming is found the most important environmental problem, the reduction costs are 24 MEuro. This is still 100% higher than in reference Policy scenario. The reduction costs depend on the selected combination of measures. Despite the fact that application of some measures was restricted because of possible side-effects, we may conclude that manure efficiency improvement is one the most promising measures because it was selected often by the model, also when using regions-specific application factors. Manure efficiency improvement includes balanced manure application, maximum manure application standard and limitation of application in sloping grounds.

Table 4c Case III (region specific applicability): Relative contribution of the environmental problems (GW) global warming and (AE) aquatic eutrophication to OEI in 2020, reduction costs relative to reference Policy scenario.

Alternative case	Relative contribution to OEI		Total reduction costs (MEuro/year)
	GW	AE	
RSA_Equal	26%	73%	50
RSA_Ecotax_region	96%	0.1%	24

Our analyses of the three alternative cases (Case I, II, III) indicate that the model DAIRY is robust in indentifying global warming and aquatic eutrophication as two most important environmental problems associated with dairy cattle in the Czech Republic. Environmental policies need to focus on these issues to improve the environmental performance of this sector. Manure efficiency improvement is one of the most promising measures. The lowest overall environmental impact and costs to achieve 20% reduction in OEI are calculated for cases assuming that dairy cattle are kept in slurry-based systems rather than in straw-based system. A relatively cheap way to reduce the overall environmental impact is to focus on aquatic eutrophication while it is relatively expensive only to reduce emissions of greenhouse gases. It is interesting to note that current policies in the Czech Republic largely focus on ammonia and nitrate reduction. Our study indicates that ammonia reduction is not ammonia reduction is not an effective strategy to improve the environmental performance of dairy cattle. In addition, region-specific applicability factors for reduction measures may increase reduction costs considerably.

Our study illustrates the importance of analysing possible future trends in the environmental impact by the agriculture sector in an integrated way. Policy makers and farmers are increasing more aware of the need for environmental improvement and over possible effects of emission reduction measures. This study indicates how an integrated and systematic analysis may help to find optimal solutions.

Appendix 5.A

Table 5.1A Environmental indicators for nine study regions in the Czech Republic as used in the DAIRY model

Impact category	Environmental Indicator (EI)	National average	Study regions								
			1(HHHL)	2(HHLL)	3(HLHL)	4(HLLL)	5(HLLH)	6(LHHH)	7(LLLH)	8(LHLH)	9(LLHL)
Acidification	Critical load for acidity	1582	1284	1749	1320	1727	1712	1533	1589	1656	1839
Terrestrial eutrophication	Critical load for nitrogen	515	509	532	478	555	495	478	588	459	502
Aquatic eutrophication	% of agriculture land in nitrate vulnerable zones	38	52	44	32	27	15	48.5	26.5	64	21
Human toxicity	Population density	130	70	114	73	123	149	177	180	159	92
Global warming	Cows/100ha agric. land	10	14.5	14	12	11	11	6	8.5	7	6

Source: Havlikova et al., (2008)

Table 5.2A Valuation factors used in Case I based on environmental taxes (Ecotax) for Czech Republic as whole ($W_{e,cr}$) and for nine study regions ($W_{e, region}$)

Environmental problem (e)	$W_{e,cr}$	$W_{e, region}$								
		1(HHHL)	2(HHLL)	3(HLHL)	4(HLLL)	5(HLLH)	6(LHHH)	7(LLLH)	8(LHLH)	9(LLHL)
Acidification	0.10	0.10	0.04	0.10	0.04	0.04	0.10	0.10	0.04	0.04
Terrestrial eutrophication	0.20	0.29	0.09	0.29	0.09	0.29	0.29	0.09	0.29	0.14
Aquatic eutrophication	1.20	2.40	1.80	1.50	1.50	1.50	2.10	1.50	1.80	0.60
Human toxicity	3.20	1.60	4.80	1.60	1.60	4.80	4.80	4.80	4.80	1.60
Global warming	3.80	5.70	5.70	5.70	3.80	3.80	1.90	3.80	1.90	1.90

Source: Cenia (2006), Finnveden (2006) and Amann et al. (2006)

Table 5.3A National (reference) and region-specific applicability of emission reduction measures, expressed in % of sources of emissions to which the measure can be applied at maximum

Measures	Reference Applicability (%)	Region-specific applicability (%)								
		1(HHHL)	2(HHLL)	3(HLHL)	4(HLLL)	5(HLLH)	6(LHHH)	7(LLLH)	8(LHLH)	9(LLHL)
Low nitrogen feed	75	100	100	0	100	100	100	100	100	0
Stable adaptation	50	75	75	100	100	100	75	100	75	75
Covered manure storage *Low efficiency*	50	50	50	50	50	50	100	100	100	100
Covered manure storage *High efficiency*	50	50	50	50	50	50	100	100	100	100
Low nitrogen application *Low efficiency*	20	45	20	45	20	45	70	100	70	100
Low nitrogen feed *High efficiency*	20	45	20	45	20	45	70	100	70	100
Timing manure application	50	25	75	0	50	0	25	0	50	25
Manure efficiency improvement	50	50	50	50	50	50	50	50	50	50
Propionate	100	100	100	100	100	100	100	100	100	100
Probiotics	100	100	100	100	100	100	100	100	100	100
Daily spread	30	5	5	55	80	55	5	55	55	55
Anaerobic digestion small scale	75	75	75	75	75	25	25	25	25	25
Anaerobic digestion centralized	75	75	75	75	75	25	25	25	25	25
Storage with minimum leaching	100	100	100	50	50	50	100	50	100	50
Restriction on grazing	30	30	30	5	5	5	30	5	30	5

Note: General assumptions on region-specific applicability

Low nitrogen feed: No adverse side-effects on emissions, but may reduce milk yield. Therefore, it is not applicable in regions with low milk yield.

Stable adaptation: Decreases in ammonia emissions. Therefore higher applicability in regions sensitive to acidification and terrestrial eutrophication, but side-effect increase in nitrate losses therefore lower applicability in regions with large area of agricultural land in nitrate vulnerable zones.

Covered manure storage: Decreases in ammonia, nitrogen oxide and nitrous oxide, but increases methane emissions. Therefore this measure is less applicable to regions with high number of diary cattle

Low nitrogen application: Decreases in ammonia but increase in nitrogen and nitrous oxide and nitrate leaching. Therefore this measure is less applicable in regions with high number of dairy cattle but more applicable in regions sensitive to terrestrial eutrophication

Timing manure application: Decreases nitrate emissions. Therefore, higher applicability of this measure is in regions sensitive to aquatic eutrohication. The measure increase ammonia emissions and nitrous oxide and therefore it is less applicable in regions sensitive to acidification and/or terrestrial eutrophication and with high number of dairy cattle

Manure efficiency improvements: The measure is considered to have no negative side-effect. Therefore, there we assume full applicability of measure.

Propionate: The measure is considered to have no negative side-effect. Therefore, there we assume full applicability.

Probiotics: The measure is considered to have no negative side-effect. Therefore, there we assume full applicability.

Daily spread: Increases in ammonia emissions and nitrate. Therefore this measure is less applicable in regions sensitive to acidification, terrestrial and aquatic eutrophication.

Anaerobic digestion small scale and centralized: The measure is considered to have no side-effect. The applicability is increased in regions with high dairy cattle number, while less in less intensive regions the applicability is lowered.

Storage with minimum leaching: Decreases in nitrate emissions. Therefore higher applicability is in regions sensitive to aquatic eutrophication.

Restriction on grazing: Increases in ammonia, decrease nitrate and nitrous oxide. Therefore, there is no change in applicability of this measure in regions with sensitive to aquatic eutrophication and in regions with high dairy cattle number, while in region sensitive to acidification and terrestrial eutrophication this measure is less applicable.

Appendix 5.B

Descriptions of DAIRY model, for more details see Chapter 4.

Objective function and restrictions (Eq.1)

The objective function is to minimize costs (C) of emission control per study region (sa) and source (p):

$$\text{Min} \sum_{sa}\sum_{p} \mathbf{C}_{\mathbf{sa.p}}(\mathbf{v}_{\mathbf{sa,p}}) \text{ with } v_{sa,p} \text{ as vector with elements } a_{sa,p,n} \quad (1)$$

The model minimizes total costs (C) of abatement to achieve constraints on either emissions (E) (Eq.6), the potential impact (I) (Eq.7) or the overall environmental impact (OEI) (Eq.8-9).

Model Variables (Eq.2-5)

$$C_{sa,p} = \sum_{n\in N} a_{p,n,sa} \times c_{p,n} \times A_{p,sa} \quad (2)$$

$$E_{p,x,sa} = \sum_{i\in I} ef_{p,i,x,sa} \times A_{p,sa} \times \left(1 - \sum_{n\in N} a_{p,n,sa} \times r_{p,i,n,x}\right) \quad (3)$$

$$I_{e,sa} = \sum_{p\in P}\sum_{x\in X} E_{p,x,sa} \times CF_e \quad (4)$$

$$OEI_{sa} = \sum_{e\in E} \frac{I_{e,sa}}{N_e} \times W_e \quad (5)$$

Costs (C) of emission reduction for study region (sa) and source (p) are a function of application rate (a) of reduction measures, unit costs, and activity rates (cattle numbers). Emissions (E)of pollutants (x) from sub-source (i) of source (p) in study region (sa) are a function of emission factors (ef), activities (A), application rate (a) and reduction potential (r) of the emission reduction measure (n) . Potential environmental and health impact (I) for impact category (e) in study region (sa) is a function of emissions (E) of pollutants (x) from source (p) and characterisation factors (CF) for environmental impact category (e). CF is region specific for: human toxicity, country- specific for acidification, terrestrial and aquatic eutrophication and worldwide for global warming. The overall potential impact (OEI) in study region (sa) is the sum of the normalized environmental and health impacts for impact category (e) in study are (sa) multiplied with valuation factors (W). For normalization, the potential environmental and health impact at European level (N) is used.

Restrictions (Eq. 6-11)

The total emissions level (E) may not exceed level $\overline{E}$ (Eq.6), potential environmental and health impact (I) of specific impact category (e), may not exceed level $\overline{I}$ (Eq.7). Overall environmental impact (OEI) per study region (sa) or at national level, this may not exceed level $\overline{OEI}$ (8-.9). In addition, there are technology specific constraints for application rate (a) which cannot be lower than 0 and larger than 1(Eq. 10-11).

$$\sum E_{p,x,sa} \leq \overline{E}_{p,s,sa}$$

(6)

$$\sum I_e \leq \overline{I}_e$$

(7)

$$\sum OEI_{sa} \leq \overline{OEI}_{sa} \tag{8}$$

$$\sum OEI \leq \overline{OEI} \tag{9}$$

$$\sum a_{p,n} \leq 1 \tag{10}$$

$$\sum a_{p,n} \geq 0 \tag{11}$$

References

Amann, M., Asman, W., Bertok, I., Cofala, J., Heyes, C., Klimont, Z., Schöpp, W. and Wagner, F., 2007 Updated Baseline Projections for the Revision of theEmission Ceilings Directive of the European Union. NEC Scenario AnalysisReport #4. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Brink, J.C., 2003. Modelling cost-effectiveness of interrelated emission reduction strategies, the case of agriculture in Europe. PhD thesis. Wageningen University. The Netherlands

Brooke, A., Kendrick, A., Meeraus, R., Raman, R.E., Rosenthal, 1998. GAMS: a user's guide. GAMS Development Corporation, Washington D.C. http://www.gams.com

Cenia, 2008. Czech Environmental Information Agency; Statistical Environmental Yearbook of the Czech Republic for 2005. http://www.cenia.cz/web/www/web-pub2.nsf/$pid/MZPMSFI6XLLF

Dämmgen, U.,Lüttich, M., Döhler, H., Eurich-Menden, B., Osterburg, B., 2006 Calculations of emissions from German agriculture-national Emission Inventory Report (NIR) 2006 for 2004. Part 3: Methods and Data (GAS_EM). Landbouforschung; Volkenrode; Special Issue 291:47-221

Engrstrom, R., Wadeskog, A., Finnveden, G., 2007. Environmental assessment of Swedish agriculture. Ecological Economics; 60: 550-563

Ericsson, O., Finnveden, G., Ekvall, T., Bjorklund, A., 2007. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion Energy Policy; 35:1346-1362

Haushilds, M., and Potting, J.M.B., (Eds), 2004. Spatial differentiation in life cycle impact assessment the EDIP2003 Methodology; Guidelines from the Danish Environmental Protection Agency: Copenhagen

Finnveden, G., Eldh P., Johansson, J., 2006. Weighting in LCA based on ecotaxes. Development of a mid point method and experiences from case studies. International Journal of Life Cycle Assessment; Special Issue 1: 81-88.

Havlikova, M., Kroeze, C., Huijbregts, M., A., 2008. Environmental and health impact by dairy cattle livestock and manure management in the Czech Republic. Science of the Total Environment; 396:121-131

Havlikova, M., Kroeze C. Cost-effective reduction of environmental impact by dairy cattle in Czech Republic. Submitted to Journal of Environmental Management

Johansson, J., 1999. A Monetary Valuation Weighing Method for Life Cycle Assessment Based on Environmental Taxes and Fees. Master thesis. Department of Systems Ecology, Stockholm University

Lindeijer, E., 1996. Normalization and valuation, in: Towards a methodology for life cycle, in: Towards a methodology for life cycle impact assessment. H.A. Udo de Heas (ed), Society of Environmental Toxicology and Chemistry (SETAC), Brussels. pp 75-93

Masquera, J., Hol, J.M.G., G.J. Monteny, 2006. Gaseous emissions from deep litter farming systems for dairy cattle. International Congress Series 1293:291-294

Oenema, O., Bannink, A., Sommer, S. G., Velthhof, G., 2001. Gaseous nitrogen emissions from livestock farming systems p.255-289. *In* Follet, R.F.and Hatfield, J.L. (Eds) Nitrogen in the Environment: Sources, Problems and Management. Elsevier Science B.V

Pluimers, J.C., 2001. An environmental systems analysis of greenhouse horticulture in the Netherlands. PhD Thesis Wageningen University, Netherlands

Seppala, J., Posch, M., Johanson, M., Hettelingh, J-P., 2006. Country Dependent Characterisation Factors for Acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator. Int. J LCA; 6: 403-416

Soleile, S., 2005. How to deal with the uncertainties of the RAINS model. A few suggestion. Integrated Assessment Modelling for Air Pollution. A seminar on the RAINS methodology, January 20-21, 2005 at IIASA. http://www.iiasa.ac.at

Stranddorf, H.K, Hoffmann, L., Schmidt, A., 2005. Update on impact categories, normalization and weighting in LCA. Selected EDIP-97data. Environmental project nr.995, 2005. Miljoprojekt. Danish Ministry of the Environment. Copenhagen, Denmark: Environmental Protection Agency; 290pp.

Van Asselt, M.B.A., Rotmans, J., 1996 Uncertainty in Perspective. Global Environmental Change. Vol.6 No.2, 121-157

Zhou, V., Schoenung, J.M., 2007. An integrated impact assessment and weighting methodology: Evaluation of the environmental consequences of computer display technology substitution. Journal of Environmental Management; 83:1-24.

CHAPTER 6 Conclusion and discussion

6.1. Introduction

European agriculture significantly influences the environment and human health. Current environmental policies aim at reducing the negative impacts of emissions of air, soil and water pollutants. Research and policies nowadays typically deal with different emissions and pollution problems separately. However, there is a tendency towards integrated policies, taking into account possible linkages between human activities, emissions, environmental impacts and policies.

This study focuses on agricultural activities in the Czech Republic. During the last decades, there have been large changes in agriculture practices associated with the transformation from a centrally planned economy to a market oriented economy. This implies many new regulations to which the country has to comply. Chapter 1 presents an overview of the changes in agricultural practices during the last few decades in the Czech Republic and lists current environmental policies in European agriculture. This thesis as whole contributes to the literature related to integrated assessments of the environmental impact by agriculture at the national and sub-national level. Therefore, is relevant for international studies and models used at the European level for international negotiations on environmental targets.

The overall objective of this thesis is to assess the future environmental impact by the agricultural sector in the Czech Republic. National and European environmental policies and the interaction between human activities and environmental trends are considered. The novel aspect of this thesis is to include process-based emission factors in a region specific model to quantify both emissions and their potential environmental and health impacts. Additionally, these results are used in another purposely developed model to assess the reduction costs involved.

In the following, first the main conclusions of this study are drawn (6.2). Next, section 6.3 presents a comparison of the results with other studies. Section 6.4 discusses the strengths and weaknesses of the model used in this thesis. Section 6.5 indicates possible implications of the results for environmental policy in the Czech Republic. Recommendations for future research are presented the last section.

6.2 Conclusions

In order to meet the objectives of this thesis four research aims were formulated (Chapter 1). Our conclusions regarding the four research aims are presented here.

Complete, detailed and consistent estimates of agricultural emissions are essential for integrated assessment methods and models. The first research aim is therefore to comprehensively analyse different **emission estimation methods** to be used for an integrated assessment of environmental problems by agriculture at the national scale.

Our approach for comprehensive evaluation of emission estimation methods is based on three steps (1) Comparison of emission estimation methods with respect to specific characteristics, (2) Scoring of methods based on quality and country-specific criteria and the extent to which interrelations between pollutants are accounted for, and (3) Multi-Criteria Analysis taking into account the relative importance of the different criteria. These criteria include quality criteria, country specific criteria and to what extent emission estimation methods consider interrelations.

We applied this evaluation framework in a case study focusing on the agricultural sector in the Czech Republic. This indicates that there are large differences in emission estimation methods. Nevertheless, step 2 and step 3 resulted in the same subset of methods that are to be preferred. Analyses of illustrative examples of selected methods indicate that the IPCC Guidelines best perform in terms of quality criteria, while the model INITIATOR (De Vries et al., 2003) and the detailed approach in the EMEP/CORINAIR Guidebook better account for specific agricultural and environmental conditions. In addition, INITIATOR takes into account important interrelations between pollutants.

We conclude that integrated assessments of the environmental problems associated with the agricultural sector at the national scale preferably combine emission factors based methods, process-based methods and regression analyses. However, there is still a lack of the studies applying such combinations for emission inventories.

The potential environmental impact of agricultural emissions is influenced by many factors, including, for example, the location of the sources of emissions and the sensitivities of ecosystems. For effective allocation of emission reduction measures all these factors should be considered. The second research aim of this thesis, therefore, evaluates the **potential environmental and health impact** by dairy cattle at the sub-national level by applying a site-dependent methodology.

We argue that in an integrated assessment it is not always needed to quantify all environmental impacts explicitly. Instead, indicators can be used for different impact categories. In this thesis different characterisation factors available in the literature were compared and evaluated with respect to usefulness for a study focusing on dairy cattle in the Czech Republic. We conclude that for our case the most appropriate set of characterisation factors are those from Sepällä et al. (2006) and EDIP (2003). These factors are based on the most recent data and best available scientific models and take into account, where possible, national and regional differences. However, a weakness of these combinations may be potential internal inconsistencies.

Within the Czech Republic, there are large regional differences in the environmental and health impacts per unit of agricultural production. In some regions, the acidifying, eutrophying and global warming impact of dairy cattle is calculated to be up to three times the national average, and largely depending on the dairy cattle intensity. Aquatic eutrophication is found to be a problem in regions with relatively high eutrophying emissions per hectare of so-called nitrate vulnerable zones. A large number of people living in rural areas are potentially exposed to human toxicity problems caused by emissions from dairy cattle.

Our analysis may help to indicate which regions within the Czech Republic are more appropriate than others for dairy cattle production, from an environmental point of view. This may add to the development of agricultural and environmental policies. It can, for example, be useful to assess the effects of implementation of Common Agriculture Policy (CAP) reform in the Czech Republic.

The emission estimation methods and potential assessment of the environmental impact are integrated into a new linear optimisation model to analyse the **cost-effectiveness of policy measures** to reduce environmental impact of dairy cattle in the Czech Republic for the current situation and to **explore future trends up to 2020**.

We developed a linear optimisation model which combines emission factors in part derived from a process-based model, with site-dependent characterisation factors that take into account national environmental characteristics for acidification, terrestrial and aquatic eutrophication and regional characteristics for the assessment of human toxicity. Global warming is estimated based on site-generic indicators. An overall environmental impact (OEI) indicator is used to assess the environmental performance of dairy cattle in the Czech Republic. The DAIRY model values all environmental problems equally important.

Our results show that the potential environmental and health impact of dairy cattle has been decreasing over time since 1990. In a scenario that assumes no emission control (No Control scenario), the 2020 environmental impact is 9% lower than in 2005 as a result of continued decreasing cattle numbers. In addition, applying only technical measures to reduce ammonia emissions may result in a 10% reduction of the overall environmental impact in 2020 relative to the situation in 2005. Implementation of technical measures to reduce emissions of ammonia, greenhouse gases and nitrate together, may result in 30% reduction of overall environmental impact in 2020 relative to 2005. These reductions reflect the technical potential of the measures included in the DAIRY model regardless of costs of these measures.

Next, we used the DAIRY model to indentify cost-effective combinations of reduction measures to achieve specific environmental targets. In these optimised scenarios, the overall environmental impact by dairy cattle is 1-30% lower than in the No Control scenario, while the reduction costs range between 0.2 and 16 MEuro. These differences are caused by scenario assumptions and not by differences in model design. We can conclude that technical emission reduction measures have limited potentials to reduce the environmental impact of dairy cattle. Non-technical measures such as closure of dairy farms are needed to further reduce the environmental impact.

It is interesting to note, that reduction of nitrate and methane is selected first by the model in cost-effective scenarios. Current environmental policies in agriculture in the Czech Republic focus on acidification and terrestrial and aquatic eutrophication. This indicates that the current focus of Czech environmental policy is not cost-effective.

Our results indicate that cost-optimal solutions at the national level are not always the cheapest solutions at the regional level. The IMPACT scenario which aims to reduce acidification, terrestrial and aquatic eutrophication, global warming and human health problems simultaneously, is cost-effective at the national level. However, for specific regions it is rather expensive. In a way, these regions invest in solutions that keep costs at the national level lowest.

The robustness of the model outputs is important for potential model users. Environmental models like DAIRY are surrounded with many uncertainties. Therefore, model output related to **future environmental impacts** is explored as affected by different views of model users on the importance of environmental impact, projected dairy cattle numbers and animal management and different assumed application of emission reduction measures.

Two reference scenarios were analysed: a No Control scenario reflecting a hypothetical case with no implementation of emission reduction measures, and a Policy scenario aiming at cost-effective reduction of OEI by 20%. The overall environmental impact of dairy cattle is mainly associated with global warming and aquatic eutrophication. These two environmental problems account for more then 95% of the calculated overall environmental impact and are largely associated with methane and nitrate. 90% of the overall environmental impact by dairy cattle is from leaching and housing including enteric fermentation of dairy cattle. The costs of reducing the overall environmental impact by 20% relative to the No Control scenario are 12 MEuro. Manure efficiency improvement and improved manure timing application are selected as the most cost effective measures.

Calculating an OEI indicator requires valuation of different environmental problems. We argue that this valuation needs to be user-defined. The default version of the DAIRY model set up assigns each environmental problem equal valuation factors. However, model users may prefer a different weighting of the environmental problems. Therefore, we changed the model using different sets of valuation factors, reflecting different hypothetical views on the environment. Our analysis reveals that global warming and aquatic eutrophication are still the two most important environmental problems regardless of the valuation factors used. However, the relative shares of these two in the overall environmental impact depend on valuation of the environmental impact categories. This, in turn, has an impact on the costs of reducing overall environmental impact, because it is cheaper to reduce emissions of nitrate than emissions of greenhouse gases.

Our analysis indicates that the DAIRY model is sensitive to variation in animal numbers, milk yield as well as in type of animal management system. We found that the changes in animal numbers influence the overall environmental impact and the reduction costs more than changes in milk yield. In addition, relatively high reduction costs are always found for cases in which no changes in milk yield are assumed, regardless of animal numbers. Dairy cattle kept in slurry-based systems have a better environmental performance than dairy cattle kept in straw-based systems. Clearly, reducing the overall environmental impact of dairy cattle kept in straw-based systems is more expensive than in slurry-based system. It can be concluded that current practice in the Czech Republic, which is mainly straw-based is not effective from an environmental nor from an economical point of view.

It is interesting, that applying region-specific restrictions on the applicability of emission reduction measures related to possible side-effects of these measures lead to a considerable increase in reduction costs. However, manure efficiency improvement, which includes balanced manure application, maximum manure application standard, and limitation of application in sloping grounds, was selected in the reference Policy scenario as well as in alternative cases with region-specific restrictions on applicability. We may conclude that manure efficiency improvement is a robust option.

The changes in the model assumption on (i) valuation factors used, (ii) projected cattle numbers and animal management, and (iii) applicability of emission reduction measures, changed the calculated costs of 20% reduction in overall environmental impact relative to No Control scenario. These costs range from 7 to 26 MEuro for different valuation factors, while for changes in animal management the costs range between 2 and 16 MEuro. The changes in applicability of emission reduction measures lead to costs ranging from 24 to 50 MEuro. These results demonstrate how different agricultural practices may possibly influence the costs of environmental policy.

6.3 Comparison with other studies

There are many different approaches to assess the environmental impact of agriculture. In this thesis the linear optimisation model DAIRY is developed to assess the current and future potential environmental impact, and to find cost-optimal solutions at the national and regional level. The model can be used to analyse individual or multiple environmental problems. In the following, we confront our approach with selected other studies on the environmental impact of agriculture and discuss advantages and disadvantages of our methodological choices.

The DAIRY model has been developed based on the model by Brink (2003) and on the GAINS/RAINS model (Amann et al., 2007). Both models are described in Chapter 1. Novel aspects of the DAIRY model include a number of new features such as region and country specific emission factors derived from the process-based model GAS_EM (Dämmgen et al., 2006) and site-dependent characterisation factors for most impact categories (acidification, terrestrial and aquatic eutrophication and human toxicity (Potting and Hauschild, 2006)). In addition, one aggregated indicator referred to as the OEI is used to analyse the effects of simultaneous reduction of different pollutants. Our DAIRY model adds to the literature by providing a sub-national assessment of dairy cattle. This is particularly relevant for checking and complementing large-scale assessment models (e.g. GAINS/RAINS) which are used extensively to support European environmental policy. A national study as performed for this thesis describes in more detail the various parts of integrated modelling and may provide more region and country-specific information. In addition, the DAIRY model is one of the first models dealing with agriculture in the Czech Republic. Even for Central and Eastern European countries in general, currently only few models exist (Leip, 2005).

Thomassen (2008) used Life Cycle Assessment (LCA) to assess the environmental impact of dairy cattle production systems in The Netherlands. In her study she compares organic and conventional types of dairy farms. Like Thomassen (2008) we also used methods from Life-Cycle Impact Assessment (LCIA): (i) classification of impact categories, (ii) characterisation, (iii) normalisation and (iv) weighting. Thomassen (2008) limited herself to the first two steps while in the present study all four steps were performed. In addition, Thomassen (2008) ignored spatial consideration in the characterisation step despite of the fact that there is extensive methodology available. Reap et al. (2007) and Potting and Hauschild (2006) indicate that spatially explicit methods are currently quite ofthen ignored by LCA users and suggest and motivate for their application. In Chapter 3, we demonstrate the usefulness of application of site-dependent characterisation factors at the regional level. In fact, the DAIRY model analyses may be considered as one of the few comprehensive applications site-dependent characterisation factors currently available.

The present study and the study by Thomassen (2008) differ with respect to system boundaries. The DAIRY model considers only processes which can be influenced by management at the farm level while Thomassen (2008) considers also purchased pesticides, fertilizers and concentrates, and the use of diesel and electricity. These off-farm processes may influence the environmental performance of dairy farms.

Like Brink (2003) we included side-effects of emission reduction measures (Chapter 4) on other pollutants in the DAIRY model. A difference with Brink (2003) is that the DAIRY model includes not only ammonia, nitrous oxide and methane but also emissions of nitrogen oxide, particulate matter and nitrate. The DAIRY model, therefore, includes measures to reduce nitrate which may as a side-effect reduce other pollutants such as nitrous oxide and ammonia. This may counter balance an increase in nitrous oxide emissions due to ammonia emission reduction measures which Brink (2003) identified as an important issue. Oenema (2007) showed that nitrate emission reduction measures may have both decreasing as well as increasing effects on both ammonia and nitrous oxide. This agrees with our results for the IMPACT scenario (Chapter 4) which sets a target for reduction of the OEI of dairy cattle. Manure efficiency improvement was selected as one of the most cost-effective measures in this IMPACT scenario. This may have a decreasing effect on all emissions considered here. Improved timing of manure application was also found to be cost-effective, but may lead to increased ammonia emissions.

6.4 The model: strengths and weaknesses

The DAIRY model like many other models analyses complex environmental problems by agriculture through many simplifications. The model should be always interpreted while taking into account the scope and limitations of the model. Models never give exact answers to questions of policy makers or farmers. They can, however, be used to explore possible solutions to problems, given the knowledge of that problem. The DAIRY model is described in detail in Chapter 4 and extensively applied in Chapters 4 and 5. Several strengths and weaknesses of DAIRY model became obvious from the analyses and these are discussed below. Table 6.1 summarises the main strengths and weaknesses of the DAIRY model.

Table 6.1. Overview of main strengths and weaknesses of the DAIRY model

Characteristics	Strengths (+)	Weaknesses (-)
Modelling approach	Covers whole cause-effect chain. Transparent and relatively simply.	Non-linear relations are not explicitly modelled.
Scope of the analysis	Comprehensive and detailed analysis of dairy cattle production at the regional level.	Focus is only on dairy cattle, no comparison with other sectors.
Aggregation of study regions	Qualitative information on environmental indicators reflects differences and similarities in environmental and agricultural conditions between administrative regions.	No change over time in the number of regions as environmental and agricultural conditions change over time.
Emissions included	Comprehensive and consistent with international methods.	Phosphorus, heavy metals, non-methane volatile organic compounds, carbon dioxide and odour are not included.
Environmental impact	Complete assessment of impact categories. Site–dependent characterisation factors reflect country-specific characteristics	Region-specific indicators for acidification, terrestrial and aquatic eutrophication are not included.
Overall environmental impact	Relatively straightforward and easy to use for decision making Allows for benchmarking for regions and farms	Possible loss of information through aggregation. Valuation factors are subjective, but no model users were consulted.
Reduction measures	Complete set of technical reduction measures and their costs.	No region-specific costs and reduction factors.
Model application	Both scenario analysis and optimisation can be performed.	-

Modelling approach

The DAIRY model is a static optimisation model minimising total abatement costs to meet restrictions on emissions, individual environmental impact categories and the overall environmental impact. One of the main strengths of the DAIRY model is that it covers the whole cause-effect chain of environmental problems caused by dairy cattle, while being transparent and relatively simple especially when it is used for policy purposes. This is associated with the choice to develop the DAIRY model as a linear optimisation model and not as a non-linear. The relatively large number of pollutants, environmental problems, emission reduction measures and possible interactions between them include many non-linear relations which may lead to a large complexity of the model and, as a consequence, loss of transparency and understandability for policy makers. Brink (2003) argues that changing from a linear to a non-linear model would result in optimisation problems caused by an increasing size of the model. However, relatively simple parameterisation may not be always desirable, especially when calculating pollutant fluxes. Therefore, a strength of the

DAIRY model is that it uses emission factors for each study region in the Czech Republic derived from the process-based model GAS_EM (Dämmgen et al., 2006). This allows to some extent to differentiate regional conditions. In non-linear models coefficients are dependent on other model parameters and are not constant. For example, the amount of nitrogen flowing through the farm is dynamically changing through the different stages (excretion – pasture – housing – storage - application) depending on the application rate of emission reduction measures in each stage. The DAIRY model linearises this non-linear process by using constant values for each parameter (stage) to estimate emissions.

Scope of the analysis: dairy cattle
The DAIRY model focuses on dairy cattle production as one of the important agriculture sub-sectors in the Czech Republic. This could be seen as a strong point because it allows for a comprehensive analysis at the sub-sector level. The results are highly relevant for farmers and policy makers focusing at dairy cattle only. However, such separate analyses for one sector have their weaknesses in broader interpretations of the results for environmental policy. For policy purposes integrated analyses of other agricultural sectors such as pig and poultry are needed as well. This may result, for example, in lower reduction costs for dairy cattle production due to possible cheap pollution reductions in other sectors, or vice versa.

Aggregation of study regions
The emissions, environmental impact and reduction costs are calculated by the DAIRY model in nine study regions in the Czech Republic. These nine study regions represent one or more administrative regions and are characterised based on four environmental indicators. The value of these four selected indicators (number of dairy cows per hectare of agricultural land, critical loads for nitrogen and acidity, percentage of agricultural land located in nitrate vulnerable zones and human population density) are for the year 2004. However, the agricultural and environmental conditions within the regions may change over time and, as consequence, the number and composition of study regions. The dynamic change over time of the environmental indicators is not considered in the thesis and could be subject for further research. Nevertheless, for the purpose of this study we consider our approach appropriate.

Pollutants included
We consider the DAIRY model as complete and comprehensive. The selected pollutants are associated with major element cycles (C, S, N) and are subject to international protocols and directives to which the Czech Republic is party. Nevertheless, from a methodological point of view a weakness is that phosphorus is not fully included in the analysis. Chapter 2 discuses methods to be used for estimating phosphorus and in Chapter 3 we estimate leaching and surface run off of phosphorus (P) from agricultural soils to surface waters after plant uptake and retention as suggested by EDIP2003 (Haushilds and Potting, 2004) for all land types to be 10%. Phosphorus is not included in the DAIRY model (Chapters 4 and 5). There are several reasons for this. In Chapter 1 we proposed to use INITIATOR as process-based model, however, no detailed and sufficient data were available to adopt this model for application to the Czech Republic. In Chapter 2 it was sufficient to calculate P as

fraction of leaching and runoff, regardless of land types, because our main aim was to demonstrate the usefulness of site-dependent characterisation factors at the regional level. However in Chapters 4 and 5 emission factors for P were needed to allow for differences in animal performance and housing systems. A possible solution could have been to calculate phosphorus by farm-gate surplus as Thomassen (2008) did. This is an indicator for accumulation of P in the soil and leaching to surface water. According to Oenema et al. (2007) the Czech Republic has relatively low P surplus in comparison to other European countries. In total they estimated the P balance to be around 35 kg P_2O_5 per hectare per year in the Czech Republic, of which more than 12 kg P_2O_5 per hectare per year are from manure, while mineral fertilizers account around 18 kg P_2O_5 per hectare per year, and around 5 kg P_2O_5 per hectare per year are from grazing and atmospheric deposition. From this balance 25 kg P_2O_5 per hectare per year are removed by harvested crops. In total this results in a P surplus estimated to be around 10 kg P_2O_5 per hectare per year. Clearly, this will differentiate regionally. Based on this we argue that including P may not affect the model output to a large extent.

Emissions of heavy metals (mainly cadmium), non-methane volatile organic compounds (NMVOC), carbon dioxide (CO_2) and odour from dairy cattle livestock and manure management were also not included in the DAIRY model. However, we assume that their contributions to the overall environmental impact are small compared to that of emissions which were included. These emissions are also not reported in the national emission inventories in the Czech Republic. For example, we estimate that emissions of NMVOC from dairy cattle by the GAS_EM model account for 5-6 kt per year, which is indeed low compared to other compounds contributing to ozone formation. Likewise, Howard et al. (2008) indicate that ozone formation by NMVOC from dairy cattle is relatively small.

Environmental impact

The environmental impact of emissions from dairy cattle is not explicitly calculated in the DAIRY model. Rather, the potential environmental impact is estimated by means of site-dependent and site-generic characterisation factors combined with region-specific data (Chapter 3). This model is the first for the Czech Republic to use site-dependent characterisation factors. We consider this as one of the novel aspects of this study. There are, however two limitations to the approach taken. Country-specific characterisation factors were applied to each region to assess the potential contribution of dairy cattle to acidification, terrestrial and aquatic eutrophication. Differences in model results between regions are thus only the results of differences in the emission estimates and in environmental characteristics. It may be more desirable to use characterisation factors which are region-specific. As yet, these are however not available. Obtaining such factors would require region-specific source receptor matrices for atmospheric pollutants and more detailed information about transport of N to surface waters. A second limitation is that the DAIRY model is a static model and that the characterisation factors do not take into account dynamic processes. There are several dynamical processes that are important to consider. For example, Schmieman et al. (1999) show that soil dynamics play an essential role in identifying optimal policies. Their results indicate that current European policies, which are based on a critical load approach instead of on a dynamic analysis of soil quality, are not optimal from both an ecological and economic point of view. Likewise, nitrogen cycling shows some important dynamical aspects. Bakken and Bleken (1998) show how it can take decades to centuries before nitrogen is transported from soils to coastal waters depending on the route of transport (e.g. via sub-soils or freshwaters). Ignoring these temporal characteristics in nitrogen budgets may lead to large errors in estimates of nitrogen loads in aquatic systems. Clearly, deriving characterisation factors by dynamic approaches would be a valuable step in the improvement of the DAIRY model. As yet, such characterisation factors do not exists..

Overall environmental impact
The DAIRY model presents one indicator for overall environmental impact. This requires weighting of different environmental problems. Clearly, policy makers need to weigh the different problems in order to set priorities in environmental policy. The valuation factors used in the DAIRY model reflect the relative importance of environmental problems. We emphasise that these should be user-defined. The advantage of one OEI is that it allows for relatively straightforward use by decision-makers (Constanza, 2000). For example, if the value of OEI is high it means a potentially large environmental impact and vice versa. In addition, the OEI allows for benchmarking of farms, as well as of different regions. One of the major disadvantages of using such overall environmental impact indicators is loss of information due to aggregation (Van Passel, 2007). However, Constanza (2000) argues that underlying detailed information is available, but that decision makers typically do not pay attention to them. Another disadvantage is that, as Van Passel et al. (2007) argue, methods to reach such aggregation are subjective. The valuation factors were extensively analysed in Chapter 5 to evaluate how different valuation may influence the total calculated reduction costs and the selection of cost-effective measures. In Chapter 5 we used five sets of valuation factors as in Pluimers (2001), Hermann et al. (2006), Jawit (2006) and Neto (2007). These valuation factors differ considerably in values assigned to individual impact categories. We conclude that the DAIRY model results are robust in that aquatic eutrophication and global warming are the two most important environmental problems to which dairy cattle contribute, while manure efficiency improvement as reduction measure is always selected by the model in optimal solutions, regardless of the valuation factors used.

Reduction measures
Another strength of the model DAIRY is that it includes a large range of technical reduction measures. These reduce emissions directly, or as a side-effect. The advantage of technical add-on measures is that they are usually not only easy to implement into the model structure, but also in real life. Another category of measures is more related to changes in human behaviour. These are so called non-technical measures. How to include non-technical reduction measures in environmental models has been addressed recently during international meeting under the Convention on Long Range Transboundary Air Pollution (CLRTAP) (see ASTA, 2005). One of the conclusions of this workshop was that it is not easy to define reduction potentials and costs comparable to those of technical reduction measures. In Chapter 4 we include one non-technical measure in the analysis: an arbitrary decrease in cattle number as a result of closing farms in study regions. Tentative

estimates of the costs of closure of farms were taken from the literature (Van Pul et al., 2004). However, it is clear that reducing the number of cattle may influence local employment and the prices of food and development of other economic sectors more than technical reduction measures. And this was not considered in the DAIRY model. The model can, therefore, only be used to assess the potential contribution of non-technical measures to cost-effective emission reduction strategies.

Model application
The DAIRY model can be used for both scenario analysis and for optimisation. This is a strong point, because many regional models limit theirselves either to scenario analysis or to optimisation. In this thesis a model is developed that can be used for both types of analysis. In scenario analysis, agricultural activities and selected reduction measures are considered to be a model input, illustrating the future consequences of policy plans for the environment. The environmental impact of the resulting emissions and the costs of emission reduction measures are the model output. In optimisation analysis it is possible to identify the most "efficient" set of reduction measures to achieve an environmental target. This target is user defined and input to the model (Fig. 6.1).

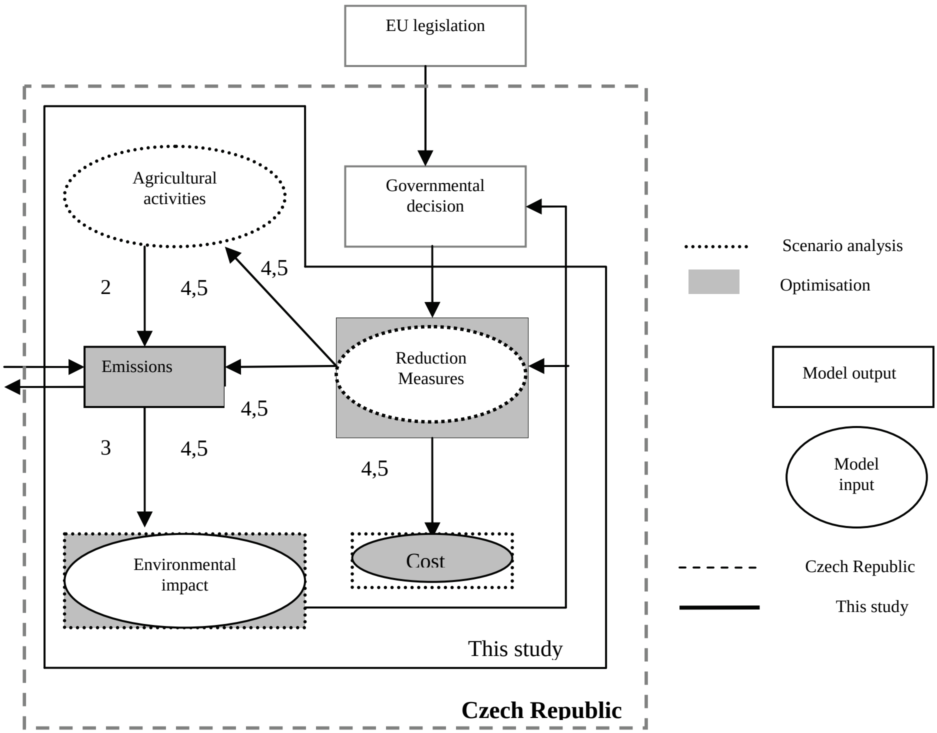


Figure 6.1 Schematic overview of relationships between agricultural activities, emissions, environmental impacts and reduction measures. Numbers indicate which chapters deal with a particular link.

6.5 Implications for environmental policy in the Czech Republic

This thesis presents an integrated environmental assessment of agriculture in the Czech Republic with a case study focusing on dairy cattle. The model developed allows to analyse current and future environmental policies in agriculture. For policy makers it may be interesting that the model can address questions like "*How does the dairy cattle sector contribute to different environmental problems?*" and "*Where in the country should emissions be reduced in the future to minimise the environmental burden in the cheapest way?*". Therefore, this study may contribute to the development of future planning in agricultural production while taking into account the environmental impact. This is currently lacking in the Czech Republic. Agricultural production is currently driven by market demand, rather than by environmental concern.

In the Czech Republic, specific reduction targets were set for ammonia emissions and nitrogen oxide for 2010 following the National Emission Ceilings Directive of European Commissions (European Commissions, 2001) and the Gothenburg Protocol of CLRTAP (United Nations, 1999). In addition, there is a target for nitrate in surface and ground waters (European Commissions, 1991). However, currently there is no target for greenhouse gas emissions or for emissions of particulate matter from agriculture. From a recent survey by EEA (2008) it is clear that the Czech targets for ammonia emissions and nitrogen oxide will be met. The target for ammonia emissions is established at the national level and at the level of administrative regions. The emission targets for administrative regions were set by the Czech government based on emission intensity regardless of the type of farming and environmental conditions. Most likely, achieving the targets for 2010 will result from continued reduction in livestock numbers.

In 2003 farmers started to implement a so-called Code of Good Agriculture Practice which obligates them to apply measures reducing ammonia emissions in all stages of farming such as housing, storage and application of manure. In addition, farmers have to respect the Nitrate Directive which was implemented in the Czech Republic in 2003. Currently, there is no specific policy strategy for emissions of greenhouse gases from agriculture. A more ambitious national target for ammonia is expected for 2020 as a part of the revised NEC Directive. The expected reduction target for ammonia ranges between 20% and 65% relative to the year 2000 (Amann et al., 2008). To achieve such targets may have large economical implications for the agricultural sector, result in a large economic burden on farmers and will require a more sophisticated reduction strategy to be set at the regional level.

In Chapter 3 it is argued to define environmental targets not only at the sector level, but also at the regional level, where regions are defined depending on agricultural intensity and potential contribution to the environmental impact. Four study regions, including seven administrative regions (Jihočeský, Vysočina, Kralovehradecký, Pardubický, Středočeský, Ústecký, Plzeňský) were indentified to have the largest potential contribution to acidification, terrestrial and aquatic eutrophication per hectare of agricultural area and per litre of milk produced. We argue that environmental policy should, therefore, target these most polluting areas first. The results of Chapter 4 suggest that cost-effective reduction in these regions should focus on aquatic eutrophication and global warming. This is different than current policies, which are a combination of policies focusing on acidification and eutrophication. Moreover, there is lack of integration of these policies. The DAIRY model indicates that reducing nutrient input by applying manure efficiency improvement or improving timing of manure application may improve the overall environmental performance of dairy cattle cost-effectively.

The research approach taken in this thesis is based on a unique combination of methods to estimate emissions, their potential environmental impact and possible solutions. These serve as essential building blocks of the DAIRY model. A major strength of the DAIRY model is that it allows for comprehensive analyses at the sector level and for identification of cost-effective ways to reduce the overall environmental impact of dairy cattle. As such, it can serve as example for other countries and sectors.

6.6. Recommendations for future research

Future research aiming to improve environmental impact assessments of dairy cattle may focus on better input data (activity data, emission factors, costs, reduction potentials) and improved methodology (study region definition, emission estimates, characterisation factors, uncertainty and sensitivity analysis). In addition, future research could be directed towards model completeness. This may include an extension of the scope of the analysis regarding sources, pollutants and environmental impacts, and inclusion of social aspects into the modelling structure.

The DAIRY model now calculates emissions from livestock and manure management. A valuable addition would be to take into account emissions from purchased fertilizers to grow feed for animals and purchased concentrates, and use of diesel and electricity on the farm. It would be interesting to investigate whether such additions would suggest different cost-effective solutions. In addition, growing livestock requires large area of land. It would therefore, be interesting to analyse the land use effects of growing feed for cattle. This may be particularly interesting in comparison with bio-fuel production because both are competing for land. This is a highly relevant issue for the environmental policy makers in the Czech Republic, because the agricultural land used for rapeseed production is one of the fastest growing forms of land use, and now accounts for 10% of agriculture land which may increase up to 20 to 30% in the near future.

Currently, most integrated assessment models link the economy with the geo-physical environment without an explicit link to social behaviour. In the DAIRY model different views on environmental problems are reflected through the valuation factors. These may in the future be extended to reflect farm-specific environmental strategies. However, next to the valuation factors, the model would improve when it could reflect behavioural changes such as dietary changes towards eating less meat and milk as a result of certain social learning. This may be possibly achieved by better co-operation with social scientists.

Reference

Amann, M., Asman, W., Bertok, I., Cofala, J., Heyes, C., Klimont, Z., Schöpp, W. and Wagner, F., 2008. National Emission Ceilings for 2020 based on the 2008 Climate and Energy Package.. NEC Scenario AnalysisReport #6. International Institute for Applied Systems Analysis (IIASA),Laxenburg, Austria

ASTA, 2005. International and national abatement strategies for transboudary pollution. The importance of Non-Technical Measures for reductions in emissions of air pollutants and how to consider them in Integrated Assessment Modelling - A Workshop in collaboration with the UN/ECE Task Force on Integrated Assessment Modelling 7-9 December 2005, Göteborg, Sweden http://asta.ivl.se/

Bakken, L.R. and M. Bleken, 1998. Temporal aspects of N enrichment and emission of N_2O to the atmosphere. Nutrient Cycling in Agroecosystems; 52: 107-121.

Brink, J.C., 2003. Modelling cost-effectiveness of interrelated emission reduction strategies, the case of agriculture in Europe. PhD thesis. Wageningen University. The Netherlands

Constanza, R., 2000. The dynamics of the ecological footprint concept. Ecological Economics; 32:341-345

Dämmgen, U.,Lüttich, M., Döhler, H., Eurich-Menden, B., Osterburg, B., 2006 Calculations of emissions from German agriculture-national Emission Inventory Report (NIR)2006 for 2004. Part 3: Methods and Data (GAS_EM). Landbouforschung, Volkenrode Special Issue 291

European Commissions, 1991. Council Directive of 12 December 1991concerning the protection of waters against pollution caused by nitrates from agriculture sources (91/676 EC)

European Commissions, 2001. Directive 2001/81/EC of the European Parliament and of the council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants, Official Journal of the European Communities. L309/22

EEA, 2007. NEC Directive status report, 2006. Member states reporting under Direcitve 2001/81/EC of European Parliament and of the Council of 23 October, 2001 on national emissions ceilings for certain atmospheric pollutants. EEA Technical Report NO 15/2007

Haushilds, M., and Potting, J.M.B. (Eds), 2004. Spatial differentiation in life cycle impact assessment the EDIP2003 Methodology; Guidelines from the Danish Environmental Protection Agency: Copenhagen

Hermann, B.G., Kroeze, C., Jawit, W., 2006. Assessing environmental performance by combining life cycle assessment, multi-criteria and environmental performance indicator. Journal of Cleaner Production; 15:1787-1796

Neto, B., 2007. MIKADO: A decision support tool for pollution reduction in aluminium pressure die casting. PhD thesis Wageningen University, The Netherlands

Jawit, W., 2006. An environmental systems analysis of the kraft pulp industry in Thailand. PhD thesis Wageningen University, The Netherlands

Oenema, O., Velthof, G.L., 2007. Analysis of international and European policy instruments: pollution swapping. Service contract “Integrated measures in agriculture to reduce ammonia emissions” Contract number 070501/2005/422822/MAR/C1

Pluimers, J.C., 2001. An environmental systems analysis of greenhouse horticulture in the Netherlands. PhD Thesis Wageningen University, Netherlands

Potting, J., Hauschild M.Z., 2006. Spatial differentiation in life cycle impact assessment: a decated of method development to increase the environmental realism of LCIA. Int. Journal of Life Cycle Assessment 11:11-13

Reap, J., Roman, F., Duncan, S., Bras,. B., 2007. A survey of unresolved problems in life cycle assessment. Part 2: Impact Assessment and interpretation. Int. Journal of Life Cycle Assessment. DOI: 10.1007/s11367-008-0009-9

Schmieman, E.C., van Ierland, E.C., 1999. Dynamic of soil acidification: an economic analysis. Ecological Economics 31,449-462

Thomassen, M., 2008. Environmental Impact of dairy cattle production systems: an integral assessment. Phd thesis. Wageningen University. The Netherlands

UNECE, 1999. Protocol to the 1979 Convention on Long-range Tansboudary Air Pollution to abate compounds. EB. AIR/1999/2-V. United Nations Economic Comissions for Europe (UNECE), Geneva.

Van Pul, W.A.J., de Haan, J.D. van Dam, M.M. van Eerdt, J.F. de Ruiter, A. van Hinsberg, H.J. Westhoek, 2004. Cost-effectiveness of generic and locally applied ammonia abatement measures. RIVM report : 500033001/2004, RIVM The Netherlands. In Dutch

Van Passels, S., Nevens, F., Mathijs, E., Van Huylenboeck, G., 2006. Measuring farm sustainability and explaining differences in sustainable efficiency. Ecological Economics; 62:149-161

SUMMARY

Agricultural activities strongly affect landscapes and also cause a variety of environmental and health problems in many European countries. Environmental policies to minimise this negative impacts of agriculture differ between countries. This thesis focuses on environmental consequences of agricultural activities in the Czech Republic and possibilities to reduce the associated environmental problems. The causes and solutions of these air, water and soil pollution problems are complex, and designing sustainable farming systems requires integration of social, economic, and natural sciences.

The agriculture practices in the Czech Republic have changed dramatically due to political changes during last decade. These changes ameliorate environmental problems to some extent through a reduction in the use of fertilizers and livestock numbers. However, agriculture still poses a threat to the environment and human health. The agricultural productivity may intensify in the future leading to increased pollution. Now the Czech Republic is a member of the European Union, Czech farmers have to deal with many new regulations set by European Commission aiming at reducing environmental problems.

The overall objective of this thesis is to assess the future environmental impact by the agricultural sector in the Czech Republic. National and European environmental policies and the interaction between human activities and environmental trends have been considered. The novel aspect of this thesis is to include process-based emission factors in a region specific model to quantify both emissions and their potential environmental and health impacts. Additionally, these results are used in another purposely developed model to assess the reduction costs involved. To achieve the overall objective three specific research aims are defined.

The first aim is to analyse different **emission estimation methods** with respect to their usefulness for an integrated assessment at the national scale. The second is to evaluate the **potential environmental impact** of agricultural emissions at the sub-national level while considering different agricultural practices and environmental characteristics. The third aim is to integrate emission estimation methods and impact assessment approaches in a model to assess the **cost-effectiveness of environmental policy measures**. This model is applied in a case study focusing on dairy cattle as one of the most polluting sub-sectors of Czech agriculture. It is used to analyse the current situation and to **explore future trends** up to 2020 as affected by (i) different views of hypothetical model users on importance of environmental impact, (ii) changes in projected animal numbers and management and (iii) changes in the application of emission reduction measures.

Integrated assessments that analyse environmental problems by agriculture simultaneously, need complete, detailed and consistent emission estimates that consider possible interrelations between different pollutants. Three types of emission estimation methods were analysed: emission factor, regression analyses and process-based methods. Selected examples of emission estimation methods were reviewed to illustrate the large variety in methods available. These methods were evaluated based on three steps: (1) Comparison of emission estimation methods with respect to specific characteristics, (2) Scoring of methods

based on quality and country-specific criteria and the extent to which interrelations between pollutants are accounted for, and (3) Multi-Criteria Analysis taking into account the relative importance of the different criteria. The usefulness of this approach was demonstrated by applying it to a case study focusing on agriculture in the Czech Republic.

The evaluation of emission estimation methods reveals large differences. We conclude that the following methods best meet our criteria: the IPCC Guidelines for National Greenhouse Gas Inventories, methods from the INITIATOR model and the detailed method of the EMEP/CORINAIR Guidebook. Based on this analysis we suggest that combining parts of each of the four methods forms a sound basis for a new emission estimation method for quantifying agricultural emissions of air, water and soil pollution simultaneously.

The potential environmental and health impact of selected agricultural emissions was evaluated based on a new innovative approach. Emission estimates were combined with a country-specific set of indicators to assess the environmental impact of dairy cattle in nine regions defined according to specific environmental characteristics. In this thesis different characterisation factors available in the literature were compared and evaluated with respect to usefulness for a study focusing on dairy cattle in the Czech Republic. We conclude that for our case the most appropriate set of characterisation factors are those from Sepällä et al. (2006) and EDIP (2003). These factors are based on the most recent data and best available scientific models and take into account, where possible national and regional differences. However, a weakness of these combinations may be potential internal inconsistencies

We estimate the contribution of emissions of ammonia (NH_3) nitrogen oxides (NO_x), nitrate (NO^-_3), phosphate (PO_4^{-3}), particulate matter (PM_{10} and $PM_{2.5}$), methane (CH_4), and nitrous oxide (N_2O) to a number of environmental and health problems. The results show large regional differences in the current environmental and health impact per unit of agricultural production in the Czech Republic. The regional acidifying, eutrophying and global warming impact of dairy cattle is calculated to be up to three times the national average, depending on the dairy cattle intensity. Aquatic eutrophication is found to be a problem in regions with relatively high eutrophying emissions per hectare of so-called nitrate vulnerable zones. Human toxicity problems caused by dairy cattle livestock and manure management are problematic in regions with a high population density in rural areas.

A linear optimisation model (DAIRY) including Multi-Criteria Analysis was developed to analyse cost-effectiveness of policy measures to reduce the environmental impact of dairy cattle in the Czech Republic. The DAIRY model combines process-based and emission factor approaches to calculate the above-mentioned emissions, and site-dependent characterisation factors to assess their contribution to acidification, terrestrial and aquatic eutrophication, global warming and human toxicity. In addition, a so-called overall environmental impact (OEI) indicator was used to assess the environmental performance of dairy cattle. The DAIRY model was used to analyse the current situation and to explore future trends up to 2020, under different environmental and cost constraints.

The analysis of past and future trends of environmental and health impact by dairy cattle reveals decreasing trends over time, mainly as a result of reduced cattle numbers. In 2005 the OEI was considerably lower than in 1990. In the No Control scenario, which assumes no emission control, the 2020 environmental impact is 9% lower than in 2005, mainly as a

result of continued reduction in cattle numbers. Technical measures aimed at reducing ammonia emissions may reduce the 2020 uncontrolled OEI levels by 10%. Implementation of all technical measures considered would reduce the 2020 OEI levels by 30% at the national level. In optimised scenarios, the reductions in OEI in 2020 range from 1% to 30% relative to the No Control scenario, while the costs to achieve this reduction range between 0.2 and 16 MEuro. We show that targets for OEI close to maximum feasible reduction can be realized at about one-third of the costs of non-optimised scenarios. In such cost-effective scenarios the model tends to select measures to reduce aquatic eutrophication and climate change first, which is in contrast to current policies aiming at acidification and terrestrial eutrophication. Cost-optimal solutions at the national level are not always the cheapest solutions at the regional level.

The future environmental impact of dairy cattle in the Czech Republic was analysed for two reference scenarios. The No Control scenario assumes no emission control while the Policy Scenario aims at cost-effective reduction of the OEI by 20% relative to No Control scenario. Next, we explored how these calculated trends change as result of different assumption on (i) different views of hypothetical model users on importance of environmental impact, (ii) changes in projected animal numbers and management and (iii) changes in the application of emission reduction measures.

The reference scenarios indicate that the overall environmental impact by dairy cattle is mainly associated with global warming and aquatic eutrophication while leaching and housing are the two most contributing processes. The costs to reduce OEI by 20% are 12 MEuro. The most cost-effective combination of measures to achieve this target includes manure efficiency improvement and improved timing of manure application. The results suggest that regardless of model users views on the relative importance of different environmental problems, global warming and aquatic eutrophication are most important. However, the relative shares of these two in OEI depend on the valuation of the environmental impact categories. This, in turn, has an impact on the costs of reducing OEI, because it is cheaper to reduce emissions of nitrate than emissions of greenhouse gases. As a result costs to reduce 20% OEI range from 7 to 26 MEuro for different sets of valuation factors. The model result also suggests that dairy cattle kept in slurry-based systems have a better environmental performance than dairy cattle kept in straw-based systems. In addition, cattle numbers influence the OEI and the reduction costs more than changes in milk yield. The costs of reducing OEI by 20% relative to uncontrolled level range between 2 and 16 MEuro for scenarios with different assumptions on animal numbers and manure management. Taking into account unintended side-effects of reduction measures on the environment as a criterion for selection of measures, increases the reduction costs considerably. The changes in applicability of emission reduction measures lead to costs ranging between 24 and 50 MEuro.

The research approach taken in this thesis is based on a unique combination of methods to estimate emissions, their potential environmental impact and possible solutions. These serve as essential building blocks of the DAIRY model. A major strength of the DAIRY model is that it allows for comprehensive analyses at the sector level and for identification of cost-effective ways to reduce the overall environmental impact of dairy cattle. As such, it can serve as example for other countries and sectors.

SAMENVATTING

De landbouw heeft een grote invloed op het landschap en veroorzaakt tevens verschillende milieu- en gezondheidsproblemen in veel Europese landen. Milieumaatregelen om deze negatieve effecten van de landbouw te minimaliseren verschillen tussen landen. Dit proefschrift behandelt de milieukundige consequenties van de landbouw in Tsjechië en mogelijkheden om de daaraan gerelateerde milieuproblemen te verminderen. De oorzaken en oplossingen van deze lucht, water en bodemvervuiling zijn complex, en het ontwerpen van duurzame landbouwsystemen vereist integratie van kennis uit de sociale, economische en natuurwetenschappen.

De landbouwkundige praktijk in Tsjechië is dramatisch veranderd door de politieke veranderingen in de afgelopen tien jaar. Deze veranderingen verminderen de milieuproblemen enigszins als gevolg van een minder gebruik van kunstmest en een kleinere veestapel. Toch vormt de landbouw nog steeds een bedreiging voor het milieu en de gezondheid van mensen. In de toekomst zal, naar verwachting, de productiviteit van de landbouw toenemen, resulterend in meer vervuiling. Nu Tsjechië lid is van de Europese Unie geldt de uitgebreide regelgeving van de Europese Commissie, die streeft naar een vermindering van milieuproblemen, ook voor Tsjechische boeren.

Het centrale doel van dit proefschrift is om de toekomstige milieu impact van de landbouw sector in Tsjechië te analyseren. Hierbij wordt zowel nationaal als Europees milieubeleid in beschouwing genomen, evenals de interacties tussen menselijke activiteit en milieukundige trends. Het vernieuwende aspect van dit proefschrift is dat procesgerelateerde emissiefactoren zijn geïntegreerd in een geregionaliseerd model, om zo de emissies te kwantificeren en de daarmee samenhangende potentiële milieu- en gezondheidsproblemen. Daarnaast zijn deze resultaten gebruikt in een ander, specifiek voor dit onderzoek ontwikkeld model, om de reductiekosten te berekenen. Om dit centrale doel te realiseren, zijn drie specifieke onderzoeksdoelen geformuleerd.

Het eerste doel is om verschillende methoden voor het schatten van emissies te analyseren met betrekking tot hun bruikbaarheid in een *integrated assessment* op nationale schaal. Het tweede doel is om de potentiële milieu-impact van emissies uit de landbouw te evalueren op subnationale schaal, rekening houdend met verschillende landbouwkundige praktijken en omgevingsfactoren. Het derde doel is om methoden voor het schatten van emissies met *impact assessment* benaderingen in één model te integreren om zo de kosteneffectiviteit van milieumaatregelen te analyseren. Dit model is toegepast op een casus over de melkveehouderij als één van de meest milieuvervuilende subsectoren van de Tsjechische landbouw. Het model is gebruikt voor een analyse van de huidige situatie en van toekomstige trends tot het jaar 2020 en hoe deze veranderen onder invloed van (i) verschillen van mening van hypothetische modelgebruikers over het belang van milieuproblemen, (ii) verschillen in de veronderstelde grootte van de veestapel en het management daarvan en (iii) verschillen in de toepassing van emissiereducerende maatregelen.

Integrated assessments waarin de verschillende milieuproblemen die veroorzaakt worden door de landbouw gezamenlijk worden bestudeerd vereisen complete, gedetailleerde en consistente emissieschattingen die rekening houden met mogelijke interacties tussen verschillende vervuilende stoffen. Drie typen methoden voor het schatten van emissies zijn geanalyseerd: emissie factoren, regressie analyses, en procesgebaseerde methoden. Geselecteerde voorbeelden van emissieschattingsmethoden zijn geëvalueerd om de grote variatie in beschikbare methoden te illustreren. Deze methoden zijn geëvalueerd in drie stappen: (1) een vergelijking van de methoden met betrekking tot specifieke karakteristieken, (2) scoren van de methoden op kwaliteits- en landenspecifieke criteria en (3) een Multi-Criteria Analyse waarin rekening wordt gehouden met het relatieve belang van de verschillende criteria. De toepassing van deze benadering in een case studie van de landbouw in Tsjechië illustreert de bruikbaarheid ervan.

Uit de evaluatie blijkt dat er grote verschillen bestaan tussen de verschillende methoden voor het schatten van emissies. We concluderen dat de volgende methoden het best voldoen aan onze criteria: de *IPCC Guidelines for National Greenhouse Gas Inventories*, methoden die gebruikt zijn in het model INITIATOR en de gedetailleerde methode uit het EMEP/CORINAIR *Guidebook*. Op basis van deze analyse stellen wij voor om van elk van deze methoden delen te combineren. Een dergelijke combinatie vormt een goede basis voor een nieuwe methode voor het gelijktijdig schatten van landbouwgerelateerde emissies van lucht-, water- en bodemverontreinigende stoffen.

De potentiële milieu- en gezondheidseffecten van een aantal emissies uit de landbouw is geëvalueerd op basis van een nieuwe methode. Emissieschattingen zijn gecombineerd met een landenspecifieke set indicatoren voor de milieu-impact van de melkveehouderij in negen regio's die gedefinieerd werden volgens specifieke omgevingsfactoren. In dit proefschrift zijn hiertoe verschillende indicatoren voor milieu-impact (zogenaamde karakterisatiefactoren) uit de literatuur vergeleken en geëvalueerd met betrekking tot hun bruikbaarheid in een studie van de melkveehouderij in Tsjechië. We concluderen dat voor onze casus de meest geschikte set van karakterisatiefactoren die van Sepällä et al. (2006) en EDIP (2003) zijn. Deze factoren zijn afgeleid van de meest recente data en beste beschikbare wetenschappelijke modellen en houden rekening, waar mogelijk, met nationale en regionale verschillen. Een zwak punt van deze combinatie is echter dat er mogelijk interne inconsistenties kunnen optreden.

We schatten de bijdragen van emissies van ammonia (NH_3), stikstofoxiden (NOx), nitraat (NO_3^-), fosfaat (PO_4^{-3}), deeltjes (PM_{10} en $PM_{2.5}$), methaan (CH_4) en lachgas (N_2O) aan een aantal milieu- en gezondheidsproblemen. Uit de resultaten blijkt er grote dat regionale verschillen zijn in de huidige milieu- en gezondheidsimpact per eenheid landbouwproductie in Tsjechië. De berekende regionale verzurende, vermestende en opwarmende impact van de melkveehouderij is tot driemaal groter dan het nationaal gemiddelde, afhankelijke van de intensiteit van de melkveehouderij. Vermesting van aquatische systemen blijkt vooral een probleem in regio's met een relatief hoge emissie van vermestende stoffen per hectare zogenaamde *nitrate vulnerable zones*. Humane toxiciteit gerelateerd aan de melkveehouderij blijkt vooral een problem in regio's met een hoge bevolkingsdichtheid in het landelijk gebied.

Een lineair optimalisatiemodel (DAIRY) is ontwikkeld, dat een Multi-Criteria Analyse bevat, voor het analyseren van de kosteneffectiviteit van beleidsmaatregelen ter reductie van de milieu-impact van de melkveehouderij in Tsjechië. Het DAIRY model combineert procesgebaseerde en emissiefactor benaderingen om de emissies van bovenstaande stoffen te schatten, en *site-dependent* karakterisatiefactoren voor het bepalen van de bijdrage van deze stoffen aan verzuring, terrestrische en aquatische vermesting, klimaatverandering en humane toxiciteit. Daarnaast is een zogenaamde *overall environmental impact* (OEI) indicator gebruikt voor het bepalen van de milieuperformance van de melkveehouderij. Het DAIRY model is gebruikt voor een analyse van de huidige situatie en om toekomstige trends te verkennen tot het jaar 2020 onder verschillende randvoorwaarden voor milieu en kosten.

Uit de analyse van historische en toekomstige trends blijkt dat de milieu- een gezondheidsimpact van de melkveehouderij een dalende trend vertonen. Dit is vooral het gevolg van een krimpende veestapel. In 2005 was de OEI aanzienlijk lager dan in 1990. In een *No Control* scenario, waarin geen emissiereductie wordt verondersteld, is in 2020 de milieu-impact 9% lager dan in 2005, vooral omdat het aantal melkkoeien blijft afnemen. Technische maatregelen om ammoniak emissies te verminderen, kunnen de OEI in 2020 met 10% reduceren ten opzichte van het *No Control* scenario. Implementatie van alle technische maatregelen zou de 2020 OEI met 30% kunnen verminderen op nationaal niveau. In geoptimaliseerde scenario's is de OEI in 2020 1% tot 30% lager dan in het *No Control* scenario. De kosten van deze reductie bedragen tussen de 0.2 en16 MEuro. We laten zien dat doelen voor OEI die dichtbij het maximaal haalbare liggen gerealiseerd kunnen worden tegen ongeveer een derde van de kosten van niet-geoptimaliseerde scenario's. In deze kosteneffectieven scenario's selecteert het model vooral maatregelen om vermesting van het aquatisch milieu en klimaatverandering tegen te gaan. Dit contrasteert met het huidige beleid, dat gericht is op verzuring en vermesting van het terrestrische milieu. Kostenoptimale oplossingen op nationaal niveau zijn niet altijd de goedkoopste oplossingen op regionaal niveau.

De toekomstige milieu-impact van de melkveehouderij in Tsjechie is geanalyseerd voor twee referentiescenario's. Het *No Control* scenario veronderstelt geen emissiereductie, terwijl het *Policy* scenario streeft naar kosteneffectieve reductie van de OEI met 20% ten opzichte van het *No Control* scenario. Vervolgens is onderzocht hoe deze berekende trends veranderen als gevolg van verschillende veronderstellingen over (i) verschillen van mening van hypothetische modelgebruikers over het belang van milieuproblemen, (ii) de grootte van de veestapel en het management daarvan en (iii) de toepassing van emissiereducerende maatregelen.

In de referentiescenario's wordt de *overall environmental impact* van de melkveehouderij vooral bepaald door klimaatverandering en vermesting van het aquatische milieu, vooral veroorzaakt door uitspoeling en stallen. De kosten om de OEI met 20% te reduceren bedragen 12 MEuro. De meest kosteneffectieve combinatie van maatregelen om dit doel te halen zijn verbetering van de efficiëntie van mest en verbetering van de *timing* van mest toediening. De resultaten suggereren dat ongeacht de mening van modelgebruikers over het relatieve belang van verschillende milieuproblemen, klimaatverandering en aquatische vermesting het meest belangrijk zijn. Het relatieve aandeel van deze twee in de OEI hangt echter wel af van de weging van milieuproblemen. Dit beïnvloedt vervolgens de kosten van OEI reductie, omdat het goedkoper is om emissies van nitraat te verminderen dan emissies van broeikasgassen. De kosten van een 20% reductie van de OEI variëren hierdoor van 7 tot 26 MEuro voor verschillende sets van wegingsfactoren. De model resultaten suggereren eveneens dat melkvee dat gehouden wordt in stalsystemen met dunne mest een betere milieuperformance hebben dan melkvee in systemen met vaste mest. De grootte van de veestapel blijkt de OEI en de reductiekosten meer te beïnvloeden dan veranderingen in melkopbrengst. De kosten van een reductie in OEI van 20% ten opzichte van het ongecontroleerde niveau variëren tussen de 2 en 16 MEuro in scenario's met verschillende veronderstelde groottes van de veestapel en verschillen in mestverwerking. Rekening houden met onbedoelde neveneffecten van emissiereducerende maatregelen als een selectiecriteria voor de maatregelen, resulteert in aanzienlijk hogere reductiekosten. Veranderingen in toepasbaarheid van emissiereducerende maatregelen resulteert in kosten die variëren van 24 tot 50 MEuro.

De onderzoeksbenadering in dit onderzoek is een unieke combinatie van methoden voor het schatten van emissies, de daarmee samenhangende milieueffecten en mogelijke oplossingen daarvoor. Dit zijn essentiële bouwstenen van het DAIRY model. Een belangrijk sterk punt van het DAIRY model is dat het een volledige analyse op sectorniveau mogelijk maakt, evenals identificatie van kosteneffectieve oplossingen voor milieuproblemen veroorzaakt door de melkveehouderij. Het kan als zodanig als voorbeeld dienen voor andere landen en sectoren.

CURRICULUM VITAE

Martina Havlíková was born January 13, 1978 in Pardubice, Czech Republic. In 1997, she completed secondary agriculture school in Chrudim and started her study at the Institute of Tropical and Subtropical Agriculture of the Czech Agriculture University in Prague. In 2000 she was as Erasmus exchange student for five months at Wageningen University in The Netherlands. After this she received a Wageningen university grant and a Matra fellowship to finish her MSc in Environmental Science with a specialisation in Environmental Systems Analysis. She graduated in Wageningen in 2003 and started her job at the Czech Hydrometeorological Institute (CHMI) in Prague. In 2004 she started her "sandwich" PhD program of Wageningen University with the Environmental Systems Analysis Group. In 2005 she was selected to participate in the three months Young Scientists Summer Program of the Institute for Applied Systems Analysis in Austria. Since January 2008 she has been appointed at the Ministry of Environment of the Czech Republic at the department of Air Quality Protection.

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- Research Context Activity: "Organizing meeting of Task Force on Integrated Assessment Modelling (TFIAM), held on 2-4 May 2007 in Prague, Czech Republic"
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Other Phd and MSc courses:

- Multi-Agent Systems for Natural Resource Management
- Techniques for writing and presenting scientific papers
- Writing a grant proposal

Research and Management Skills:

- YSSP (young scientists summer program) IIASA, 1 June – 30 August 2005, Austria
- Agricultural Advanced GAMS class, IIASA, 5 – 8 May 2008, Austria

Oral Presentations:

- Fourth International Symposium on Non-CO2 Greenhouse Gases: Science, Control, Policy and Implementation (NCGG-4), 4 - 6 July 2005, Utrecht, The Netherlands
- Acid Rain Conference, 12 - 17 July 2005, Prague, Czech Republic
- IIASA Late summer workshop, 21 July 2005, Laxenburg, Austria
- First Ammonia Conference, 19 - 21 March 2007, Ede, The Netherlands

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