

## THE NITROGEN DECISION SUPPORT SYSTEM: NitroGenius

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## Acknowledgement/Preface

The Ministry of the Environment, VROM, Wageningen Software Labs and SERC are acknowledged for their financial support. We thank Julio Mosquera and Julie McDill of ECN for their useful input. The players of the game at the 2nd international nitrogen conference are acknowledged for their comments, suggestions and enthusiastic playing of the game.

## Abstract

NitroGenius, a decision support system in the form of a game, was developed. A first version was demonstrated at the Second International Nitrogen Conference in order to support scientists and policymakers as they seek solutions to the nitrogen problems in the Netherlands' extensive agricultural, industrial and transportation areas. The aim of NitroGenius is: (i) to improve the understanding of complex relationships within the nitrogen pollution situation and (ii) to search for optimal solutions and policies, which could prevent pollution and its effects, while incurring minimal economic costs and societal impacts. NitroGenius includes a modelling system, which describes all major nitrogen flows at several relevant spatial and temporal scales. Outputs of this model include: (i) the annual emissions of ammonia, nitrogen oxides and di-nitrogen oxide to the atmosphere and (ii) the annual leaching and runoff of ammonium and nitrate to groundwater and surface water, including the resulting annual average concentrations of those compounds. An economic module was developed to describe relationships occurring between all important economic sectors of the Netherlands, and the effect that different actions would have on the Gross Domestic Product (GDP), unemployment, energy use and environmental quality. Several possible abatement options are described and parameterised so that their effects can be calculated using the modelling system. The modelling system and abatement options form the heart of NitroGenius. About 50 groups of people played the game during the Second International Nitrogen Conference. The results show that nitrogen problems can be solved in the Netherlands with careful planning and selection of a range of abatement options.

# CONTENTS

SUMMARY	5
1. INTRODUCTION	7
2. THE NITROGEN PROBLEM IN THE NETHERLANDS	9
3. THE NITROGEN DECISION SUPPORT SYSTEM, NITROGENIUS	10
3.1 The multi-user system	11
3.2 Single user system	18
4. REFERENCES	23
APPENDIX A NITROGENIUS	25
1. INTRODUCTION: THE NITROGEN PROBLEM IN THE NETHERLANDS	27
2. THE CASCADE OF NITROGEN AND ITS PARAMETERIZATION	29
3. THE NITROGEN DECISION SUPPORT SYSTEM, NITROGENIUS	31
4. PLAYING WITH NITROGENIUS	37
LESSONS LEARNED FROM GAME RESULTS	39
CONCLUSIONS	40
ACKNOWLEDGEMENT	40
REFERENCES	41
APPENDIX B ASSESSMENT OF NITROGEN PRODUCTION CEILINGS ON A REGIONAL SCALE AVOIDING ADVERSE ENVIRONMENTAL IMPACTS	43
1. INTRODUCTION	45
MODELLING APPROACH AND MODEL APPLICATION	46
MODEL RESULTS	50
DISCUSSION AND CONCLUSIONS	54
REFERENCES	55



## SUMMARY

The atmosphere contains almost 80% of nitrogen gas ( $N_2$ ). In this form nitrogen is not relevant for environmental issues. Once nitrogen is in a reactive form, either reduced or oxidized, it has a very different role. In this form it is essential for life on earth. Proteins need nitrogen and therefore a certain amount of reactive nitrogen in the bio-chemical cycles is necessary. The global nitrogen cycle is being perturbed in many ways. Fossil fuel combustion, mineral fertilizers and livestock manure's all provide major sources of fixed reactive nitrogen (N). This leads to a cascade of effects as the N is transported and transformed through the environment. Reactive nitrogen comprises all forms of n-bounds, other than atmospheric  $N_2$  or nitrogen fixed in bedrock.

Reactive nitrogen production in the Netherlands is very high as the result of intensive agriculture and energy intensive society and industries. This does lead to a series of environmental impacts, including: (i) nitrate contamination of drinking water, (ii) eutrophication of freshwater lakes, (iii) acidification and biodiversity impacts on terrestrial ecosystems and (iv) global climate change induced by emissions of  $N_2O$ . Measures to control reactive nitrogen emissions were up to now directed towards different environmental themes such as acidification, eutrophication and climate change.

Models have been developed to analyze the nitrogen problem in the Netherlands in an integrated way, which means that all relevant aspects are taken into account simultaneously. A set of models describing the major N-flows at the relevant scales were developed, representing all crucial processes in the N chain. NitroGenius, a decision support system in the form of a game and as a single user decision support system, was developed in order to support scientists and policymakers as they seek solutions to the nitrogen problems in the Netherlands' extensive agricultural, industrial and transportation areas. The aim of NitroGenius is: (i) to improve the understanding of complex relationships within the nitrogen pollution situation and (ii) to search for optimal solutions and policies, which could prevent pollution and its effects, while incurring minimal economic costs and societal impacts. NitroGenius includes the modeling system, which describes all of the nitrogen flows at several relevant spatial and temporal scales. Outputs of this model include: (i) the annual emissions of ammonia, nitrogen oxides and di-nitrogen oxide to the atmosphere and (ii) the annual leaching and runoff of ammonium and nitrate to groundwater and surface water, including the resulting annual average concentrations of those compounds. An economic model was also developed to describe economic relationships occurring between all important sectors of the nation, and the effect that different actions would have on the Gross Domestic Product (GDP), unemployment, energy use and environmental quality. Several possible abatement options are described and parameterized so that their effects can be calculated using the modeling system. The modeling system and abatement options form the heart of NitroGenius. About 50 groups of people played the game during the Second International Nitrogen Conference. The results show that nitrogen problems can be solved in the Netherlands with careful planning and selection a range of abatement options.



## 1. INTRODUCTION

Reactive nitrogen in the environment is a major policy issue. Nitrogen pollution and its emissions are difficult to control, because they are associated with two of the most important human needs: food and energy. In the Netherlands several measures have been taken to decrease emissions with varying success. So far policy has been focussed on individual environmental issues related to specific sources. Erisman et al. (2000) summarises the results of a study to analyse the nitrogen problem in the Netherlands in an integrated way. All relevant aspects were taken into account simultaneously. This was done by deriving regional agricultural nitrogen production ceilings, including all relevant nitrogen flows in agriculture and most relevant effects i.e., protection of ground and surface water from nitrate pollution and N- eutrophication, controlling NH<sub>3</sub> volatilisation in view of impacts on terrestrial ecosystems and reducing NO<sub>x</sub> and N<sub>2</sub>O emissions in view of climate change policies. For agriculture, nitrogen ceilings provide a good basis for regulating nitrogen through fertiliser use and feed import. Results show that reactive nitrogen production in the Netherlands should be decreased by 50-70% in order to reach the ceilings necessary to protect the environment against nitrogen pollution from agriculture.

Complex interactions within the nitrogen flows and the high variability of these flows in time and space not only makes the issue difficult to comprehend but also complicates the development of efficient abatement strategies. Consequently, policy up to now has focused on parts of the system, without considering all the interactions and the possible implications for other environmental problems (Erisman et al., 2001). A decision support system could help policy makers understand complexity of this situation and could also make it easier to visualize the consequences of different abatement options. Examples of successful decision support systems are the RAINS model for support of acidification abatement strategy in Europe (Schoepp et al., 1999) and the Integrated Modeling of Global Climate Change (IMAGE) (Alcamo, 1994). Until now there has not been a similar system which examined N-management issues and included the relevant temporal and spatial scales necessary for anticipating all relevant interactions.

Actually, Erisman et al. (2000) focussed on agricultural nitrogen, but to develop an integral approach, oxidised nitrogen from combustion processes must also be included. Furthermore, a fully integrated approach should also include tools to analyse economical aspects. A nitrogen decision support system in the form of a game (NitroGenius) was developed for the Second International Nitrogen Conference. The aims were to: (i) improve understanding among scientists and policy makers about the complexity of nitrogen pollution problems in an area of intensive agricultural, industrial, and transportation activity (the Netherlands) and (ii) search for optimal policy solutions to prevent pollution effects at lowest economic and social costs. NitroGenius includes a model of nitrogen flows at relevant spatial and temporal scales including emissions of ammonia and nitrogen oxides and contamination of surface- and ground waters. NitroGenius also includes an economic model describing relationships for important sectors and impacts of different nitrogen control measures on Gross Domestic Product, unemployment, energy use, and environmental costs.

This report describes the nitrogen decision support system. The report contains a description of the nitrogen problem in the Netherlands, on which the system is presently focused (Chapter 2) and a manual to run the system (Chapter 3). Furthermore, two appendices are included, which provides copies of two papers that describe the scientific background of NitroGenius as a whole (Appendix A) and the agricultural submodel (Appendix B).



## 2. THE NITROGEN PROBLEM IN THE NETHERLANDS

The Netherlands is a small country at the delta of several large European rivers: the Rhine, the Meuse, and the Waal. The Netherlands has always been a country that imported raw materials to be manufactured into products for export. In addition, agriculture has always been an important economic factor. Table 1 gives some pertinent numbers for the Netherlands. Since the industrial revolution, there has been a growing overload of nutrients and related emissions into the atmosphere ( $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{N}_2\text{O}$ ) and groundwater and surface water ( $\text{NO}_3^-$ ). The Netherlands is known for having one of the highest reactive nitrogen (Nr) emissions densities in the world. The term reactive nitrogen (Nr) as used in this paper includes all biologically active, photochemically reactive, and radiatively active N compounds in the atmosphere and biosphere of the Earth. Thus Nr includes inorganic reduced forms of N (e.g.,  $\text{NH}_3$ ,  $\text{NH}_4^+$ ), inorganic oxidized forms (e.g.,  $\text{NO}_x$ ,  $\text{HNO}_3$ ,  $\text{N}_2\text{O}$ ,  $\text{NO}_3^-$ ), and organic compounds (e.g., urea, amines, proteins). Vehicular traffic and animal husbandry are the principal sources of oxidized and reduced forms of Nr. The impacts of these emissions in the Netherlands and many other countries include eutrophication of nature areas and surface waters, soil acidification, and nitrate pollution of groundwater, particle formation leading to impacts on human health and influencing the earth's radiation balance, ozone formation leading to effects on humans and vegetation, and to climate change when it is transformed into nitrous oxide (e.g. Cowling et al., 1998; Snijl, 2002; Galloway and Cowling, 2002). One molecule of Nr can thus contribute to a cascade of effects, e.g. by first contributing to direct effects, then, when deposited, to eutrophication and groundwater pollution and eventually to  $\text{N}_2\text{O}$  emissions after denitrification.

Table 2.1 *Illustrative numbers for the year 2000 related to nitrogen problems in the Netherlands.*

Some important numbers	N emission factors
16 million inhabitants	362 kton N input by forage
100 million poultry	396 kton N input by fertilizers
15 million pigs	90 kton N input by deposition and biological fixation
4 million cattle	180 kton $\text{NH}_3$ emissions
6 million cars	490 Kton $\text{NO}_x$ emissions
454 people per $\text{km}^2$ of land	72 kton $\text{N}_2\text{O}$ emissions
60% agricultural area of the total land area	

During the past decade, several measures have been taken to control Nr emissions and limit their effects. These measures were mainly directed towards individual environmental problems such as acidification, eutrophication, climate change. It appears that these measures are not as effective as was predicted beforehand. In some cases results were lower than expected, and in other cases the decreases in emissions achieved were counterbalanced by growth of the activity. Nr is difficult to abate, because of the intimate linkages between its various forms: this applies equally to agriculture, where decreasing  $\text{NH}_3$  emissions may increase  $\text{N}_2\text{O}$  and nitrate, and to transport emissions, where decreasing  $\text{NO}_x$  emissions is leading to increased  $\text{NH}_3$  and  $\text{N}_2\text{O}$  emissions (Galloway and Cowling, 2002). Although some technical measures can be implemented relatively cheaply, many are expensive. The most difficult sources to abate are vehicles, small combustion sources, and agricultural sources. Large industrial point sources are much easier to abate, because industrial abatement technology is well developed, even though it is rather expensive.

### 3. THE NITROGEN DECISION SUPPORT SYSTEM, NITROGENIUS

The heart of a decision support system should contain models with simple parameterizations describing all necessary and relevant interactions. These should be accurate enough to produce realistic results for the present time and for the future, and should be influenced by a range of abatement options. These parameterizations are usually based on complex models, which contain process descriptions and are validated with observations. The nitrogen decision support system described here contains several coupled modules, as outlined in Figure 1:

- a module to calculate emissions to the air based on activities and abatement options,
- a module, called INITIATOR, to describe the agricultural nitrogen flows and emissions to groundwater and surface water,
- a deposition model and a module to calculate ozone concentrations and effect parameters, and
- a sociological and economic module.

The different modules are generally described in Erisman et al. (2001) as presented in Appendix A. INITIATOR is separately described in the paper by de Vries et al. (2002), whereas an example of its application in terms of nitrogen ceilings is given in de Vries et al. (2001), as presented in Appendix B. The models and their parameterizations are usually based on complex models, which contain detailed process descriptions and are validated with observations. The nitrogen decision support system described here was developed for the Netherlands because of the country's large nitrogen problems, and the availability of data that are necessary to run the models. There are two ways to use this modeling system. It can be used as a single user nitrogen decision support system, or as a multiple user game (NitroGenius). In both cases all modeling components are involved.

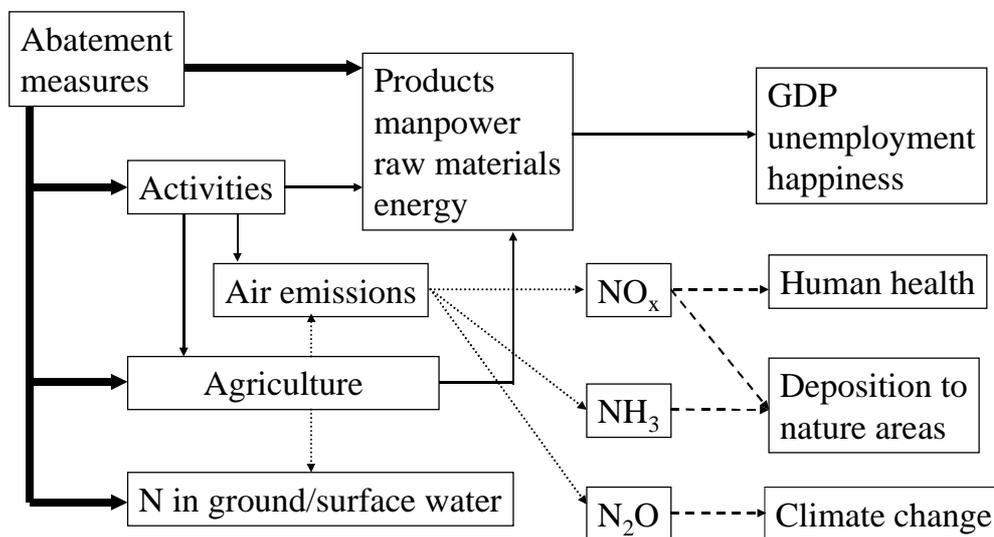


Figure 3.1 Outline of the Nitrogen Decision Support System, NitroGenius

### 3.1 The multi-user system

The goal of NitroGenius is to solve the Dutch nitrogen problems against the lowest costs and social consequences. In order to do so, you can choose from a set of abatement measures and see their effect in different key parameters. The scientific basis of NitroGenius can be found in the issue of Ambio that contains all the keynotes of the conference (see Appendix A). This game is unique, because it contains an integrated nitrogen model that calculates all the N-flows on the relevant scale in the Netherlands of all sectors and all compartments. Each individual model is tested with measurement data. Furthermore, the models use databases containing relevant data on plot scale in the Netherlands. These data are detailed and not available for other areas in the world. Therefore, at this time the models can only be run for the Netherlands situation.

In this section NitroGenius is described and the different options and possibilities are presented. This is necessary to play NitroGenius. Four computers connected to each other in a network are necessary. On one computer both the server software and the client software are installed, on the other three only the client software. The server runs the models, the interaction software and the database. The outcome of the game is stored in a database on the server computer.

#### *Outline of NitroGenius*

The game can be played by 4 players. Just as in a real society four different representatives of target groups will work together to solve the nitrogen problems. The goal of the **team of four players** is to solve the Dutch nitrogen problems against the lowest costs and social consequences. However, **each player** also has its own targets, just as in real life!. He or she has to reach these targets in order to earn as much as possible individual points. At the end of the second International Nitrogen Conference in Pototmac, USA, in October 2001 the winning team and the individuals with the highest score were awarded. In order to select the winning team, a tool was developed that read the scores in the database and applied a weighting factor on the environmental and economical parameters resulting from the management options. The individual targets for the four different roles are:

1. for the agricultural representative to increase the agricultural production, make profit, with a positive image;
2. the industrialist also is concerned about his profits and his image;
3. the governmental representative wants to be elected and is therefore very concerned about the image;
4. the society wants jobs, high income and be happy!

These individual targets are not necessarily in line with the general aim of the group to solve the Dutch nitrogen problems, just as in real life! In order to make the game more attractive, during the simulation, after 4 rounds the roles will switch and each will be confronted by the budgets and measures the predecessors selected! Also the aims will change, because of the new role. During the simulation different measures can be select. The list of options change every round.

#### *Playing NitroGenius*

The game starts with an opening screen, which is the same for each player. Quickly fill in the role you want the play and push the log on button, because the first who selects a role gets it! If everybody has logged in and pushed the START button, the game has started.



Figure 3.2 *Role select screen.*

The second screen gives an overview of the individual targets (figure 3.2). At the bottom of the screen you will find information on your score, budget and the year. At the top the time is displayed that remains to select measures and to view the changes in different parameters.



Figure 3.3 The target screen for the four roles

The selection of measures to reach the targets is displayed in the third screen (fig. 4). This is probably the most important screen with links to the historical development and to the regional details. The largest part of this screen provides totally 7 measures that can be selected. Two measures are fixed: one to increase production or the income, the other to take a real effective measure. The other 5 will change during the game, depending on the amount of measures selected and the year. You can select a **maximum of 3 measures**. If your budget is not high enough you will not be able to select measures that cost money: you will have to wait until the next round, when the production or your income or tax has increased your budget. Each description of the measure gives an indication of the effect of the option on your budget and on environmental parameters. The real costs and effects can only be determined after the models have calculated the changes due to the measures selected by all four players! Certain measures can be made regional specific, for different animal categories or with different intensities. **Note: at the start the selection is full intensity, for all regions and animal categories!**



Figure 3.4 *Decision screen*

At the left and the bottom of the screen indicators are shown. All indicators are made for the whole of the country. For 4 indicators Dutch targets are displayed, if relevant. The Dutch policy aims at reaching these targets. These indicators are:

- Total nitrogen deposition: target  $14 \text{ kg N ha}^{-1} \text{ y}^{-1}$  ( $1000 \text{ mol ha}^{-1} \text{ y}^{-1}$ )
- Groundwater  $\text{NO}_3$  concentration: target  $50 \text{ mg l}^{-1}$  at 1 m depth below the surface
- Ecosystem area with an excess AOT40 of 3 ppm.hours. The AOT40 is a target for natural vegetation. There is no target for the area ecosystems with excess AOT40.
- Happiness: this is defined as the way foreigners judge the happiness of the Dutch people. It is based on criteria for the environmental conditions, GDP, employment, etc.

At the bottom the history during the game of these parameters is displayed to give an impression of the progress.

The Dutch map displays the N concentration in surface waters. The target for this parameter is  $2.2 \text{ mg l}^{-1}$ . Next to the map is the button: **details**. When this button is pushed the following screen is displayed (figure 3.5).



Figure 3.5 Screen showing details of different parameters.

The three maps show the average N-deposition,  $\text{NO}_3$  in groundwater and area excess AOT40 for the five regions in the Netherlands: North, Middle-West, Middle-East, South-West and South-East. The models calculated on  $1 \times 1 \text{ km}$  scale, but the data are aggregated to better comprehend the results. Annual emissions of  $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{N}_2\text{O}$  are displayed as country totals. Three bar charts give information per role (Agriculture, government, industry and society) on the budgets, image and no. of jobs. The current and previous data are displayed. By selecting the **<<<** button, you can view the details of all the previous rounds in order to see the changes during the game. By selecting **close** you can go back to the decision screen. Watch the time: you only have 3 minutes to make your decisions!

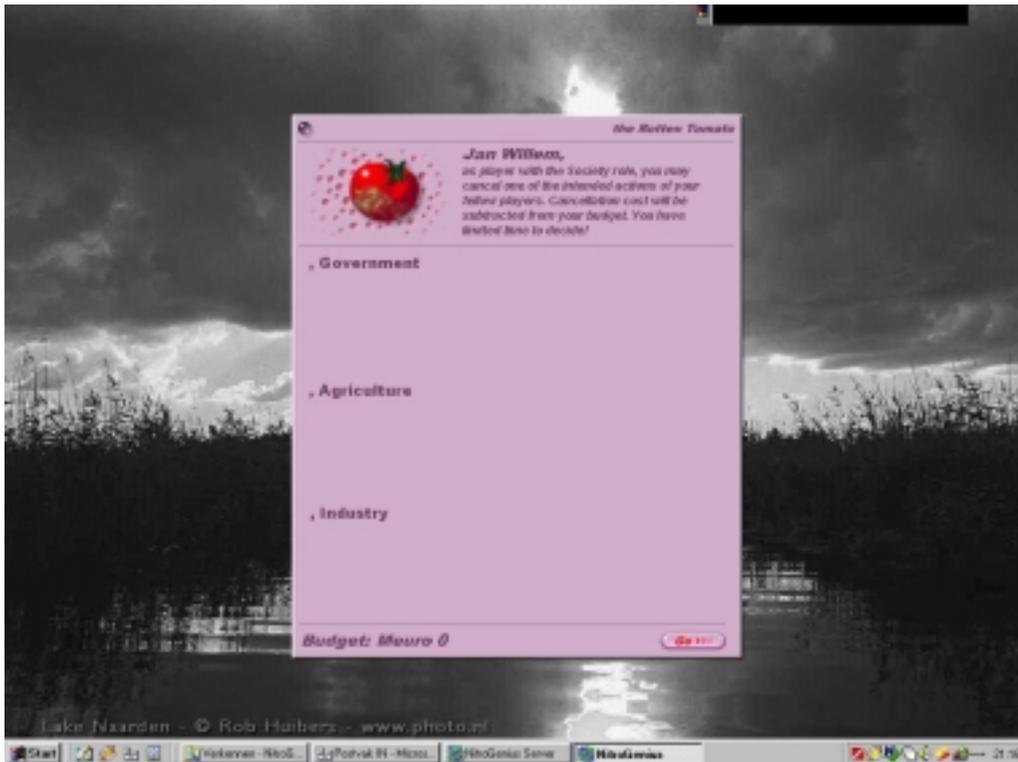


Figure 3.6 *Tomato screen.*

Click **Done** as soon as you are finished, don't wait until the 3 minutes pass. If everybody has chosen **Done**, the 'Tomato screen' appears (figure 3.6). This lists all the measures that have been selected and 10% of the costs of the measures. The measures society has selected are not displayed. The representative of Society will have one rotten tomato, which he or she can throw at one measure. This measure will then be disregarded before the models calculate the result of the selection of management options. In this way society will have an extra means to influence the happenings. The cost of 10% is always lost, whether a measure is selected by Society or not. If Society has selected **go on**, the models will start their calculations and the points, budgets and different parameters are updated. The newspaper screen will appear (figure 3.7).



Figure 3.7 Newspaper screen.

The newspaper gives headlines of the state of affairs. This is illustrative, but not necessarily relevant! More accurate information can be obtained by selecting the **effect** button. The screen that appears (Figure 3.8) gives a summary of the measures selected and the effect indications. At the bottom of the screen, the net effect of all the measures is given.



Figure 3.8 Effects screen.

Go back, select the **detail** button and view the details. These are the same as in the screen for making decisions!

After 4 rounds the roles will change and each player is confronted with new targets, but also with the history made by the fellow players. The game ends after 16 rounds (four per role). The final screen (Figure 3.9) gives an overview of the winner of the team, the highest score ever and the final state of affairs in the Netherlands in relation to environmental parameters. These parameters include: emissions of NH<sub>3</sub>, NO<sub>x</sub> and N<sub>2</sub>O, NO<sub>3</sub> concentrations in ground water and surface water, the AOT40 exceedance, happiness and profit (growth in GDP).



Figure 3.9 Final screen.

### 3.2 Single user system

Two single user versions were developed. The first version is NitroGenius in a mode for one player. He or she can select one role, the others are not used in first instance. Different management options can be selected and the computer runs the models to calculate the results. After four rounds (years), the role changes until all the roles have been played by the single-user during 4 rounds, just like in the case of NitroGenius with four players. The budgets are also calculated with the same method and are also restrictive for the measures that can be selected (3 at a maximum). The user is able to select the number of roles and the number role changes beforehand. In this way the user can determine the way NitroGenius is used and its function as decision support system.

The second version is specially developed as decision support system for policy makers that will use it as a decision support system to determine the influence of different types of, and combinations of, management options. Whereas NitroGenius has game elements that stimulates it's use and the communication between different players, NDSS (the Nitrogen Decision Support System) lets a single user study the effect of one or more

abatement measures. NDSS differs from NitroGenius mostly in the possibilities of selection of measures and the presentation of the possibilities and results. The models, abatement options, data and databases are the same. NDSS can be installed at a desktop computer, where the database is installed. When the program is started, the server will run and the models are initialised by selecting 'run NDSS' (Fig. 3.10).

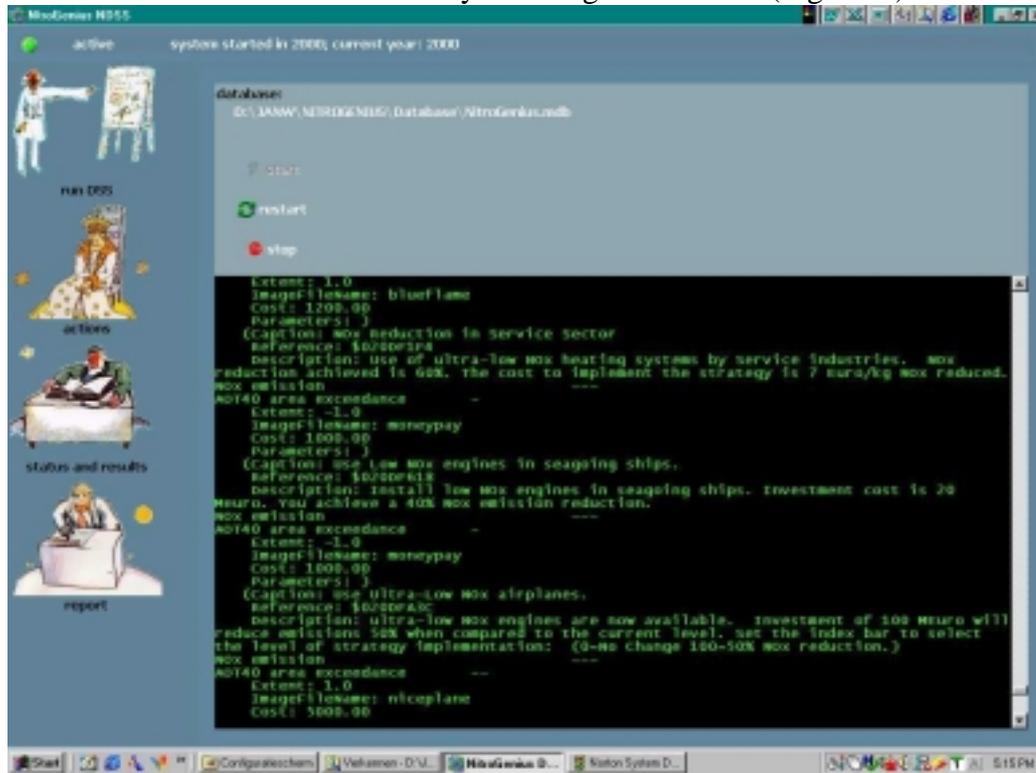


Figure 3.10 The server initialises the models.

When 'start' is selected the abatement measure screen will appear after selecting the button 'actions' (Fig. 3.11). The different measures are grouped for agriculture, government, industry and society. The different groups of measures can be selected by choosing one of the four groups. If one group is selected all the measures in the database are listed and can be selected. Different measures can be added in the database and will be in the list of options. For each measure an indication of effects and costs are given. If an option has the possibility to change the intensity or to differentiate between regions, these options are displayed and can be selected. If an option is selected, it can be added to the list by selecting 'select this action'. Options can be de-selected by 'remove this action'. All actions can be removed by 'remove all actions'. If a set of options is compiled these can be executed by 'execute actions'. Under 'Status and results' the result screen with different possibilities are displayed (Fig. 3.12).

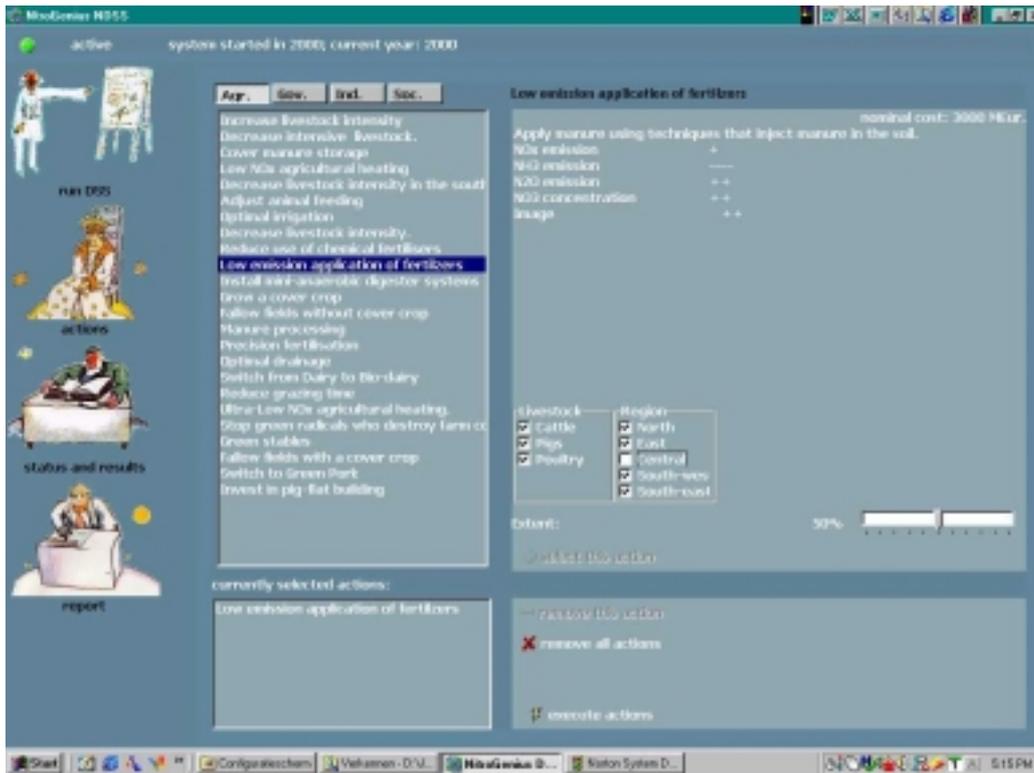


Figure 3.11 Selection of abatement measures grouped as agriculture, government, industry and society.

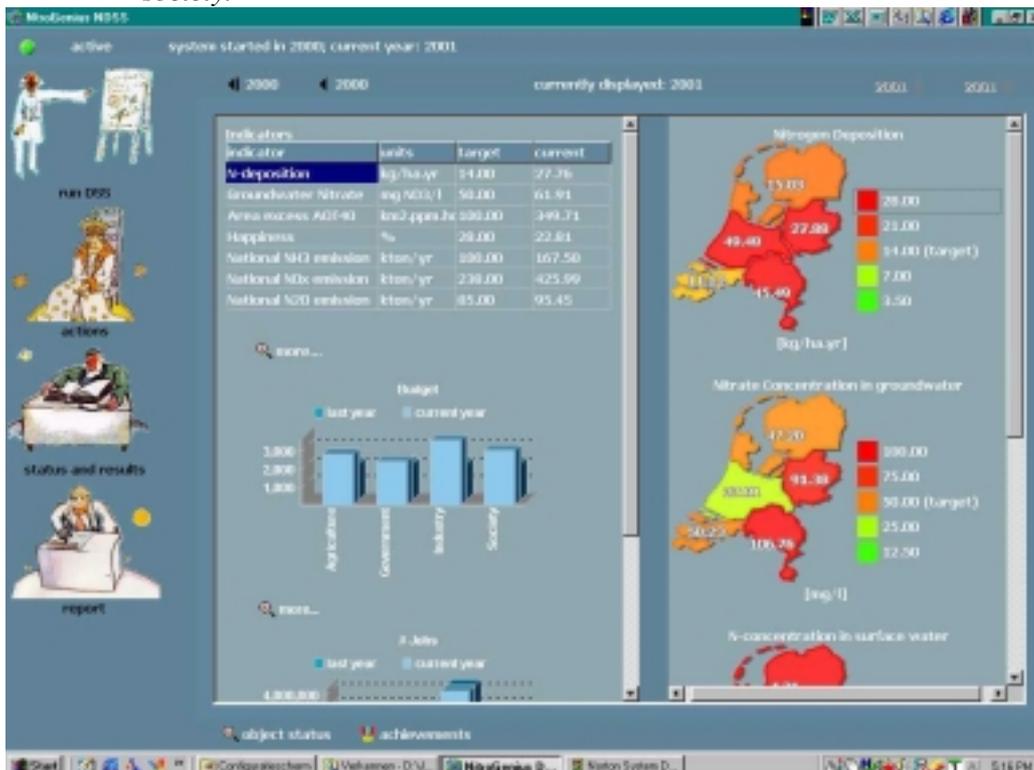


Figure 3.12 Screen displaying the results of the model calculations after selecting abatement measures.

The result screen provides maps of the Netherlands of N deposition, nitrate in groundwater and surface water and the AOT40. In a table adjacent to the maps totals (emissions) or averages (effect parameters) for the Netherlands as a whole are given. Bar charts displaying the budgets and number of jobs are given. At several places more

details can be obtained by selecting the button 'more options'. Figure 3.13 displays the screen with different emissions per sector. Figure 3.14 shows more information about the economics.

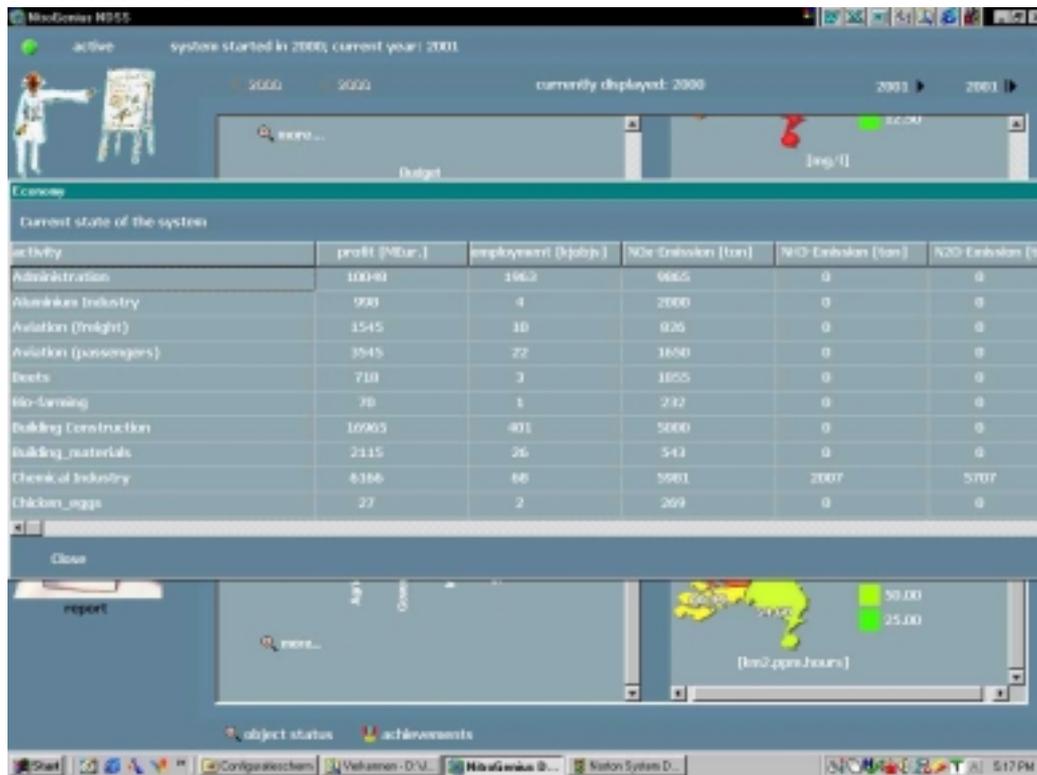


Figure 3.13 'More options' in the result screen, displaying the emissions per sector.

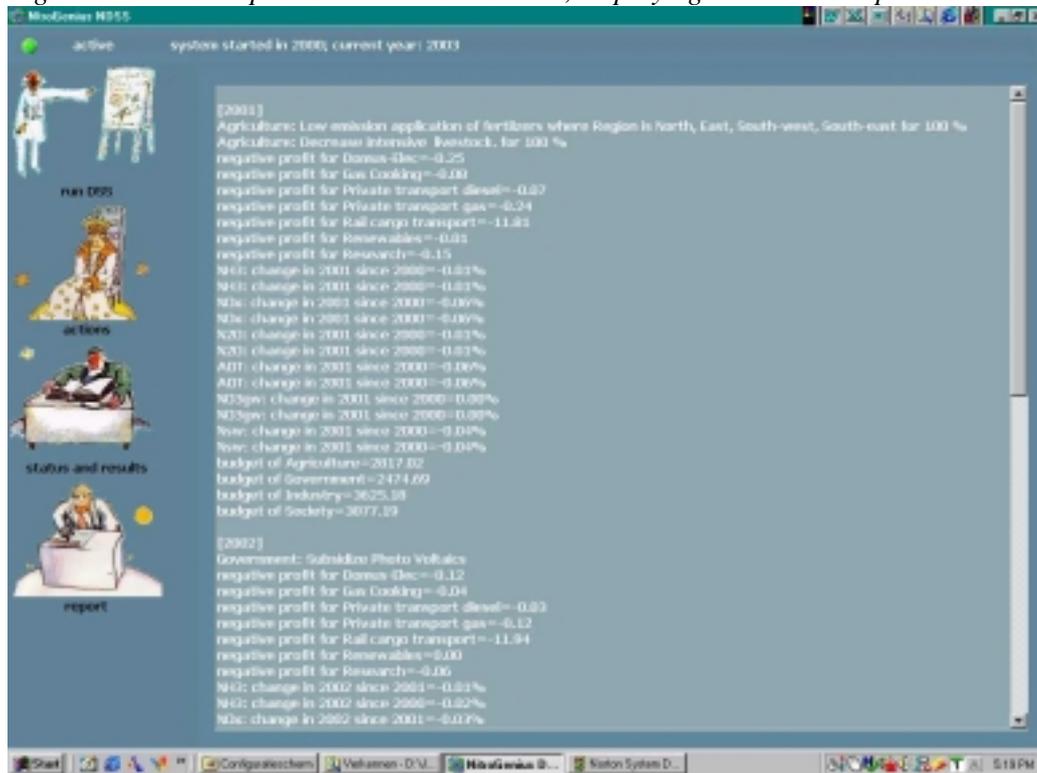


Figure 3.14 'More options' in the result screen, displaying information about the economics.

By going back to 'actions', new options can be selected and executed. The result screen displays the model results. This can be repeated without limitations. An overview of all the actions and the main results can be obtained by selecting 'Report'.

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## APPENDIX A NITROGENIUS

### **NitroGenius: A nitrogen decision support system in the form of a game to develop the optimal policy to solve the Dutch nitrogen pollution problem<sup>1</sup>.**

Jan Willem Erisman, Arjan Hensen (ECN), Wim de Vries, Hans Kros (Alterra), Tamme van de Wal, Wim de Winter, Jan Erik Wien (W!SL), Mark v.Elswijk, Matthijs Maat (SERC) and Kaj Sanders (Ministry VROM)

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### **ABSTRACT**

NitroGenius, a decision support system in the form of a game, was developed for the Second International Nitrogen Conference in order to support scientists and policymakers as they seek solutions to the nitrogen problems in the Netherlands' extensive agricultural, industrial and transportation areas.. The aim of NitroGenius is: (i) to improve the understanding of complex relationships within the nitrogen pollution situation and (ii) to search for optimal solutions and policies, which could prevent pollution and its effects, while incurring minimal economic costs and societal impacts. NitroGenius includes a modeling system, which describes all of the nitrogen flows at several relevant spatial and temporal scales. Outputs of this model include: (i) the annual emissions of ammonia, nitrogen oxides and di-nitrogen oxide to the atmosphere and (ii) the annual leaching and runoff of ammonium and nitrate to groundwater and surface water, including the resulting annual average concentrations of those compounds. An economic model was also developed to describe economic relationships occurring between all important sectors of the nation, and the effect that different actions would have on the Gross Domestic Product (GDP), unemployment, energy use and environmental quality. Several possible abatement options are described and parameterized so that their effects can be calculated using the modeling system. The modeling system and abatement options form the heart of NitroGenius. About 50 groups of people played the game during the Second International Nitrogen Conference. The results show that nitrogen problems can be solved in the Netherlands with careful planning and selection a range of abatement options.

## 1. INTRODUCTION: THE NITROGEN PROBLEM IN THE NETHERLANDS

The Netherlands is a small country in the delta of several large European rivers: the Rhine, the Meuse, and the Waal. The Netherlands has always been a country that imported raw materials to be manufactured into products for export. In addition, agriculture has always been an important economic factor. Table A.1 gives some pertinent numbers for the Netherlands [1]. Since the industrial revolution, there has been a growing overload of nutrients and related emissions into the atmosphere ( $\text{NH}_3$ ,  $\text{NO}_x$  and  $\text{N}_2\text{O}$ ) and groundwater and surface water ( $\text{NO}_3$ ). The Netherlands is known for having one of the highest reactive nitrogen emissions densities in the world. Traffic density has led to very high oxidized nitrogen emissions per hectare, and intensive animal husbandry has led to reduced nitrogen emissions.

It is well recognized that emissions of reactive nitrogen from industry and agriculture into the environment may lead to a series of environmental impacts. These impacts include: eutrophication of nature areas and surface waters, soil acidification and nitrate pollution of groundwater, particle formation leading to impacts on human health and influencing the earth's radiation balance, ozone formation leading to effects on humans and vegetation, and to climate change when it is transformed into nitrous oxide (e.g. [2,3,4]). One molecule of reactive nitrogen can thus contribute to a cascade of effects, e.g. by first contributing to direct effects, then, when deposited, to eutrophication and groundwater pollution and eventually to  $\text{N}_2\text{O}$  emissions after denitrification.

Table A.1 *Illustrative numbers related to nitrogen problems in the Netherlands.*

Some important numbers:	Environmental factors
16 million inhabitants	362 kton N input by forage
100 million poultry	396 kton N input by fertilizers
15 million pigs	90 kton N input by deposition and biological fixation
4 million cattle	180 kton $\text{NH}_3$ emissions
6 million cars	490 Kton $\text{NO}_x$ emissions
454 people per $\text{km}^2$ of land	72 kton $\text{N}_2\text{O}$ emissions
60% agricultural area of the total land area	GDP of 25 million \$ per inhabitant
Rotterdam, the largest port of the world	annual GDP growth of 3.9%
Industrial Rijnmond area with refineries, fertilizer plants, etc.	Unemployment of 5 %
Ecological Main Structure, a zone of connected nature areas through the country	
Protected areas within the Bird habitat, biodiversity habitat, etc.	

In the past decade, several measures have been taken to control reactive nitrogen emissions and limit their effects. These measures were mainly directed towards individual environmental themes such as acidification, eutrophication, climate change and dispersion. It appears that these measures are not as effective as was predicted beforehand. In some cases results were lower than expected, and in other cases the reductions made were counterbalanced by growth of the activity. Nitrogen is difficult to abate, because of the intimate linkages between its various forms: this applies equally to agriculture, where reducing  $\text{NH}_3$  emissions may increase  $\text{N}_2\text{O}$  and nitrate, and to transport emissions, where reducing  $\text{NO}_x$  emissions is leading to increased  $\text{NH}_3$  and  $\text{N}_2\text{O}$  emissions [5]. Although some technical measures can be implemented relatively cheaply, many are expensive. The most difficult sources to abate are vehicles, small combustion sources and agricultural sources. Large industrial point sources are much easier to abate, because industrial abatement technology is well developed, even though it is rather expensive.

The expected growth in food production and energy use is also important to note. The global human population is expected to continue growing while the land used for agricultural production cannot increase indefinitely. In addition, the use of fertilizers is expected to grow exponentially. Furthermore, standards of living in developing nations are expected to increase, which will also lead to a greater demand for agricultural products. Therefore, the prospects for emission reduction are limited.

Complex interactions within the nitrogen flows and the high variability of these flows in time and space not only makes the issue difficult to comprehend but also complicates the development of an efficient abatement strategy. Consequently, policy up to now has focused on parts of the system, without considering all the interactions and the possible implications for other environmental problems [5]. A decision support system could help to simplify the complexity of this situation and could also make it easy to visualize the consequences of different abatement options. Examples of successful decision support systems are the RAINS model for support of acidification abatement strategy in Europe [9] and the Integrated Modeling of Global Climate Change (IMAGE) [10]. Until now there has not been a similar system which examined nitrogen issues and included the relevant temporal and spatial scales necessary for anticipating all relevant interactions.

A decision support system containing parameterizations of the most important nitrogen flows at the relevant scale, together with parameterizations of the different policy options would enable a user to better judge the consequences of different choices and might increase the effectiveness and prevent implications for other environmental issues. A nitrogen decision support system in the form of a game (NitroGenius) was thus developed to support scientists and policymakers in finding solutions to Dutch nitrogen problems. The aim of the NitroGenius is to : (i) improve the understanding of the complex relationships within the nitrogen pollution situation in the Netherland's extensive agricultural, industrial and transportation areas and (ii) search for optimal solutions and policies which could prevent pollution and its effects, while incurring minimal economic costs and societal impacts. This paper outlines the game and its relationships, and its use. Furthermore, it describes the outcome of several sessions played by the attendees of the Second International Nitrogen Conference.

## 2. THE CASCADE OF NITROGEN AND ITS PARAMETERIZATION

The flows of nitrogen through our environment are very dynamic and are similar to the water cycle. Within the nitrogen cycle, reactive nitrogen<sup>1</sup> ( $N_r$ ) can be deposited, evaporated, retained, immobilized, mobilized, mineralized, denitrified, etc. The nitrogen cycle can be represented as a cascade, which flows with many side streams that can lead to different effects, dependent upon on the strength of the  $N_r$  source [4]. Such a cascade is depicted in Figure A.1 showing two stages, very small  $N_r$  inputs and very high  $N_r$  inputs. The cascade of reactive nitrogen in the system demands a modeling system, which can describe all the N-flows in an integrated way. Moreover, it should contain links to the carbon, sulfur and phosphorous cycles also, because that would make a real integrative decision possible [3,4]. This will be the future focus of model developments.

Models describing (part) of the nitrogen cascade in the Netherlands are ANIMO and STONE [6]. These models work to describe the nitrogen and phosphorus cycles in agriculture, especially the groundwater and surface water concentrations. Models describing ambient transport of nitrogen compounds include the lagrangian models OPS and TREND [13] and the deposition models DEADM and EDACS [7]. The National Institute of Public Health and Environment has also published the Environmental Outlook in the Netherlands [8] every 4 years since 1989, which includes a modeling system to determine the effects of nitrogen within varying environmental, social and economical parameters. These models describe the whole cycle, but differ in spatial and temporal resolution and therefore do not describe the cascade in an integrated way.

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<sup>1</sup> The term reactive nitrogen ( $N_r$ ) includes all biologically active, photochemically reactive, and radiatively active N compounds in the atmosphere and biosphere of the Earth. Thus  $N_r$  includes inorganic reduced forms of N (e.g.,  $NH_3$ ,  $NH_4^+$ ), inorganic oxidized forms (e.g.,  $NO_x$ ,  $HNO_3$ ,  $N_2O$ ,  $NO_3^-$ ), and organic compounds (e.g., urea, amines, proteins).

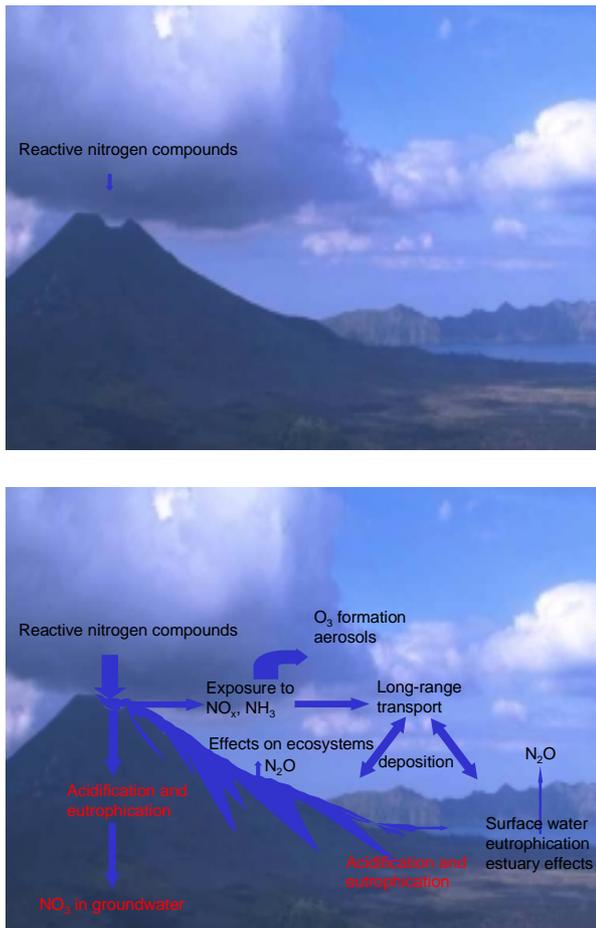


Figure A.1 *Impression of the cascade of reactive nitrogen in the environment for a situation with low input (A) and high input (B).*

### 3. THE NITROGEN DECISION SUPPORT SYSTEM, NITROGENIUS

#### *General approach*

The heart of a decision support system should contain models with simple parameterizations describing all the necessary and relevant interactions. These should be accurate enough to produce realistic results for the present time and for the future, and should be influenced by a range of abatement options. These parameterizations are usually based on complex models, which contain process descriptions and are validated with observations.

The nitrogen decision support system described here contains several coupled modules, as outlined in Figure A.2:

- a module to calculate emissions to the air based on activities and abatement options
- a module, called INITIATOR, to describe the agricultural nitrogen flows and emissions to groundwater and surface water
- a deposition model and a module to calculate ozone concentrations and effect parameters
- a sociological and economic module

The different modules are described in following sections of this paper. The models and their parameterizations are usually based on complex models, which contain detailed process descriptions and are validated with observations. The nitrogen decision support system described here was developed for the Netherlands because of the country's large nitrogen problems, and the availability of data that are necessary to run the models. There are two ways to use this modeling system. It can be used as a single user nitrogen decision support system, or as a multiple user game (NitroGenius). In both cases all modeling components are involved and in this paper we only use the term NitroGenius to describe the contents of the system.

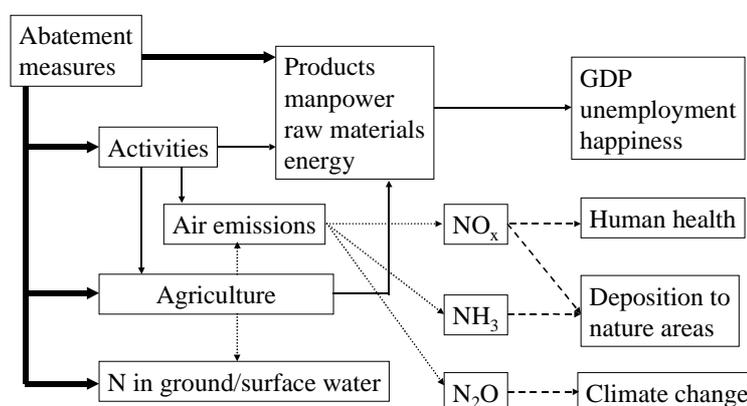


Figure A.2 Outline of the Nitrogen Decision Support System, NitroGenius.

#### *Emission module*

Emissions for all sectors except agriculture are calculated by multiplying an activity with an emission factor. The activity is defined as a product (volume) for an individual sector. The different sectors are defined in Table A.2. The emission factor is the emission per component per product (volume) of that sector. The starting point of NitroGenius (initialization) is the current (1995 – 2000) distribution of the nitrogen sources in the Netherlands and the appropriate emission factor. Abatement options change the current emission by changing the emission factor, the product (volume), or the place of production. Furthermore, a shift in emissions can take place if abatement options lead to emissions of other components. The spatial distribution of emissions is mapped on a 5 x 5 km grid that serves as input for the transportation/deposition module. The database contains large industrial sources with their stack height and exact location. Agricultural emissions are calculated by the INITIATOR module, which is described in the next section.

The user of NitroGenius can test different or new abatement options. In order to evaluate these options a comparison can be made with autonomous development of the activity/emissions, which is based on current policies in the Netherlands [8]. Foreign sources will either change according to the Dutch policy, the current EU policy [11], or they be influenced by the options selected by the user. Different abatement options are discussed in greater detail later in this paper.

*Nitrogen flow model for the agricultural and aquatic system: INITIATOR*

INITIATOR is a simple nitrogen balance model based on empirical linear relationships between the different nitrogen fluxes in the agricultural system [12]. The linear transformation constants are a function of the type of manure, land use, soil type and/or hydrological regime. A flow-chart of the module is given in Figure A.3. In agricultural systems, first the total input at the soil surface is calculated by adding available data on the input by animal manure, fertilizer, atmospheric deposition (from all sources), and biological nitrogen fixation. The  $N_r$  losses from the terrestrial system are calculated as a function of soil type, land use, and hydrology, assuming a sequence of occurrences in the order of ammonia emissions, followed by nitrogen uptake, nitrogen accumulation/immobilization, nitrification, and denitrification in the soil. All nitrogen transformation processes are linearly related to the inflow of  $N_r$  (first order kinetics), as in a cascade. This implies that ammonia emission due to application depends linearly on the  $N_r$  input at the soil surface,  $N_r$  uptake on the  $N_r$  input minus the  $NH_3$  emission,  $N_r$  immobilization on the input minus the  $NH_3$  emission minus  $N_r$  uptake, etc. The parameterization of the equations for estimating the  $NH_3$  loss was done in such a way that it included all  $NH_3$  losses, including those from animal housing and manure storage systems and from the application of animal manure, fertilizers, and dung and urine from grazing animals to the soil. In the approach it was implicitly assumed that the manure that was applied to the soil in a given grid cell (external data) came from the farms in the same grid cell.

The flux of  $N_r$  leaving the terrestrial system is calculated by subtracting all  $N_r$  losses in the system (emission, uptake, net accumulation and denitrification) from the input to the soil. The leaching loss from the terrestrial systems is partitioned to surface water and to groundwater by multiplying the leaching loss with a runoff fraction (including all pathways for  $N_r$  moving to surface waters) and a leaching fraction (1- runoff fraction), respectively. Since we are interested in the leaching of  $N_r$  to the groundwater at 1-meter depth below the phreatic level (the depth where nitrate concentrations are measured in the Netherlands), denitrification of  $N_r$  in upper groundwater is also considered. The processes considered relevant in aquatic systems are  $N_r$  retention in ditches and larger surface waters, retention being distinguished in denitrification and accumulation in the sediment. Denitrification is thus calculated in the soil, upper groundwater, ditches, and surface water (see Figure A.3). We considered run-off from terrestrial systems and direct atmospheric deposition of  $N_r$  to surface waters as input of  $N_r$  in aquatic systems. The various  $N_r$  outputs from - and the  $N_r$  immobilization in soil, groundwater and surface water are calculated with a consistent set of simple linear equations as described in [12].

The output of INITIATOR consists of aggregated  $NH_3$ ,  $NO_x$  and total  $N_2O$  emissions from agriculture on 5 x 5 km scale and  $NH_4$ ,  $NO_3$  and total N concentrations in groundwater and surface water.

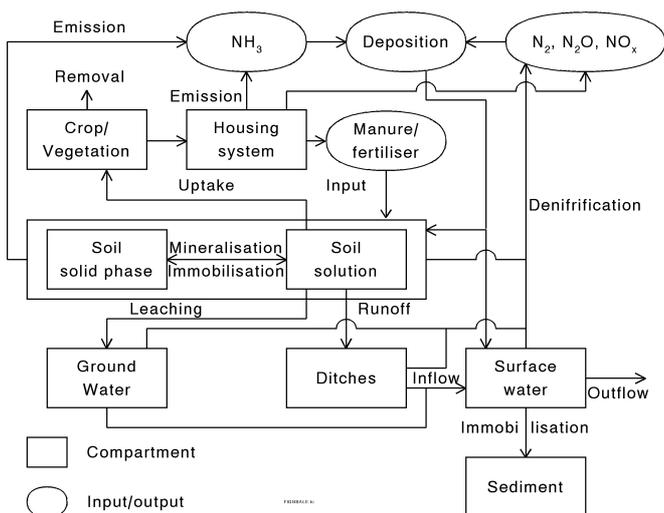


Figure A.3 Outline of the INITIATOR model

### Deposition and ozone model

Deposition is calculated by source-receptor matrices on a 5 x 5 km grid scale as derived from the OPS Gaussian dispersion model [13]. In each grid cell, a source strength was assigned and the fraction of the emission calculated after dispersion and deposition for all the grids covering the Netherlands and abroad was kept in a database. The source-receptor matrices (SRM) are the sum of all these fields [a/o 14,15]. The SRM use annual average emissions to calculate annual average deposition on a 5 x 5 km scale for NH<sub>3</sub> and NO<sub>x</sub> for high and low source heights. Source-receptor relations have been applied successfully in integrated assessment modeling, such as the RAINS model [9, 14, 16]. The deposition resulting from foreign sources was calculated for the year 2000. For other years, scenario values were calculated by taking the ratio of the new emissions versus the 2000 emissions. The deposition maps of NO<sub>y</sub> (sum of HNO<sub>3</sub>, NO<sub>x</sub> and NO<sub>3</sub>) and NH<sub>x</sub> (sum of NH<sub>3</sub> and NH<sub>4</sub>) are added to obtain the total nitrogen deposition. Following the recent Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (1999), the so-called Multi-pollutant, Multi-effect Protocol, ecosystem vulnerability has been determined for the formulation of reduction requirements in terms of critical loads and levels.) An ecosystem-specific critical load map for the in the Netherlands was created, based upon available data for critical nitrogen loads related to impacts of nitrogen deposition on biodiversity, nutrient imbalances, and groundwater quality [16]. The exceedance of critical loads is calculated by subtracting the critical loads from the total nitrogen deposition per grid.

Ozone is a secondary pollutant formed in the atmosphere in the presence of sunlight from the precursor emissions of nitrogen oxides and volatile organic compounds (VOCs). Due to the long atmospheric residence time of NO<sub>x</sub> and VOC compounds, ozone is created both from local emissions as well as from precursors emitted at distant locations. For agricultural crops and herbaceous plant communities (natural vegetation), the critical level for ozone exposure is set to an Accumulated Ozone exposure Threshold of 40 ppb (AOT40) of 3 ppm.hours [17]. No simple ozone model was available to include in NitroGenius.

To simplify the inclusion of the complex photo-stationary equilibrium, national VOC and NO<sub>x</sub> emissions in European countries were used to derive an estimate of annual average ozone concentrations. A linear relationship was found between ecosystem area weighted annual average AOT40 excess values of 3 ppm.hours in different countries and their total VOC and NO<sub>x</sub> emissions. Multiple regression gave the following relationship:

$$\text{Excess AOT40} = -1.78 \text{ NO}_x + 2.26 \text{ VOC} \quad (R^2 = 0.62). \quad [1]$$

Where:

Excess AOT40 = AOT40 value in excess of a critical level of 3 ppm.hours multiplied by the area of ecosystems exposed to this excess concentration (1000 km<sup>2</sup> ppm.hours)

NO<sub>x</sub> = Annual NO<sub>x</sub> emission (kton)

VOC = Annual VOC emission (kton)

The same dataset gave the following equation for annual VOC emissions:

$$\text{VOC} = 1.06 \text{ NO}_x + 35 \quad (R^2 = 0.97). \quad [2]$$

The cumulative vegetation exposure index (Excess AOT40) in Eq. 1 is calculated as the AOT40 in excess of the critical level of 3 ppm.hours multiplied by the area of ecosystems that are exposed to excess concentration [17]. Figure A.4 shows the relationship between excess ozone exposure and VOC and NO<sub>x</sub> emissions. There are no critical excess levels. The ultimate goal is to go down to zero, but as shown in Figure A.4 this would mean almost zero emissions. From Figure A.4 a critical value of 100 (1000 km<sup>2</sup> ppm.hours) seems reasonable, at emissions of 100-200 kton of VOC and NO<sub>x</sub>.

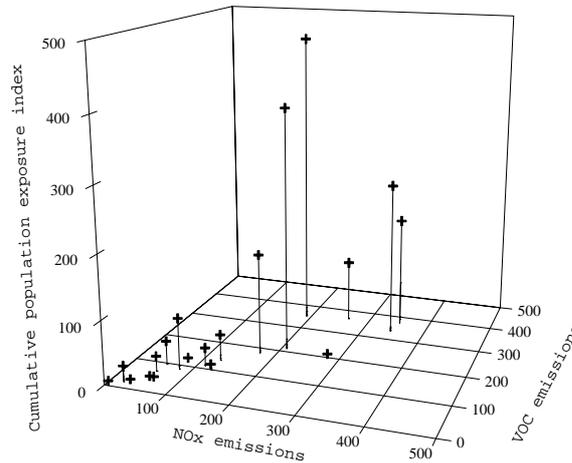


Figure A.4 *Three-dimensional plot showing excess ozone AOT40 values for ecosystems in the Netherlands as a function of total VOC and NO<sub>x</sub> emissions (kton).*

### *Socio-economic model*

Economic and social aspects play a very important role for the acceptance of environmental measures/control. NitroGenius has an economic model for the evaluation of these aspects, based on available data in the Central Bureau of Statistics [18]. In this module the main economic sectors in the Netherlands that contribute to the Gross Domestic Product (GDP) are included. The sectors distinguished are given in Table A.2. For each sector the current (1998-2000) production volume, costs, fuel and electricity use, raw and other materials, number of jobs, salary (all per region), and emissions were obtained from different sources (a/o [1, 18]) and stored in a database. These data form the starting point for the economic module in NitroGenius. Other sectors influencing GDP (but not affected by the measures included in the module) are taken into account by a “business as usual scenario,” leading to an annual GDP growth of 3%. Using all parameters for the different sectors in Table A.2, the current production volume, GDP, and unemployment rate are calculated and compared with the official number given by the Dutch Central Planning Office. The current GDP in the Netherlands is 373 Geuro. The contribution of the different sectors to the current GDP is given in Table A.2. The different

abatement options (see next section) which influence or change different parameters of the economic model and its effects are calculated accordingly.

Table A.2 *Sectors, sub categories and roles distinguished in the economic model and their contribution to GDP in 2000.*

Sector	Sub categories	Role in NitroGenius	Contribution to GDP in 2000 (%)
Agriculture	production of meat (veal, chicken, pork), dairy, eggs, crops (potatoes, beets, wheat, corn, other), bio-farming and horticulture	Agriculture	3
Industry	Refineries, steel, aluminum, zinc, paper, chemical, fertilizer, building materials and other	Industry	17
Energy	Oil, gas, coal, H <sub>2</sub> , renewables and energy distribution	Industry	4
Transport	Private (petrol, diesel, gas), industry diesel, water (inland, overseas), aviation (freight, passengers), rail (cargo, passengers),	Industry/ consumer	2
Waste management	Processing, water treatment, incinerators	Industry	0
Administration	Administration, research, subsidy, taxes	Policy	1
	Trade and services		73

### *Abatement options*

The abatement options form an important part of the decision support system. Within the NitroGenius modeling system, a separate database is used for these options. It contains the name of each option and a unique code, a brief description, its impact on certain defined (model) parameters, and the sectors, which it will affect. This database can be modified or extended separately from the models. It is therefore very flexible and new options can be tested directly. Currently there are more than 300 options available in the database. Examples include:

- increasing or decreasing production of different kind of animals within the agricultural system,
- changing the use of fertilizer,
- optimization of fertilizer and organic manure,
- changing concentrate composition and imports,
- changing energy sources for different sectors (switching to gas),
- implementing catalysts to reduce NO<sub>x</sub>,
- stimulating public transport,
- installing fuel cells in cars or in houses,
- implementing renewables,
- subsidizing or taxing different activities or products,
- implementing emission ceilings,
- implementing waste processing,
- carbon sequestration.

There are no scenarios in the system, apart from the population growth and an annual standard growth of the production in the different sectors, based on the average growth. The user compiles his/her own scenario by selecting different options. In NitroGenius the certain sequence of measures appearing is programmed, but not fixed, as the options per role change according to selections made by the players.

### *Data*

In order to run NitroGenius, an extensive database is necessary. Spatially differentiated data on land use, soil characteristics, hydrology (groundwater levels, drainage, run-off), sources (emissions to the atmosphere per sector) and manure and fertilizer application data are

necessary. Furthermore, models use spatial data on meteorology (temperature, wind speed, precipitation). For the abatement options, data on costs per activity and measure, employment per sector, etc. are used, next to gross economic data per sector. Model parameters include emission factors, de-nitrification, retention, immobilization, mineralization, evaporation, transpiration and interception rates as a percentage of the nitrogen or hydrological flows.

## 4. PLAYING WITH NITROGENIUS

### *Gaming*

Games and simulations are very closely related. In fact, a game could be thought of as a simulation that determines the consequences of actions taken by one or more actors (players) within the simulated world. In other words, the actors become part of the simulation - the 'human factor.' Players will be confronted with the results of their own actions and the actions of others and can act upon them.

To be effective as a game, a number of restrictions apply to the simulation model. First of all, players should have a clear goal and have access to an appropriate but limited set of actions they can take. The simulation also must provide quick responses to player actions that give adequate insight into the consequences of the choices made. (See [19, 20] for a more elaborate description of games in relation to simulation.) Although restricted as a simulation, games are useful for many reasons, including:

- Games allow decision makers to experiment in a safe and cost-effective way (NitroGenius supports, within its game limits, analysis of what-if scenarios);
- Games can be used for awareness building (NitroGenius, for instance, can be used to make people aware of the integral nitrogen issues). – The fact that playing games could also be fun only strengthens this effect;
- Games support knowledge transfer and can help novices understand complex theories and problems (e.g. NitroGenius can be used during lectures to demonstrate effects of different actions);
- Games can provide insight into complex problems (even for experts because sometimes the complexity of a given situation is too difficult to comprehend).

### *NitroGenius*

NitroGenius was developed as a game where four players, each with a different role could select abatement options with the aim of solving the Dutch nitrogen problem while incurring minimal economic costs and societal impacts. The players become a politician, consumer, industrialist or farmer, and the four roles form a group and play the game together. Each player has their own aims and score but the group should be focused upon the main aim of solving nitrogen problems. Each game has an individual winner who fulfills his/her aim best and the group that fulfills the overall aim best also wins. The aim of the industrialist and farmer is to make money, of the politician is to have a good image and of the consumer is to become and/or stay happy. For the latter, a happiness indicator was developed. The happiness indicator increases when the environmental condition and the economic situation improve. Furthermore, if the consumer's salary increases, the happiness indicator increases. Each player starts with a budget, which is based on the economy and develops according to the different options selected during the game.

NitroGenius runs over a hypothetical timeline of 30 years, divided over several sessions. Each session lasts no more than three minutes, during which time the players can choose from seven different options belonging to their role. The screen with option selections also includes a lumped and a detailed overview of different environmental model outputs, such as nitrate in groundwater, total nitrogen in surface water, nitrogen deposition and annual NH<sub>3</sub>, NO<sub>x</sub> and N<sub>2</sub>O emissions. There are also socio-economic model outputs, such as the GDP and unemployment rate per sector, which are needed in order for the players to make decisions. The changes over time of the parameters can also be obtained. When the politician, industrialist and farmer have selected their options, the consumer has the option of blocking one of the actions taken by the three others, thereby providing balanced input in the game. Then the session closes, the models run and the effect on the different model outputs is estimated. For several options the region and the intensity of the action can be specified. A newspaper appears after each session showing the main developments and a list of actions taken. As the next round proceeds, several new abatement options are available and the selection and calculation processes start again.

Environmental disasters can happen, depending on the development of different model outputs. The whole game session lasts about one hour. Figure A.5 provides a few screenshots of NitroGenius.



A

B



C

D

Figure A.5 Screenshots NitroGenius: A. role selection and introduction, B. selection of abatement options, C. detailed overview of different parameters, and D. newspaper with session overview.

## LESSONS LEARNED FROM GAME RESULTS

The game was played at the Second International Nitrogen Conference, 18-21 2001 October, USA. The outcome of each session was stored and the results were analyzed. More than 85 people in about 50 groups played the game during the conference. The results of each round (actions taken and changes in parameters) were stored in a database, together with the end results of each game. The 50 plays were analyzed. Several groups were able to solve the Dutch nitrogen problem, defined as effect parameters below the targets set by the Dutch government. Many of these teams, however, came to the result with large social and/or economic consequences. Figure A.6 e.g. shows the profit, defined as the growth of GDP after each play, versus the environmental score. The environmental score was calculated as the weighted average of all the environmental parameters including emissions to the atmosphere, effects on ecosystems, human health and climate change. It is clear that when very little environmental progress is made, the growth in the GDP is high. However, very high environmental progress can be made both with very high and very low GDP growth! This shows that it is very important to have a good strategy and sequence when exercising management/abatement options. The team that scored best did not initially start by selecting abatement options, but first acted to increase their budget by increasing production. Then, after their budget had grown they implemented abatement options to reach the targets. Figure A.6 shows that it is possible to solve the Dutch nitrogen problem by annually using only 0.5% of the annual growth in GDP, which is 2.5 – 3% (2.5 –3% of what?) per year, for abatement options.

The feedback received from those who played NitroGenius was very positive. Many expressed thoughts that it could be used for educational purposes, for demonstrating the complexity of the nitrogen problem, and as a decision support system and a tool to help different kinds of community stakeholders communicate better and understand and appreciate each other's points of view.

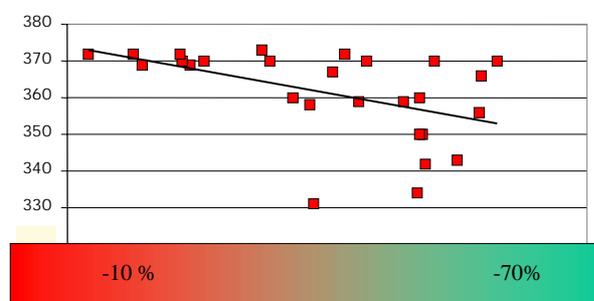


Figure A.6 *Growth in GDP (profit) versus the environmental score.*

## CONCLUSIONS

The many interactions in the nitrogen cycle and cascade of nitrogen's effects make it necessary to have a simple, accurate instrument to show all the consequences of different abatement options targeted at decreasing environmental impacts. In principle this holds not only for the nitrogen cycle, but also for other cycles in the environment, such as carbon, phosphorus and sulfur, and their respective interactions. In the future such interactions should be included in a support system for decision makers. We have developed a nitrogen decision support system, based on a parameterization of the relations and interactions in the nitrogen cycle of the Netherlands, related to many different activities and products and their economic and social aspects. The system provides insight into different emissions to soil, air, and water produced by different economic sectors and activities. Several indicators are calculated in order to evaluate the full impact of different abatement options. These indicators include environmental parameters, such as nitrate in groundwater and surface water, ambient emissions of NO<sub>x</sub>, NH<sub>3</sub> and N<sub>2</sub>O, nitrogen deposition and exceedances of critical nitrogen loads for ecosystems and critical ozone exposure levels. Several abatement options are parameterized and included in a database, which can be modified separately from the model system. In this way the system can be extended or modified by the user, without changing the system.

The decision support system can be used as single user system or as a game where four players take on different individual roles: politician, farmer, consumer and industrialist. The aim of the team during one play is to solve the Dutch nitrogen problem while incurring minimal economic costs and societal impacts. Furthermore, each player has his or her own target. In this way the game simulates a society where the different interests of target groups might interfere with one another. This could help to solve conflicts and improve relations in situations where stakeholders have conflicting interests.

The game and the decision support system proved useful during the Second International Nitrogen Conference in the US in 2001. NitroGenius provided insight into relationships and impacts of nitrogen in the environment. Furthermore, different teams playing the game during the conference provided optimal solutions. A range of solutions were recorded showing that the nitrogen problems in the Netherlands can be solved, but the pricetag on solutions can range from spending the entire annual growth in GDP of 2.5% on abatement measures to spending only 0.5% of that growth! The next step will be to have the game played by policy makers, industrialists and consumers, in order to develop an optimal real life solution for nitrogen problems in the Netherlands.

## ACKNOWLEDGEMENT

The Ministry of the Environment, VROM, Wageningen Software Labs and SERC are acknowledged for their financial support. We thank Julio Mosquera and Julie McDill of ECN for their useful input.

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## APPENDIX B ASSESSMENT OF NITROGEN PRODUCTION CEILINGS ON A REGIONAL SCALE AVOIDING ADVERSE ENVIRONMENTAL IMPACTS

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## Abstract

In the Netherlands, high traffic density and intensive animal husbandry has led to very high emissions of reactive nitrogen into the environment. This does lead to a series of environmental impacts, including: (i) nitrate contamination of drinking water, (ii) eutrophication of freshwater lakes, (iii) acidification and biodiversity impacts on terrestrial ecosystems and (iv) global climate change induced by emissions of  $N_2O$ . Measures to control reactive nitrogen emissions were up to now directed towards different environmental themes such as acidification, eutrophication and climate change. Here we summarize the results of a study to analyze the nitrogen problem in the Netherlands in an integrated way, which means that all relevant aspects are taken into account simultaneously. A simple N balance model was developed, representing all crucial processes in the N chain, to calculate maximum acceptable nitrogen inputs to the farm (so-called N ceiling) and to the soil surface (application in the field) by forage, organic manure, fertilizer, deposition and N fixation. The maximum acceptable N inputs were calculated on the basis of critical limits for nitrate concentrations in ground water and nitrogen concentrations in surface water and ammonia emission targets related to the protection of biodiversity of natural areas. Results show that in most parts of the Netherlands, except the western and the northern part, the ammonia emissions derived from critical N loads for nature areas are more restrictive than those based on limits for both ground and surface water. On the national scale the maximum allowable N import ranges between 346 and 856 kton per year depending on the choice of critical limits. The current N import is 848 kton per year. A reduction of 60% is therefore needed to reach the ceilings necessary to protect the environment against all adverse impacts of nitrogen pollution from agriculture.

## 1. INTRODUCTION

Human interference in nutrient cycles has increased greatly over the last two centuries. Compared to the preindustrial era, human activities (i.e. agriculture, industry and traffic) have roughly doubled the amount of nitrogen that enters the biosphere (Galloway et al., 1995; Smil, 1999). Industrialisation and increasing traffic have rapidly increased fossil fuel consumption during the last century, also contributing to increased levels of nitrogen in the environment. In various countries in western Europe, nutrient inputs and outputs have even more than doubled, as a result of the intensification of the agriculture through increases in fertilizer consumption and animal production and by industrialisation and increasing traffic (Smil, 1997; Socolow, 1999). On a global scale, the intensification of agricultural production will continue to increase further, as the quest for food and animal protein continues, in response to the increasing human population and the increasing prosperity of a great part of the human population (Tilman et al., 2001).

Human interference with the biogeochemical nutrient cycles generally lead to imbalances in nutrient budgets. The recognition that imbalances are not sustainable in the long term has given the impetus to use nutrient budgets as indicators and policy instruments for nutrient management planning. The Netherlands is one of the countries with the highest reactive nitrogen emissions density in the world, where reactive nitrogen stands for all forms of oxidized and reduced nitrogen except for  $N_2$ . The animal manure production in the Netherlands is approximately five times the average European value (OECD, 2001). These enhanced levels of reactive nitrogen in the environment (in air, soil, ground water and surface water) lead to a cascade of effects. Observed effects in the Netherlands include: (i) decreased species diversity and acidification of non-agricultural soils, (ii) eutrophication of surface waters, including excess algal growth and a decrease in natural diversity, (iii) pollution of ground water due to nitrate leaching, (iv) global warming due to  $N_2O$  emissions and (v) air pollution by ozone for which  $NO_x$  is a precursor (Erismann et al., 2001, De Vries et al., 2001).

At present, different targets are defined in the Netherlands that are directed towards different environmental themes such as eutrophication, acidification and climate change. To reduce the leaching of nitrate to groundwater and the runoff of nitrogen to surface waters, N loss targets have been set, where N loss stands for the difference between inputs and outputs at farm level. Annual N loss targets are 60-100 kg N per ha for arable land and maize land and 140- 180 kg N per ha for grassland by the year 2003, depending on the drainage status and soil type. These targets aim at an N leaching and runoff such that the  $NO_3$  concentration in upper groundwater stays below the EU quality criterion of 50  $mg.l^{-1}$  and the N concentration in stagnant surface waters below a target of 2.2  $mg.l^{-1}$ . A Mineral Accounting System (MINAS) has been introduced as regulatory policy instrument in agriculture to reach the above-mentioned N loss targets and to fulfil the EU nitrate directive. Furthermore, the EU proposed that the maximum animal manure application should be 170  $kg.ha^{-1}.yr^{-1}$ .

The original Dutch policy objectives for ammonia emissions were a 50% reduction by the year 2000 and of 70% by the year 2005, compared to the emissions in the year 1980 of 200 Gg  $NH_3-N$  (LNV, 1993). Recently, the Dutch Ministry of Environment has set national ammonia emission targets in Gg  $NH_3.yr^{-1}$  of 100 for the year 2010, 50 for the year 2020 and 30 for the year 2030 to avoid adverse impacts (specifically in view of biodiversity) on natural ecosystems. In 1995 annual ammonia emissions in the Netherlands were estimated at 146 Gg  $NH_3-N$ , equivalent to 175 Gg  $NH_3$  (After RIVM/CBS, 1999), implying a succeeding reduction in ammonia emissions of approximately 45%, 70% and 80% compared to this target year. Finally, the emission target for  $N_2O$  is a 6% reduction compared to 1995, whereas the ultimate target is background emission.

On the basis of the above-mentioned targets, several measures have been in the Netherlands to control the reactive nitrogen emissions and limit its effects. It appears that these measures are not as effective as predicted beforehand, either because its effectiveness is lower than expected or it is compensated by growth of the activity. Furthermore, it was found that measures taken to decrease emissions have led to a shift in other emissions. Examples of this are the prohibition to apply slurry in winter to decrease leaching of nitrate, which induced higher ammonia emissions because slurry was applied at higher temperatures (Erisman et. al., 1998). The example given above illustrates the need for an integrated nitrogen approach, since measures to reduce N leaching negatively affects N impacts due to eutrophication and acidification of natural ecosystems. This has led to discussion about the possibilities to develop a more successful nitrogen policy.

To allow the implementation of an integrated nitrogen policy, we calculated 'regional specific ceilings for reactive nitrogen'. The nitrogen ceiling is defined as the maximum amount of reactive nitrogen that is allowed in the environment which does not lead to exceedance of critical limits or targets within or outside the region, that aim to protect the environment. Examples are critical limits for ambient concentrations of reactive N in the atmosphere ( $\text{NH}_3$ ,  $\text{NO}_x$ ,  $\text{N}_2\text{O}$ ), deposition of reactive N to sensitive areas (critical N loads) and concentrations of  $\text{NO}_3$  or total N in groundwater and surface water. In this paper, we present results of calculated nitrogen ceilings for various criteria with respect to environmental protection, using a simple model on the nitrogen balance in terrestrial (agricultural) and aquatic ecosystems on a national scale. Criteria are limited to targets for ammonia emission and concentrations of  $\text{NO}_3$  or total N in groundwater and surface water, that are most limiting the maximum acceptable N input in agriculture.

## MODELLING APPROACH AND MODEL APPLICATION

### *Modelling approach*

To gain insight in the uncertainty of all major nitrogen flows in the Netherlands, a model was developed called INITIATOR (Integrated Nitrogen Impact Assessment model on a Regional Scale), representing all crucial processes in the N chain by simple process descriptions. A flow chart of the considered N inputs and N transformation processes in the model for both terrestrial and aquatic ecosystems is given in figure B.1. This flow chart is a simplified picture of the fate of N that enters the terrestrial system. We have chosen for a simple approach to maintain transparency and to be able to apply the model with available data.

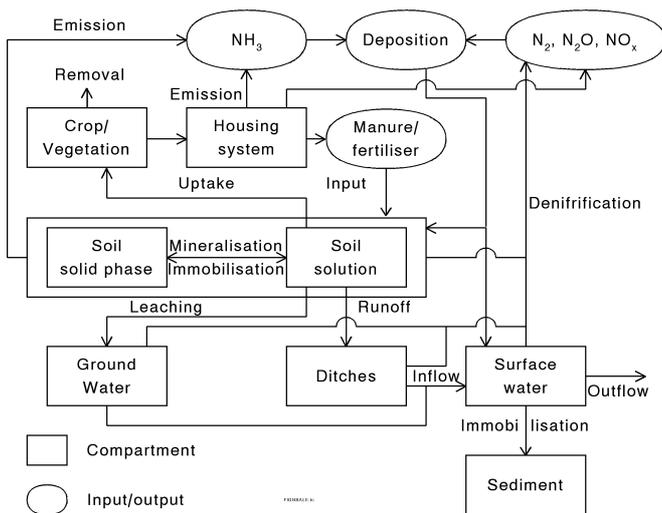


Figure B.1 Overview of the N inputs and N processes in terrestrial and aquatic ecosystems considered in INITIATOR.

INITIATOR is a simple N balance model based on empirical linear relationships between the different N fluxes. In agricultural systems, first the total input at the soil surface is calculated by adding available data on the input by animal manure, fertiliser, atmospheric deposition and biological N fixation. The N losses from the terrestrial system are calculated as function of soil type, land use and hydrology, assuming a sequence of occurrences in the order ammonia emissions, followed by N uptake, N accumulation/immobilisation, nitrification and denitrification in the soil. All N transformation processes are linearly related to the inflow of N (first order kinetics). This implies that ammonia emission due to application depends linearly on the N input at the soil surface, N uptake on the N input minus the NH<sub>3</sub> emission, N immobilisation on the input minus the NH<sub>3</sub> emission minus N uptake etc. The linear transformation constants are a function of type of manure, land use, soil type and/or hydrological regime. The parameterisation of the equations for estimating the NH<sub>3</sub> loss was done in such a way that it included all NH<sub>3</sub> losses, including those from animal housing and manure storage systems and from the application of animal manure, fertilisers and dung and urine from grazing animals to the soil. In the approach it was implicitly assumed that the manure that was applied to the soil in a given grid cell (external data) came from the farms in the same grid cell.

The flux of N leaving the terrestrial system is calculated by subtracting all N losses from the system (emission, uptake, net accumulation and denitrification) from the input to the soil. The leaching loss from the terrestrial systems is partitioned to surface water and to groundwater by multiplying the leaching loss with a runoff fraction (including all pathways for N moving to surface waters) and a leaching fraction (1- runoff fraction), respectively. Since we are interested in the leaching of N to the groundwater at 1-meter depth below the phreatic level (the depth where nitrate concentrations are measured in the Netherlands), denitrification of N in upper ground water is also considered. The processes considered relevant in aquatic systems are N retention in ditches and larger surface waters, retention being distinguished in denitrification and accumulation in the sediment. Denitrification is thus calculated in the soil, upper ground water, ditches and surface water (compare Figure 1). We considered runoff from terrestrial systems and direct atmospheric deposition of N to surface waters as input of N in aquatic systems. The various N outputs from - and the N immobilisation in soil, ground water and surface water are calculated with a consistent set of simple linear equations as described in De Vries et al. (2001).

The unique point of INITIATOR is that the model is also able to calculate a maximum allowable nitrogen input to the soil or nitrogen ceiling in agriculture on the basis of different quality criteria. This includes a critical limit for the  $\text{NO}_3$  concentration in upper groundwater ( $50 \text{ mg.l}^{-1}$ ), for the N concentration in stagnant surface water ( $2.2 \text{ mg.l}^{-1}$ ) and  $\text{NH}_3$  emission targets (Erisman et al., 2001). The maximum allowable nitrogen input to the soil equals the N inputs in animal manure, fertilizer, deposition and biological N fixation, whereas N ceilings on farm level are equal the maximum allowable N inputs in feed products, fertilizer, deposition and biological N fixation.

As stated before, the model calculates N leaching and runoff from the N input minus ammonia emission, net N removal through agricultural products, N immobilization and denitrification in both soil and surface water. Since all N loss fluxes from the system are described sequentially, the model can derive those fluxes also for a calculated critical N leaching rate to ground water (leaching times the target of  $50 \text{ mg.l}^{-1}$  for the  $\text{NO}_3$  concentration) and runoff rate to surface water (runoff times the quality target of  $2.2 \text{ mg.l}^{-1}$  for the N concentration). Mathematically, this approach is described in detail in de Vries et al. (2001b). In back calculating the acceptable N input, the corresponding ammonia emission is also calculated, assuming that the ratio between the N input by animal manure (divided in cattle manure, pig manure and poultry manure, and dung/ urine from grazing animals) and fertilizers stays the same as in the year 2000. By comparing this emission with the acceptable ammonia emission related to the protection of biodiversity of natural areas, the maximum acceptable N input can be calculated such that the biodiversity of natural areas, ground water quality and surface water quality are all protected.

The acceptable ammonia emission was optimized for the Netherlands on the basis of available data for critical N loads related to impacts of nitrogen deposition on biodiversity, nutrient imbalances and ground water quality (De Vries et al., 2000) using emission–deposition relationships. The approach is illustrated in Figure B.2 (after Erisman et al., 2001). The maximum allowable N input is re-calculated when the acceptable ammonia emission related to protection of biodiversity of natural areas is lower than the ammonia emission related to protection of ground water and surface water quality. In this case, the fertilizer input is kept constant, since reduction of fertilizer input is not adequate in reducing ammonia emissions. Instead, the input by animal manure is scaled back, assuming that the ratio between the N input by cattle manure, pig manure, poultry manure, and dung/urine from grazing animals stays the same as in the year 2000.

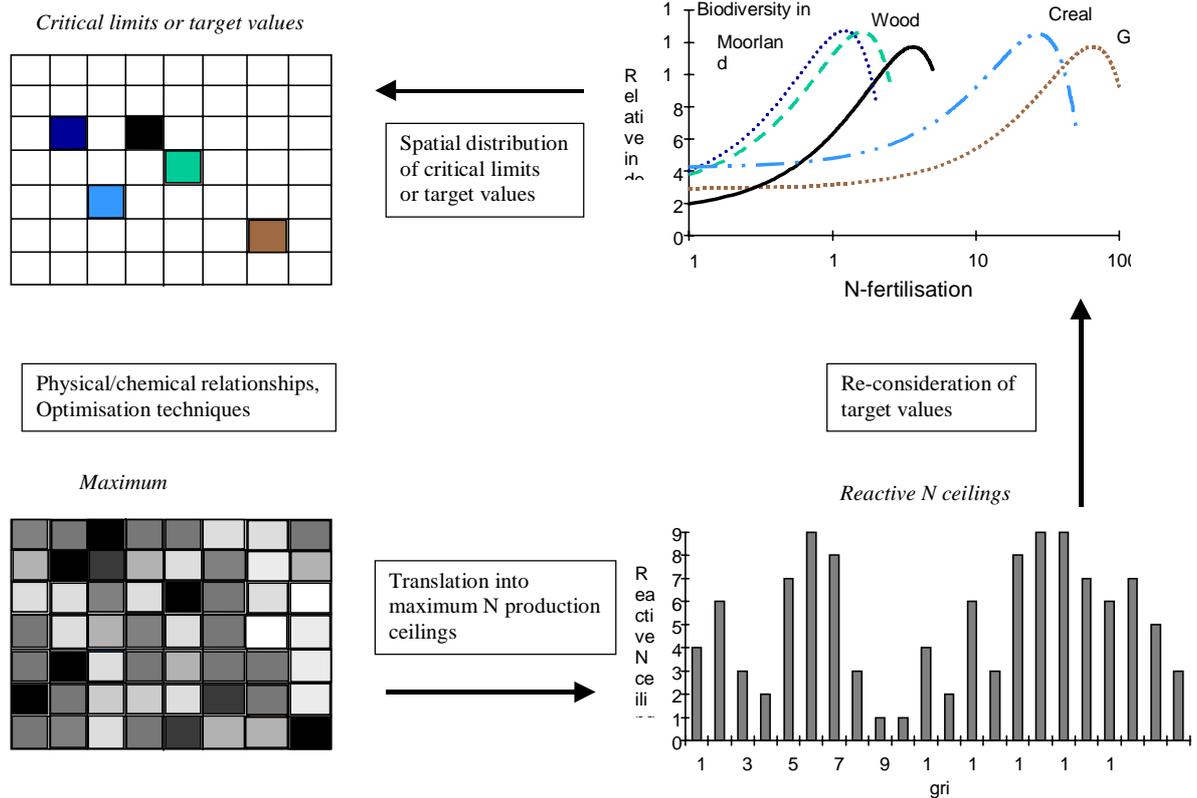


Figure B.2 Illustration of the calculation of reactive N ceilings on a regional scale.

### Model application

The modelling approach was applied to the whole of the Netherlands, distinguishing grid cells with unique combinations of soil type, land use, N inputs and hydrology, which determine the parameterisation of N transformation processes. For agriculture, a total number of 2543 so-called WSV plots were distinguished, consisting of a multiple of 500x500 m<sup>2</sup> grid cells with unique combinations of soil use, soil type and ground water table class. Geo-referenced data for the N input via animal manure and fertilisers were based on data statistics at farm and municipal level for the year 2000. Animal manure was divided in cattle, pig and poultry manure and in dung and urine deposited on grassland by grazing animals, since this has an influence on the ammonia emissions from either housing and manure storage systems or the soil (Boers et al., 1997). Nitrogen deposition data were based on modelled N deposition data at a 1km x 1km grid scale for the year 2000, using the model DEADM (Erisman et al., 1998). N fixation was estimated as a function of land use (De Vries et al., 2001). Estimated total N inputs to agricultural land were slightly larger for animal manure (501 Gg.yr<sup>-1</sup>) than for fertiliser (441 Gg.yr<sup>-1</sup>). About 66% of this amount originated from cattle, 23% from pigs and 11% from poultry including other animals. Cattle manure includes the N in excrements from grazing animals, being equal to approximately 35% of the annual N excretion. N deposition on agricultural land was 76 Gg.yr<sup>-1</sup> and on non-agricultural land it equalled 19 Gg.yr<sup>-1</sup>, reflecting the ratio in the area of those land use types.

The model parameters describing N transformation processes and transfers, were estimated as a function of land use, soil type and ground water table class, thus allocating them to combinations occurring in distinct plots. In the agricultural plots, a distinction was made in grassland, maize and arable land. Soils were divided in sand, loess, clay and peat. Furthermore, a distinction was made in different hydrological regimes (wetness classes), using ground water table classes (Gt) from the 1: 50 000 soil map with information on the mean highest water level (MHW) used in the plots, according to: (i) wet (poorly drained): MHW < 40cm, (ii) moist

(moderately drained): MHW 40-80cm and (iii) dry (well drained): MHW >80cm. Model parameters describing the various N transformations were based on literature data, field observations, results from more detailed model calculations and expert judgement, as described in De Vries et al. (2001).

## MODEL RESULTS

Model results include: (i) nitrogen fluxes to air, ground water and surface water, (ii) nitrogen ceilings and maximum allowable soil inputs and (iii) areas exceeding different N ceilings when implementing the Mineral Accounting System (MINAS) and the EU target of  $170 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  of animal manure. Values are results based on the assumption that:

- All animal housing systems are transformed to low emission (green lable) stables. This is needed when one wants to reach the ammonia emission targets and is foreseen in the future. For reasons of comparison, this effect was also included in all criteria.
- Animal manure is exported in situations where the N produced by eating grass and maize only (no feed products) already exceeds the acceptable N input. This is needed to still have animal husbandry and reach the targets. Otherwise, the land has to be abandoned. The effect of not exporting manure on the set-aside of land is also discussed.

### *Nitrogen fluxes to air, ground water and surface water for different protection levels.*

National estimates of N fluxes to air, ground water and surface water for various criteria with respect to the protection of ground water, surface water and nature are given in Table B.1. Calculated total annual fluxes ( $\text{Gg N} \cdot \text{yr}^{-1}$ ) using the input for the year 2000 were 132 for ammonia emission ( $160 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$ ), 29 for nitrogen oxide emission, 50 for N inflow to ground water and 15 for N inflow to surface water. The N inflow to ground water and surface water decreased by approximately 25% when the N ceiling related to ground water protection has to be reached and by nearly 80-70%, respectively when N ceiling related to both ground water and surface water protection has to be reached. The need to reach ammonia emission targets in addition to ground water protection still causes a clear decrease in N inflow to both ground water and surface water. The additional gain is small when ammonia emission targets need to be reached in addition to ground and surface water protection (Table B.1).

The present  $\text{NH}_3$  emission decreases from an estimated value of  $160 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$  to  $68 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$  when all housing systems are converted to low emission stables. This amount was calculated to increase ( $108 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$ ) when one would only protect ground water, due to the calculated possible increase in manure application instead of fertilizers (see Table B.3). The ammonia emission related to the protection of ground water and surface water is slightly higher ( $79 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$ ) than the ammonia emission related to ground water protection only and an emission target of  $93 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$  ( $71 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$ ), despite the lower N ceiling in the first case. This is again because the ratio between fertiliser and animal manure is different in both cases (Table B.3). When one only focuses on leaching to ground water and surface water, it is relatively efficient to reduce fertiliser inputs, whereas the reduction of ammonia emissions is best obtained by reducing animal manure inputs. The calculated  $\text{NH}_3$  emission of  $71 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$  is lower than the emission target of  $93 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$ , since ground water protection is sometimes more stringent than this ammonia emission target. This is even more true for surface water. For example, the combination of ground water and surface water protection and an emission target of  $93 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$  leads to an emission of  $49 \text{ Gg NH}_3 \cdot \text{yr}^{-1}$  only.

The reduction of the N input in agriculture will lead to a significant reduction in the emission of the greenhouse gas  $\text{N}_2\text{O}$ . At present the aim for  $\text{N}_2\text{O}$  is a 6% reduction compared to the year 1995. The average national estimate for  $\text{N}_2\text{O}$  emission in 2000 is  $29 \text{ Gg N} \cdot \text{yr}^{-1}$ , being equal to an estimate by Kroeze en Bogdanov (1997), who estimated this flux on the basis of the IPCC

Guidelines for National Greenhouse Gases (IPCC, 1997). The results show that if the ammonia targets would be reached in combination with the protection of ground water and surface water, the reduction in N<sub>2</sub>O emission is likely to be much larger. This implies that the target for N<sub>2</sub>O emission reduction is a less ambitious than the targets for ammonia. The calculated increase in N<sub>2</sub>O emission for the targets related to ground water only or even ground water and surface water compared to the present situation is due to the different allocation of manure and fertiliser to the land. To meet the targets it is efficient to spread the manure preferentially on peat and clay soils with a high denitrification potential. This does however cause an increase in N<sub>2</sub>O emission, which is related to denitrification.

*Nitrogen ceilings and maximum allowable soil inputs for different protection levels.*

National estimates obtained for N ceilings on farm level (input by forage, fertiliser, deposition and biological fixation) were always lower than the maximum allowable N application to the soil (input by animal manure, fertiliser, deposition and biological fixation) as indicated in Table B.1. Apparently, the ammonia emission from the animal housing systems, included in the calculation of the N ceiling, is less than the difference between the total N removal in grass and maize from the soil (maximum allowable N application) and the farm N output in meat and milk (N ceiling).

Table B.1 *N ceilings and N fluxes to air, ground water and surface water, related to criteria for groundwater (GW), surface water (SW) and optimised ammonia ceilings of 93 Gg NH<sub>3</sub> (AM93) and 50 Gg NH<sub>3</sub> (AM50).*

Criterion	N ceiling (Gg N.yr <sup>-1</sup> )	N input to soil (Gg N.yr <sup>-1</sup> )	NH <sub>3</sub> emission (Gg NH <sub>3</sub> . yr <sup>-1</sup> )	N <sub>2</sub> O emission (GgN.yr <sup>-1</sup> )	N inflow to ground water (Gg N.yr <sup>-1</sup> )	N inflow to surface water (Gg N.yr <sup>-1</sup> )
Input in 2000	848	950	68 (160) <sup>1</sup>	29	50	15
GW+P-limit	856	955	108	38	37	11
GW+SW	595	725	79	33	11	5
GW+AM93	601	784	71	29	26	10
GW+AM50	397	618	42	20	18	7
GW+SW+AM93	379	560	49	19	10	4
GW+SW+AM50	263	466	32	14	7	3

<sup>1</sup> The value in brackets is the calculated ammonia emission at present without conversion to low emission stables. The value of 160 Gg NH<sub>3</sub>.yr<sup>-1</sup> is equal to a national average emission of 132 Gg N.yr<sup>-1</sup>.

The division of N ceilings and maximum allowable N inputs to soil in the various sources are given in Table B.2 and Table B.3, respectively. On a national scale, the N ceiling and the maximum allowable N input at the soil surface is slightly higher than the present input, when one wants to protect ground water only. Protection of ground water can thus in principle be reached by a redistribution of the animal manure and fertilizer application over the Netherlands. Results show that in our calculations we also assumed a lower input of fertilizers (see modeling approach) leading to more acceptable manure input (Table B.3), but this does increase the ammonia emission (Table B.1). The national N ceiling related to the protection of both ground water and surface water is almost comparable to the N ceiling related to the protection of ground water only and an ammonia emission target of 93 Gg NH<sub>3</sub>.yr<sup>-1</sup> (Table B.2). To a slightly lesser extent, this is also true for the soil N input (Table B.3). In most parts of the Netherlands the ammonia emission targets are, however, more restrictive than those based on limits for ground water, especially when the target of 50 Gg NH<sub>3</sub>.yr<sup>-1</sup> is used. The critical limit for surface water is nearly always more stringent than for ground water, but also here the ammonia emission targets are often, more restrictive, especially when the target of 50 Gg NH<sub>3</sub>.yr<sup>-1</sup> is used (Table B.2).

Table B.2 *N ceilings related to different criteria for groundwater, surface water and optimised ammonia ceilings, including and excluding export of manure*

Criterion	N ceiling with manure export (Gg N .yr <sup>-1</sup> )			N ceiling without manure export (Gg N .yr <sup>-1</sup> )		
	Forage	Fertiliser	Total <sup>1</sup>	Forage	Fertiliser	Total <sup>1</sup>
Input in 2000	362	396	848	362	396	848
GW+P-limit	454	312	856	454	310	854
GW+SW	295	226	595	295	164	549
GW+AM93	195	329	614	195	262	547
GW+AM50	81	325	496	81	109	280
GW+SW+AM93	84	226	400	84	150	323
GW+SW+AM50	31	224	346	31	56	177

<sup>1</sup> Total N ceiling includes the input by forage, fertiliser, deposition and biological fixation. The latter two inputs were fixed at the input of 90 Gg N.yr<sup>-1</sup> in 2000, i.e. 49 Gg N.yr<sup>-1</sup> for deposition and 41 Gg N.yr<sup>-1</sup> for biological fixation.

Table B.3 *Maximum allowable soil N inputs related to different criteria for groundwater, surface water and optimised ammonia ceilings, including and excluding export of manure*

Criterion	Allowable N input to soil with manure export (Gg N .yr <sup>-1</sup> )				Allowable N input to soil without manure export (Gg N .yr <sup>-1</sup> )		
	Manure	Fertiliser	Export	Total <sup>1</sup>	Manure	Fertiliser	Total <sup>1</sup>
Input in 2000	464	396	-	950	464	396	950
GW+P-limit	552	312	1	955	550	310	950
GW+SW	409	226	51	725	348	164	602
GW+AM93	335	329	30	784	334	262	686
GW+AM50	96	325	107	618	144	109	343
GW+SW+AM93	167	226	57	560	177	150	417
GW+SW+AM50	41	224	109	466	70	56	216

<sup>1</sup> Total N input to the soil includes the input by animal manure, fertiliser, deposition and biological fixation, correcting for export. The latter two inputs were fixed at the input of 90 Gg N.yr<sup>-1</sup> in 2000.

The most stringent approach (protection of ground water and surface water and an ammonia emission target of 50 Gg NH<sub>3</sub>.yr<sup>-1</sup>) leads to a national maximum allowable N input to the soil of 466 Gg per year and an N ceiling of 346 Gg.yr<sup>-1</sup>. This is, however, based on the assumption of a net export of animal manure or animal manure processing at the farm (Table B.3). This is needed at those plots where the amount of N in animal manure produced by eating the grass and maize grown at the plot leads to N emissions to air or water exceeding the acceptable limits. Compared to the current N input of 848 Gg per year, a reduction of 60% is needed to reach this N ceiling, that is considered necessary to protect the environment against all adverse impacts of nitrogen pollution from agriculture. Assuming that the fertilizer input will be reduced less drastically, this implies that the forage input has to be reduced by 90% in this case (Table B.2). The needed reduction in animal manure input, assuming manure export or processing and low emission housing is also nearly 70% (from 464 to 150 Gg N.yr<sup>-1</sup>).

Especially in the situation where stringent ammonia targets have to be reached, it is impossible to still have animal husbandry at certain plots unless manure is exported or processed at the farm. When this is not done, the land has to be abandoned, causing zero input by forage, animal manure and fertilizer and negligible ammonia emission. Calculations of the N ceiling and maximum allowable N input thus obtained are presented in the right hand side of the Tables B.2 and B.3. In this calculation, we assumed that the N input by deposition and fixation is taken up by natural grassland, leading to a negligible leaching and runoff. Results thus obtained lead to lower soil N inputs and N ceilings. The amount of manure that is acceptable is lower than the sum of manure application and manure export (or processing) in the first case (see left hand side of Table B.3). The acceptable rate of animal manure application to the land is, however, higher for the criteria including ammonia emission targets. This is because the amount of fertilizer that is applied decreases strongly due to land abandonment. The area that has to be set aside is calculated to increase from 20825 ha when protecting ground water only, to 1.498825 ha when

protecting ground water, surface water and nature. This is approximately 1-70% of the agricultural area of the Netherlands. For the other options it varies between 15% (ground water protection and an emission target of 93 NH<sub>3</sub>. yr<sup>-1</sup>) and 60% (ground water protection and an emission target of 50 NH<sub>3</sub>. yr<sup>-1</sup>).

*The impacts of the present manure application targets on the protection level of ground water, surface water and nature*

Despite the relative low N input to ground water and surface water compared to the N input (about 6% and 1.5% respectively), it does cause an exceedance of critical limits for nitrate in ground water (50 mg.l<sup>-1</sup>) and nitrogen in surface water (2.2 mg.l<sup>-1</sup>) in large parts of the Netherlands at present. This is illustrated in table B.4, which shows that the N ceiling based on either the target of 50 mg.l<sup>-1</sup> for the NO<sub>3</sub> concentration in ground water or a phosphate target loss of 20 kg.ha<sup>-1</sup>.yr<sup>-1</sup> is presently exceeded at 57% of the plots (Table B.4). The latter target was included to avoid extremely high acceptable N inputs for clay and peat soils with a very high denitrification potential. The calculated area exceeding a critical nitrate limit of 50 mg.l<sup>-1</sup> alone was 26% only, but the area exceeding the targets for both ground water and surface water is even 83%.

Table B.4 *Areas exceeding different N ceilings when implementing the Mineral Accounting System (MINAS) and the EU target of 170 kg.ha<sup>-1</sup>.yr<sup>-1</sup> for animal manure application.*

Criterion	Area exceeding N ceilings (%)		
	Present	MINAS	EU
Input in 2000	-	-	-
GW+P-limit	57	22	28
GW+SW	83	77	78
GW+AM93	81	66	77
GW+AM50	92	79	88
GW+SW+AM93	95	84	87
GW+SW+AM50	98	94	97

We calculated that application of the MINAS system does indeed decrease the area exceeding the critical limit for nitrate of 50 mg.l<sup>-1</sup> and phosphate target losses for ground water considerably (from 57 to 22%; Table B.4). This holds specifically for the phosphate target loss, however, since the calculated area exceeding a critical nitrate limit of 50 mg.l<sup>-1</sup> reduced from 26% to 21 % only. Excesses are thus still to be expected with MINAS, especially in dry sandy soils and in loess soils on grassland with an N loss target of 140 kg.ha<sup>-1</sup>.yr<sup>-1</sup>. MINAS, however, aims to decrease target nitrogen surpluses to such a level that not only nitrate concentrations in upper groundwater but also nitrogen concentrations in surface waters do not exceed target concentrations. Considering the N ceiling for both ground water and surface water, the impact of MINAS on the area exceeding the critical limit of 2.2 mg.l<sup>-1</sup> for surface water is calculated to be much less (from 83-77%). Finally, the reduction in N inputs by MINAS do cause a decrease in NH<sub>3</sub> emissions from approximately 160 to 115 Gg NH<sub>3</sub>.yr<sup>-1</sup>, but the area exceeding optimised ammonia emission targets of 93 and especially 50 Gg NH<sub>3</sub>.yr<sup>-1</sup>, set by the Dutch Government, hardly decrease (Table B.7).

## DISCUSSION AND CONCLUSIONS

This paper presents a first quantification of “reactive nitrogen production ceilings” in the Netherlands on a regional scale. It appears to be possible to set limits to N inputs by fertilisers and feed concentrates on a regional scale to meet the environmental limits. The choice of critical limits or target values used in these calculations limit the production of reactive nitrogen and the associated activities. Therefore, the choice of the target values is very important. The first calculations show that the reactive N import in the Netherlands has to be decreased by 60% and regionally optimised in order to reach the environmental limits, even assuming low emission housing and manure export at the farm. Regionally there are large differences between the reductions needed. There are a few areas in the Netherlands where, according to this preliminary analysis, no reductions are needed, but especially the intensive agriculture areas in the centre, east and south of the country should decrease to a very large extent. This calculation is however based on the assumption that at each plot, the locally optimised ammonia emission target has to be reached. Due to this approach, the ammonia emission is always lower than the given national target. For the most stringent approach (protection of ground – and surface water and an ammonia emission target of 50 Gg NH<sub>3</sub>.yr<sup>-1</sup>) it leads to an actual emission of approximately 30 Gg NH<sub>3</sub>.yr<sup>-1</sup>, being the Dutch target for the year 2030. Another approach is to give such a target for a larger area (all farms in a certain area should not exceed an ammonia emission target) without optimising the ammonia emission targets within the area.

Maximum N-ceilings based on all critical limits (nature, ground water, surface water, greenhouse gas emission etc.) provide a solid basis for an integral nitrogen policy. It limits all the N-related impacts at the same time, it prevents shifts to other environmental issues and is therefore efficient and cost effective and probably more acceptable to the target groups. An important aspect of a successful integrated nitrogen policy is also related to the possibilities for inspection and maintenance of implementation (Erisman et. al., 2001) and this aspect has not been addressed here. A nitrogen trading system might be set up which stimulates the implementation of measures to reach the ceilings, comparable to the Mineral accounting System (MINAS). Emission trades are possible, also between different target groups. A nitrogen accounting system where regionally and locally (individual farms) the N-balance is calculated using standard/prescribed methods can assist such a system. The excess N might be taxed to stimulate reductions. The system can give guidance to the spatial planning of activities and the room for expansion in different areas and it can stimulate technological developments in the right direction.

Measures to reach nitrogen ceilings should be focused on reducing the production of reactive nitrogen and/or the import of it. Solutions to reach the N production ceilings might be sought in technological measures aimed at conversion of reactive N into N<sub>2</sub>, preventing reactive N to be formed or limiting reactive N import. This approach is not only useful for the Netherlands, with its excess nitrogen inputs, but also for other countries in the world where either nitrogen becomes a threat or need limits to growth in order to prevent situations of unbalanced nitrogen.

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