Norwegian Journal of Agricultural Sciences

Supplement No. 23 1996

Policies for Reduced Nutrient Losses and Erosion from Norwegian Agriculture

Integrating Economics and Ecology

ARILD VATN, LARS R. BAKKEN, MARINA AZZAROLI BLEKEN, PETER BOTTERWEG, HALSTEIN LUNDEBY, EIRIK ROMSTAD, PER KRISTIAN RØRSTAD AND ARILD VOLD

Ås Science Park Ltd., Norway

NORWEGIAN JOURNAL OF AGRICULTURAL SCIENCES

Norwegian Journal of Agricultural Sciences is a forum for publishing Norwegian research with international interest within the following areas: Aquaculture, Animal Science, Soil and Water Science, Agricultural Engineering and Technology, Natural Resources and Environment, Food Technology, Crop Science, Forestry, Economics and Society Planning.

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PUBLISHER

The journal is published by the Ås Science Park Ltd., Sagabygget, N-1432 Ås, Norway. Norwegian Journal of Agricultural Sciences (ISSN 0801-5341) is published four times a year, each issue containing approximately 100 pages. Four issues comprise one volume. Annual subscription NOK 500,-. Supplement issues can be ordered separately through the publisher.

REFEREE

All papers submitted for publication will be sent to competent international referees.

CORRESPONDENCE

All correspondence, editorial or otherwise, should be adressed to Ås Science Park Ltd., Sagabygget, N-1432 Ås, Norway

The drawing on the cover: Kjell Aukrust

ISSN 0801-5341

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Preface

The research presented here originates from a research program called "Economics and Ecology - Resource Management and Pollution in Agriculture". It is part of an initiative by The Research Council of Norway to initiate more interdisciplinary research – especially across the borders between social and natural sciences. The research is entirely financed by the Research Council.

A large group of researchers has contributed to the analyses underlying this report. Most of the research has been done by an interdisciplinary group placed at the Department of Economics and Social Sciences, Agricultural University of Norway (AUN). True interdisciplinary work demands that all researchers take responsibility for the totality of the product, and all core group members have been deeply involved in framing the study, developing its structure and specifying the relationships between the different parts. As to the various elements of the analysis, the responsibility has been as follows (in alphabetic order):

Lars Bakken (professor, Dep of Soil and Water Sciences, AUN): Nitrogen and nitrogen cycle modelling.
Marina Azzaroli Bleken (researcher (PhD), Dep of Economics and Social Sciences, AUN): Nitrogen cycle modelling.
Peter Botterweg (researcher (PhD), Center for Soil & Environmental Research, Aas, Norway): Soil erosion and phosphorus modelling.
Halstein Lundeby (research assistant, Dep of Economics and Social Sciences, AUN): Data management and model application.
Eirik Romstad (senior researcher, Dep of Economics and Social Sciences, AUN): Economics modelling (assistant program leader).
Per Kr. Rørstad (PhD student, Dep of Economics and Social Sciences, AUN): Economics modelling.
Arild Vatn (Associate professor, Dep of Economics and Social Sciences, AUN): Overall modelling structure, economics modelling (program leader).
Arild Vold (PhD student, Dep of Mathematics, AUN): Nitrogen modelling.

Sverre Gunnar Mansaas preceded Halstein Lundeby as research assistant.

The researchers have been assisted by a reference group. In 1995 this group had the following members:

Head of Division Ragnar Mjelde, The Ministry of Agriculture
Engineer Ingrid Nissen, Norwegian Pollution Control Authority
Managing director Arnor Njøs, Center of Soil and Environmental Research
Professor Birger Solberg, European Forest Institute
Professor Nils Christian Stenseth, The University of Oslo
Advisor Dag Petter Sødal, The Ministry of Environment

Some members have changed throughout the program period. The representative for The Ministry of Agriculture was previously Knut Børve (1990-1991) and later Magnar Sundfør (1992-1993). For the Norwegian Pollution Control Authority Sissel Grimstad (1990 - 1991) and later Elisabeth Dahle (1992-1995) have also been members. Concerning The Ministry of Environment Bent Arne Sæther was a member until spring 1994.

The following institutes and departments have been engaged to provide data or undertake analyses of importance for this report:

Center of Soil and Environmental Research: Data and parameters on hydrology and erosion modelling (Johannes Deelstra, Berevan Saban Kehreman and Lillian Øygarden); experimental crop data (Hans Olav Eggestad and Nils Vagstad).
Department of Agricultural Engineering (AUN): Data/model on ammonia losses (Kolbjørn Christoffersen and John Morken).
Department of Animal Science (AUN): Nutrient excretion from animals (Tore Bolstad, Joy Bruce and Frik Sundstøl).
Department of Biotechnological Sciences (AUN): Data/parameters describing the effect of various agronomic practices on nitrogen turnover (Tor Arvid Breland).
Department of Horticulture and Crop Sciences (AUN): Modelling crop growth in grass (Hans Ole Baadshaug, Bjørn Grønnerød and Arne O. Skjelvåg).
Department of Mathematics (AUN): Nitrogen modelling (Jan Søreng).
Department of Soil and Water Sciences (AUN): Experimental crop data, data/parameters describing the effect of various agronomic practices on yield, nitrogen turnover, leaching etc (Trond Børresen, Tore Krogstad, Ingvar Lyngstad, Steinar Tveitnes, Godtfred Uhlen and Anne F. Øgard).
Norwegian Crop Research Institute: Crop trial data, the effect of various agronomic practices on yield and catch crop data (Unni Abrahamsen, Egil Ekeberg and Hans Stabbetorp).
Norwegian Institute of Land Inventory: Soil data (GIS based), participation in erosion modelling (Tore Hoff, Rodney Leek, Ove Klakegg, Eivind Solbakken, Ragnhild Sperstad and Gunnar Tenge).
Statistics Norway: Statistical data, N cycle and farm data (Henning Høie, Anne Snellingen Bye).

Since the research is interdisciplinary, it has been an aim to write the report in a way that makes it accessible across disciplines. Thus, the text includes more elementary information, unnecessary and maybe "disturbing" for some, but of importance for other members of our potentially broad group of readers.

The text is divided into two parts. The main part covers the background of the study, its focus, the basic methodological choices, results from the analyses and a discussion of the various results. Added to this is a rather comprehensive appendix. Appendix A gives a fairly detailed description of the modelling system and the data used, while also discussing some methodological issues in more detail. Appendix B presents a more comprehensive set of data from the 20 scenarios run for this study.

Reidun Aasheim has assisted in preparing figures and tables and Anne Johannessen has assisted in proof reading and giving linguistic advice. Dag Gjerde has assisted in typing and proof correction of appendix B. We thank all contributors, whose support has been decisive for the results obtained. The material presented and the conclusions drawn in this report are still the full responsibility of the core research group.

AUN, April, 1996.

The authors.

Contents

SUMMARY

This report documents the results from an analysis of policy measures to reduce losses of nitrogen, phosphorus and soil from the agricultural sector to the environment. These kinds of losses are nonpoint, and standard emission oriented policy measures like effluent taxes are prohibitively costly to use. The policy alternatives are therefore to regulate the input of potentially polluting substances – in this case reduce the use of fertilizers, to prescribe changes in agronomic practices as conducted on the farm or to change product prices. Principally this study analyzes the effects of these types of regulations, their ability to reduce losses of nutrients and soil, and the private and social costs thereby invoked.

The research was motivated by an intense debate in Norway in the early 1990's about the effect and cost-effectiveness of taxes on nitrogen mineral fertilizers. This debate revealed large disagreements, in particular between economists and natural scientists/agronomists, about the economics of fertilization, the relationship between fertilization and plant growth and between fertilization and leaching. It was argued that other policies than a nitrogen tax were more efficient. From this debate it became clear that the resolution of these kinds of disagreements was best made through interdisciplinary research. The research program "Economics and Ecology – Resource Management and Pollution from Agriculture" was initiated to embody these concerns.

The research program has been divided into three studies:

A. The N cycle study: An analysis of the nitrogen cycle covering all sectors of the Norwegian economy.

B. The valuation study: Investigation of ecological impacts of nutrient losses and production of economic valuation estimates related to different water qualities.

C. The policy study: Evaluation of measures to induce reduced losses of N, P and soil from agriculture – a search for cost-effective strategies.

This report mainly covers study C – which is also the largest of the three. However, some elements from study A are also incorporated.

The problems studied here are characterized by complex interactions between societal institutions, choices about resource use made by farmers, and the natural processes these choices influence and are influenced by. The natural processes of interest – like plant growth, N turnover and erosion – vary greatly both in space and time due to variations in soil type, topography and weather conditions, etc. To analyze this, a detailed analysis with high resolution is warranted. Farmers' adaptions also depend on natural conditions. Other factors influencing the choice of agronomic practices include farm structures and various economic and political conditions.

Turning to the emissions, a wide range of agronomic practice elements are of importance for losses of nutrients and soil, including crop growth, crop rotation, fertilizing, feeding, manure handling practices, tillage practice and off-season plant cover. Finally, the need for a comprehensive analysis follows from the openness of agriculture towards the environment as the sector utilizes natural processes that are part of the larger ecosystems in which agricultural production takes place.

The analysis is based on mathematical modelling. This way it has been possible to handle the above described complexities in a consistent manner. Earlier studies have mainly been oriented towards one or a few of the above relationships. Our challenge has been to construct an analysis tool covering the various processes of importance, linking them consistently, and to cover the most important feedbacks in the system. While it has been possible to utilize already existing modelling tools for some parts of the analysis, it has been necessary to construct new models for other parts to fit the overall purpose of the study.

The modelling system constructed – ECECMOD – consists of six separate models that are capable of analyzing nutrient losses at the watershed level. ECMOD is the economic submodel predicting farmers' choices of agronomic practices given political and economic conditions, farm characteristics, soil and climatic conditions. The Crop growth module determines yields as a function of agronomic practice and natural conditions. SOIL and SOILN-NO describe the hydrological processes and N turnover/leaching as a function of soil conditions, farmers choices and actual crop growth. Finally, EUROSEM and GRIDSEM are used to model erosion in landscapes, incorporating topographical characteristics into the analysis. To cover variation in weather conditions, all simulations were done for a period of 20 years. The natural science modelling uses a time resolution of one day, while the time resolution of the behavioral part of the modelling varies over day, season and year depending upon the type of choices modelled.

The analyses were undertaken for three watersheds (or more precisely parts of watersheds) in South-Eastern Norway. One is Mørdre in Akershus, while the two others cover different parts of the Auli watershed in Vestfold. All areas are dominated by grain production, but animal husbandry also plays a fairly significant role in Auli. The areas are chosen to obtain variation in soil conditions and topography. Some climatic variation is also obtained. Comprehensive empirical studies are presently running in the two areas. This has been an important contributing factor for choosing the named study sites.

The main focus of the analyses has been to study the effects of changes in the political and economic conditions on nutrient and soil losses. A set of scenarios has been developed to characterize the various policy options. First, a scenario with prices and regulations as observed in 1992 was run – S-1992. This was done to test the quality of the modelling system, i.e. its ability to predict farmers' adaption and the subsequent losses compared to actual situation. This analysis showed that ECECMOD performs very well. It predicted fertilizer levels, crop choices and yield levels close to actual observations. Also the estimated losses correspond to observed levels, while the predictions obtained for P losses in the Auli areas may seem somewhat high.

Second, a so called Base scenario was constructed. Compared to S-1992, existing environmental regulations like fertilizer taxes and subsidies for spring tillage/reduced tillage were removed. Further, the Base scenario was constructed to predict farmers' adaptions in the long run. This way, a good basis for comparing the various policy options of interest were established. The results from the Base scenario were compared with the following changes in the political and economic conditions:

- Nitrogen fertilizer tax: 50, 100 and 200 % respectively.
- Reduced grain prices: -33 %
- Mandatory catch crops: 50 and 100 % of the farm's arable acreage
- Split fertilizing
- Regulations to reduce fall tillage: subsidies or mandatory requirements
- Mandatory 12 months manure storage
- Changes in feeding practices, i.e. reduced P in feed and more optimal protein (N) feeding.

Various combinations of the above policy measures were also analyzed. Both catch crops (in grain) and ordinary meadow were accepted as satisfying the catch crop requirements.

We started out asking whether a single measure like a tax (or tradeable quota) on nitrogen fertilizers could induce reductions in the losses of both N, P and soil. A tax on N should result in reduced N-leaching since both lower fertilizer intensity and better utilization of manure N could be expected. Such a tax could also result in increased use of split fertilization, and it might make catch crops economically interesting for the farmer since both practices would be more profitable as N prices increase. Catch crops could also reduce the losses of soil and P. This way one single measure could solve a wide range of environmental problems.

The analyses show that **taxing the input** does not have this kind of capacity. Our modelling shows that N losses would be reduced due to lower fertilizer levels and environmentally favorable changes in the manure practices. Such taxes do not, however, appear to induce split fertilization or the use of catch crops. Further, the effect of the tax on N leaching is rather modest. A 100 % N tax is predicted to reduce N leaching in the range of

12-15 % depending on local conditions. The impact is predicted to be largest on farms with milk/grass production, while the effect on leaching from grain producing farms is more modest. Ammonia losses were more affected than N leaching.

At low to medium levels (up to about 100 %) an N tax seems to be a fairly inexpensive policy option measured as social costs per kg N reduced leaching. For a 100 % tax average social costs were estimated to be about 10 - 15 Norwegian kroner. Few other policy measures seem to be able to induce reductions in N losses at lower costs. To obtain substantial reductions in losses, the tax needs to be fairly high. If so, the costs are increasing, and other measures become more interesting options.

The tax induces rather substantial distributional effects as it also will charge uses of inputs that are not environmentally harmful. The distributional effects can be reduced or removed, either by a scheme of reimbursement, through a system of tradeable permits or a two tiered price system.

Catch crops seem to be the most interesting alternative to a tax. It has a larger capacity to reduce N leaching. A 50 % catch crop requirement reduced losses by approximately 25-30 % according to the model predictions. Catch crops seem, however, to be a more expensive measure per kg N reduced leaching than a low to medium high N tax. On clayey and sandy soils the average social abatement costs were about 50 % higher for catch crops than for a 100 % N tax when all abatement costs were solely born by the reduction in N leaching. If we turn to the marginal cost, it increases rather sharply with increased taxes, however, while it is more constant for catch crops. The marginal costs of the tax seem to rise above that of catch crops at a tax level between 75 - 100 %.

Our analyses predict that a catch crop regime also results in a rather substantial decrease in the erosion level which here can be considered free since all costs in the above calculation are "carried" by the reductions in N leaching. The tax has no such effects. Finally, the distributional effects are much lower for a catch crop than for a tax regime.

Decreasing **grain prices** should in principle have a comparable effect to an N tax in specialized grain production. On farms with animal production, the effect of such a price cut should be less since it does not introduce the same motivation to take better care of nitrogen in animal manure as a tax does. The modelling analyses confirm this pattern. They further show that lower product prices actually results in less environmentally friendly manure handling practices. Generally, price cuts have large distributional effects and rather small effects on emissions. The latter is the case as long as these cuts do not induce reductions in the size of the agricultural sector. The net environmental effect of such more comprehensive changes is a complex issue not discussed in this report.

A **transition from fall to spring tillage** has the capacity to reduce erosion, while our analyses indicate no or low effects on N-leaching. The capacity to reduce erosion is substantial. While reduced fall tillage turns out to be a cheaper and more effective measure towards reducing soil erosion than catch crops, the latter strategy may be preferable since it also affects N-leaching strongly. In total, a larger positive environmental effect may be obtained by catch crops at the same level of social costs.

Strategies like **changed feeding** practices and **split fertilization** are also studied. Changes in the feeding practices, producing less excretion of N and P in manure, is an inexpensive strategy. Its effect on our environmental indicators is low, however, except in areas with high animal stocking rates. Split fertilization is not fully analyzed in this study, but its capacity to reduce N-leaching seems to be lower than expected, partly due to lower yields caused by additional trafficking. An estimated reduction in yields/N uptake of about 2 % seems to counter much of the effect of more precise fertilization in accord with weather development. There is an important exception from this. On sandy soils, split fertilization turns out to have rather substantial effects on N-leaching. It further seems to be profitable for the farmer to utilize this strategy at prices as given in 1992.

Generally we observe that the largest capacity to reduce losses lies in the farm level agronomic practices. This is illustrated by the catch crop and spring tillage scenarios. Another example is the finding that in grain dominated areas, **delaying fall tillage** approximately one month is estimated to have the same effect on N-leaching as a 100 % nitrogen tax. This is an effect of weed growth and germinating grains.

This illustrates one of the most important insights from this study: The high sensitivity of the results following from small changes in some elements of the agronomic practice. Looking at grain production, we observe that the average leaching in the Base scenario is about 20-25 % of a total plant uptake of approximately 150 kg N per ha and year. A change in this uptake of 3 %, will *ceteris paribus* create a potential change in leaching at the level obtained by a 100 % N tax. On clayey soils like the ones in Auli, yield losses following a transition from fall to spring tillage are about 4 %, explaining the low effect of this practice on N leaching.

The high level of detail and great effort put into securing consistency has increased reliability tremendously compared to earlier studies. Still, there are a wide range of uncertainties attached to the results. The largest uncertainties concern the catch crop scenarios due to the fact that field/experimental data are fairly restricted. There are also uncertainties pertaining to the effect of other practices, especially the effects on crop growth and yields. Finally, the results are restricted to the conditions given in the areas studied.

Still, a rather consistent pattern evolves from the analysis. Choosing the best policies among the options analyzed is, however, a difficult task as the effect of the different measures vary substantially with the natural conditions and type of production. The least costly strategy in the case of N losses – a medium (50 - 100 %) N tax – has no effect on erosion. It has large distributional consequences, and can hardly be differentiated according to variations in production patterns or environmental conditions. On the other hand, the fertilizer tax is the only instrument with any substantial potential for reducing nutrient losses in milk/grass dominated areas.

Catch crops and spring tillage are measures that can be regionally differentiated according to effects and costs. They will have small effects in areas dominated by milk/grass production, however. Whether a catch crop regime may also be interpreted as socially more costly than a medium (50 - 100 %) tax depends ultimately on the character of the recipients, i.e. the relative importance of N-leaching, P and soil losses.

Combining a catch crop requirement and a medium sized N tax may seem to be a good compromise between conflicting goals. The catch crop requirement may be differentiated according to regional production patterns, soil and environmental conditions. The problem is to find a reasonable tax level. Since it can hardly be varied between regions, one must find a level that provides sufficient reductions in environmentally sensitive areas dominated by milk production without inflicting to large extra costs in areas where catch crops may solve the problems alone, or where no or small reductions in losses are generally needed.

The extra social costs induced by a tax in some areas is a less important argument in the case of a medium sized tax level since social costs are rather low. The distributional effects may be substantial, however, even at this level. Various compensation schemes may counteract this. Some of these are discussed in the report.

An important trade-off between increased precision and the costs of administering various policy measures has become clear from the analysis. The problem follows from the high variability both in types and forms of losses and in the environmental conditions. Locally adapted regulations increase precision, while they also increase regulation and control costs. This is an issue often overlooked or superficially handled in the literature. Such conflicts become evident in interdisciplinary research of the kind conducted here. At this point more research is still needed on these issues.

1 Introduction

1.1 General background

Loss of nutrients from agricultural production may reduce ground water quality, cause eutrophication in both fresh and coastal waters, and indirectly affect the ozone layer and the global climate through interference with components of the carbon and nitrogen cycling. The local environmental impacts vary between locations not only due to variations in nutrient emissions, but also due to changing capacity of different ecosystems to resist influence.

The choices of agronomic practices, soil and weather conditions influence the losses through complex interactions. The emissions can only partly be affected by human action. In such a complex environment, the development of strategies towards influencing the environmental quality in a reasonable way, is a difficult task. In policy oriented analyses the quality of the results will be largely increased by involving both natural and social scientists in cooperative research.

The types of emissions focused here, are normally called nonpoint-source pollution. So far economic research has mostly been concentrated on point-source emissions. Thus the most important theoretical insights are developed for kinds of discharges where the character and volume can be fairly easily monitored. Here the policy recommendations are both clear and rather simple, with either taxes or tradeable quotas on emissions as recommended policy measures (Baumol and Oates 1988; Weitzman 1974). Over the last years there has been an increased awareness of the diffuse discharges that may be both extremely costly to measure and difficult to influence (see among others Segerson 1988; Xepapadeas 1992; Russell and Shogren 1993; Braden and Segerson 1993). From this literature a more complex set of recommendations follows, where ability to target and enforce are important issues in addition to standard efficiency evaluations. Both policies directed towards input use, ambient quality standards, different liability schemes and multiple instrument approaches are discussed.

In a natural science perspective, the economy should be viewed as an open and dynamic subsystem of the ecosphere. As such it does not only have to follow the law of mass conservation. The tendency towards increased entropy in any system (the second law of thermodynamics) implies that degradation or loss of matter and energy from the economic subsystem to its environment will take place *continuously* throughout the extraction, production and consumption process. Certainly, not all losses will have environmentally detrimental effects. Still this insight means that nonpoint-source pollution should be viewed as the typical case. Moreover, it implies that the costs of monitoring and control – i.e.

transaction costs – as opposed to standard production and abatement costs, are very important to consider in the regulation of polluting emissions. If this is the case, no *a priori* arguments can be made generally favoring certain types of measures over others. The conclusion is that each type of case needs to be broadly evaluated to determine what is appropriate to do.

1.2 The project in a Norwegian context

The aim of the research presented here, has been to foster a broad evaluation as described above. Historically the research grew out of an intense debate in Norway following the endorsement of The North Sea Convention of 1987 (Miljøverndepartementet 1992). This treaty formulated goals for reducing different types of harmful emissions, including nutrients, into the North Sea. As for nitrogen and phosphorus, the aim was to reduce the emissions by 50 % by the end of 1995. In the process of choosing appropriate measures, different research projects were initiated. The most debated result from this research was a proposition to tax nitrogen in mineral fertilizers.

The cost-effectiveness of such a measure was both theoretically and empirically verified in different studies (Simonsen 1989; Christoffersen and Rysstad 1990; Sødal and Vatn 1990). Their conclusions were challenged though. One part of the discussion concentrated on the form of the yield response functions used – especially those for grains. The question was whether the relation between nitrogen fertilizer use and crop yields could best be described by a smooth concave production function or a linear response function approaching a plateau – i.e. relationships based on a von Liebig way of interpretation (Enge, Heie and Tveitnes 1990; Simonsen 1990; Simonsen, Rysstad and Christoffersen 1992). These issues are also well know from the international debate (Ackello-Oguto, Paris and Williams 1985; Paris and Knapp 1989; Berck and Helfand 1990). The choice of model has obvious consequences for the expected effect of fertilizer taxes.

The debate also focussed on the relationships between fertilizer levels, conditions for plant growth and emissions. The advantages of input taxes were challenged on the basis of the following arguments:

- emissions are more strongly related to natural processes than to the level of fertilizing (Vagstad 1990).
- other agronomic factors than reduced fertilizer use has greater potential for emission reductions (Uhlen 1990; Kaarstad 1991).
- even if taxes could influence use, the relation between use and emissions would vary between different soils, agricultural products etc., making the calculated efficiency of input factor taxes somewhat questionable.

The research to be presented here was to a large degree initialized to clarify some of these important and disputed issues. The disagreements referred to above, were mainly between proponents of different disciplines. The discussion seemed thus to relate to differences in field of experience and in "world views," but also in the understanding of the relationship between science and policy. The debate occurred in spite of the fact that the research was undertaken by experts from different disciplines. The experiences gained demonstrated the need for more intensity and depth in the interdisciplinary cooperation.

Certainly natural sciences and economics are more complementary than rival. Still the experience gained both from the above debate and the research to be documented here, shows that it is important to provide comprehensive insights into how even complementary disciplines view features, especially along the boundaries between them. What seems indifferent or unimportant from one perspective or discipline may be crucial when viewed from the other. Moreover, research in border zones between disciplines is an important hypotheses generating factor.

1.3 Aims and perspectives

The research to be presented here has been conducted within a research program called "Economics and Ecology – Resource Management and Pollution in Agriculture" (EcEc/-RMPA). It was established in 1991 with the following aims:

> *"The program 'Economics and Ecology – Resource Management and Pollution in Agriculture' shall direct its work towards the integration of problems and insights from both economics and ecology. The aim is to produce knowledge contributing to a more sustainable use of the terrestrial biological production systems. More specifically the development of knowledge is to be concentrated on:*
>
> 1. *Analyzing the processes connected to supply and losses of nutrients (nitrogen and phosphorus) and loss of soil. The program shall contribute to a more comprehensive overview of the interaction between the processes and the main effects on landscape ecology and the state of air, water and soil. The considerations ought as far as possible to be carried out in both economic and ecological terms.*
>
> 2. *Producing results that make it possible to use more cost effective measures regarding these pollution problems. The analyses should be organized so as to make it possible to evaluate where action should be taken across the different sectors of the society" (Norges landbruksvitenskapelige forskningsråd 1991. Our translation).*

The guidelines for the research program acknowledged that terrestrial biological production systems constitute a very broad field of study. To simplify the analyses, it was determined to focus on agriculture and agricultural pollution. When operationalizing the general aims, it was further chosen to divide the program into three different studies:

A. The N cycle study: An analysis of the nitrogen cycle covering all sectors of the Norwegian economy.
B. The valuation study: Investigating ecological impacts of nutrient losses and producing economic valuation estimates related to different water qualities.
C. The policy study: Evaluation of measures to induce reduced losses of N, P and soil from agriculture – a search for cost-effective strategies.

Most resources have been put into study C. Study A was established to better understand the flow of nitrogen generally through the economy, to recognize the main losses and the role of agriculture in this respect. Study B was formulated to gain insights into the ecological effects of different levels of emissions and produce assessments of their economic importance. The resources available made it necessary to restrict this analysis to be based mainly on existing knowledge – although some resources have been put into a supplementary valuation study concentrated on gathering data to facilitate and test the methodology of benefit transfers (Klynderud 1994). Both study A and B are fully documented elsewhere (Bleken and Bakken 1995a; Bleken and Bakken 1995b; Magnussen and Bratli 1995). In this report we focus mainly on study C.

As previously stated, nonpoint-source pollution is difficult to regulate through a system of emission related measures. Thus it is necessary to look directly into the production systems, study changes in these systems capable of reducing emissions and analyze the effect of measures able to motivate farmers to make such changes. This emphasizes the need for cooperation between social and natural sciences.

Both social systems and ecosystems can be understood as structured in hierarchies (Costanza, Wainger and Bockstael 1995; O'Neill et al. 1986). According to hierarchy theory, nature can be partitioned into levels with similar time and space scales interacting with lower and higher levels in systematic ways. Integrating natural sciences and economics requires attention to the differences in scale and thus consistency concerning levels of resolution and aggregation. Economic analyses are normally conducted at levels far more aggregated than is the case in plant and soil sciences. Policy relevance is further gained by producing results at aggregated levels. On the other hand, it soon became clear to us that it was crucial to keep attention to the dynamics and variability of the natural systems in our analyses. It has thus been an important issue to preserve nonlinear small-scale variability in more large-scale modelling. As will be discussed later, this has created a rather comprehensive process directed towards defining the most appropriate level of resolution for different parts of the study.

The analysis focuses on losses of nitrogen, phosphorus and soil through different processes. This broad scope was chosen because it was found necessary to understand the interaction between these types of losses in order to develop better environmental policies in the field. Most measures directed towards reducing one type of loss, also influence the other losses. A combined study facilitates insights into the potential synergies and trade-offs.

At the time this program started, the models available for studying nitrogen turnover in soils were relatively well developed compared to the models for erosion and mass transport in landscapes. Thus the ambitions have been higher for detailed understanding of measures affecting nitrogen leaching, as opposed to those affecting surface processes. Still, substantial progress has been made in erosion modelling going from point to landscape estimates through the efforts of the program and the cooperative international research within which it has participated.

1.4 The structure of the report

We start the presentation by giving an overview of nitrogen (N) and phosphorus (P) in production and pollution (chapter 2). Some of the results from the nitrogen cycle study are also presented here. Information from chapter 2 is then, utilized to discuss changes in the agronomic practices that may lead to reduced losses of N, P and soil from agriculture (chapter 3). Potential policy measures to motivate farmers to conduct farming in a more environmentally friendly way are also examined in this chapter. In chapter 4 the principles of the analysis and the structure of the modelling system developed are presented. The system is called ECECMOD and consists of a set of mathematical models developed to analyze the various processes involved in an interlinked fashion. Chapter 5 gives an overview of the structure of the analysis and the characteristics of the landscapes in which the studies are undertaken. Chapters 6 - 9 present the main results. We start by presenting the outcomes of a "factorial analysis," i.e. an analysis where various changes in the agronomic practices are undertaken one by one (chapter 6). This is done to better understand the dynamics of the physical and biological components. The main analysis of the effects of various policy measures is undertaken at the level of watersheds. The results from this study are presented in chapter 7. It covers altogether about 20 different scenarios. We also present results at farm level (chapter 8) to give insights into how various policy instruments influence adaption and losses in various productions and on farms with different characteristics. In chapter 9 we analyze the precision of the various policy measures studied, the transaction costs and distributional effects related to them. The results are summarized and discussed in chapter 10.

In addition to this, there are two appendixes. Appendix A gives a detailed overview of the modelling system (ECECMOD), the modelling principles and the main properties of each sub model. Input data and methods for parameter estimations are also described. Finally, appendix B gives a joint presentation of the main results from all the scenarios run.

2 N and P in production and pollution

2.1 Nitrogen and phosphorus transports and transformations in the environment

Nitrogen (N) and phosphorus (P) are essential elements of mineral fertilizers which are used to enhance plant production in agriculture. If lost to the external environments, the same elements represent a pollution problem. The emission of P to aquatic environments is perceived as a problem since it may cause severe algal blooms which deteriorates the water quality. Algal blooms may make the water unsuitable for drinking, recreational activities, and in the most severe cases may cause fish death due to periodic anoxic conditions. As such, the P-pollution is a local pollution problem. The losses of P to the environment has a global aspect as well, due to the limited availability of rock P for fertilizer production. This aspect is at present rather hypothetical, however, since the amount of easily extractable rock-P suffice for more than two centuries at the present pace.

Nitrogen is a far more elusive element than phosphorus, and its environmental effects is clearly more complex. Key N-transformations and transports are schematically illustrated in figure 2.1. The primary producers (primarily plants and algae) assimilate mineral nitrogen (NH_4 or NO_3) or acquire nitrogen from the atmospheric pool of molecular N_2 through symbiotic nitrogen fixation. The assimilated nitrogen reappears as ammonium after being transformed through nutrient webs and decomposer communities, here indicated by the circle "Micro", suggesting a central role of microorganisms. This process is called mineralization. The stabilization of organic N as "humus N" is an important transient sink in both terrestrial and aquatic systems, which gives them the capacity to gradually change the storage of organic nitrogen over decades in response to altered climates or managements. Ammonium (NH_4) may be oxidized to nitrate (NO_3), a process called nitrification. The process is important for a number of reasons. It makes the mineral nitrogen more mobile in the environment (=> leaching of nitrate), and NO_3 is a preferred source of mineral N for many plants for this and other reasons (ion balance, local pH at root surface). Nitrification is also important since it is the gateway to the return of the N to the atmosphere through denitrification. This process, in which nitrate replaces oxygen as terminal electron acceptor, reduces nitrate to molecular nitrogen. Both nitrification and denitrification release N_2O as a sideproduct, however. N_2O is a greenhouse gas and a potential contributor to the destruction of atmospheric ozone.

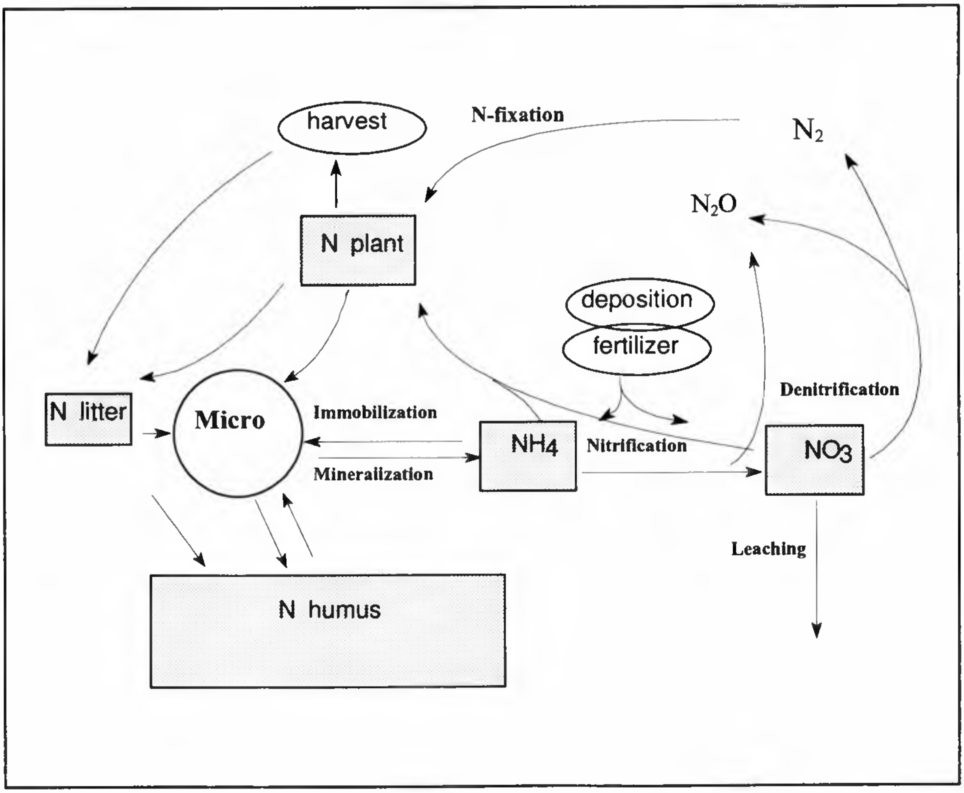

Figure 2.1: Processes and transports of nitrogen in the environment.

Mineral nitrogen may escape from the agricultural system primarily through nitrate leaching and ammonia volatilization. Denitrification (reduction of NO_3 to N_2) is also a route of escape which may be significant under certain conditions. Nitrogen in the environment is known to cause a range of environmental problems. If the deposition in terrestrial environments exceeds the system's capacity for nitrogen assimilation in the biomass ("N-saturation"), nitrate leaching will occur. This may deteriorate the ground water as a drinking water resource, and result in increased leaching of cations from the soil profile (acidification). Nitrogen enrichment of water bodies contributes to the eutrophication of these environments, although P and Fe are currently recognized as the most important limiting factors for the primary production.

Nitrogen is easily transported through both air (as NO_x and NH_3) and water (as NO_3). The rapid transport and the tremendous increase in the total industrial nitrogen fixation (fertilizer and NO_x produced by burning of fossil fuels) since 1940-50 has led to a gradual shift in the scale of the "nitrogen problem"; i.e. from a local to a regional and even to a global scale

(Heathwaite et al. 1993). The primary concern at the global scale is the accumulation of N_2O in the atmosphere. This gas contributes to global warming and destruction of ozone, and is presently increasing with 0.25% per year. The biological production of N_2O during nitrification (oxidation of NH_3 to NO_3) and denitrification is the major source of this N_2O, and the primary nitrogen sources are the industrially fixed nitrogen and biological fixation in agriculture.

Attempts to estimate global rates of fixation have demonstrated that the anthropogenic inputs (fertilizers, biologically fixed nitrogen, and formation of NO_x in combustion) equals or exceed historic or prehuman input rates (Delwiche 1977; Granli and Bøckman 1994; Vitousek 1994). Crucial problems to address in this context are the causal and quantitative relationship between such high levels of N inputs and the emissions of N_2O, and the time lag between N inputs and N_2O emissions in the various environments.

2.2 Cycles of N in the economy

2.2.1 The cycle perspective

Losses of nutrients to the environment do not only originate from agriculture. As already mentioned, other economic activities may create losses. To be able to evaluate both the relevance and the relative potential of regulations in agriculture, an analysis of the total nutrient cycles of the economy is warranted. Such study is demanding, and we have chosen to concentrate our efforts on the nitrogen cycle of the Norwegian society.

N is lost to the environment at different stages of the production and consumption processes. A "cradle to grave" analysis first of all gives information about the amount of the total N throughput. This is of great interest, since the nitrogen enrichment of the biosphere by human activity is a global problem. Further, it allows a comparison of nitrogen emissions across the different sectors of the economy, identifying the most "leaky" spots. This report presents the results of a study evaluating cost effective policy measures to reduce nitrate leaching from agriculture. It is clearly relevant to know to what extent this leaching is significant in relation to other N-losses and at which stages of the production and consumption the most important losses occur. The analysis of the N-flows and N-dissipations also allows an inspection of possible options for mitigating emissions outside primary production, such as recycling of organic waste and changes in the human diet.

Imports of human food and animal feed potentially conceals a nation's global "N-guilt", since the nitrogen emissions connected with the production of the imported food and feed occurs elsewhere. This cannot be neglected in an analysis of this kind, particularly if we are interested in the total/global emissions as affected by changes in the production structure and consumption pattern. In our analysis, such "hidden N-dissipations" can be evaluated by assuming the same N-efficiency at the production sites as that calculated for equivalent sectors in Norway.

System boundaries are crucial in a study of this kind. We have included fish farming and cultivated areas as a part of the Norwegian economic system (N-cycle). In contrast, uncultivated terrestrial and aquatic habitats are not considered a part of the system studied. Hence, N in timber, in wild fish and game animals (plus free ranging domestic ruminants) represents a net N-input to the human N-cycle. However, the nitrogen in such items do not represent a net anthropogenic input of N into the biosphere, in contrast to synthetic fertilizer, combustion products or biological N-fixation by cultivated crops. Since the main purpose of the study has been to describe the nitrogen flows and nitrogen dissipation from the whole society, we had to include all nitrogen that is manipulated by man in a wide sense. The inclusion of natural (uncultivated) habitats could be desirable for certain reasons, but would clearly represent a herculean task and create new boundary problems.

The nitrogen balance of the food producing sectors has been studied as detailed as possible in order to be able to estimate a "nitrogen-cost" of the processes. The cost is defined as the units of nitrogen needed in raw materials to produce one unit of N in the primary commodities (**I/O**-ratio, i.e. input/output ratio).

In the analysis of the whole society, two types of nitrogen inputs are distinguished: 1) nitrogen fixed in Norway as a direct consequence of human activity, 2) nitrogen in commodities imported from abroad or taken from nature, as sea catch or wild animals. For commodities which are both imported and exported, the net trade is presented. The estimated N-flows are based on available statistics supplied with and checked against direct information from the different industries. Estimates are primarily based on average data for the period 1988 - 1991, unless limitation of data forced us to use a shorter time period. Nitrogen amounts are given in **Gg** yr^{-1} (1 Gg = 10^9 g = 1000 metric tons).

Detailed results of the N-cycle study are presented in Bleken and Bakken (1995a), for the food production system and in Bleken and Bakken (1995b), for the society as a whole .

2.2.2 Total input of reactive nitrogen

During the analyzed period agriculture was the main sector with respect to nitrogen input, altogether almost 150[1] Gg N yr^{-1} (figure 2.2 and 2.3). Of this, 121 Gg N were from

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[1] 155 Gg N yr^{-1} if plants (6-7 Gg N) grazed by farm animals on uncultivated land are included.

chemicals (113) and from biological (8) N-fixation. The imported N in feed (17 Gg N yr^{-1} in grains and protein rich feed, plus materials from mills and breweries) was probably based on anthropogenically fixed nitrogen as well. Thus, a minimum of 138 Gg N yr^{-1} were fixed (chemically and biologically) to "drive" the Norwegian agricultural sector. The rest was from atmospheric deposition (5 Gg N yr^{-1}, to a large extend due to human activity), or from products based on nitrogen fixed under natural or semi-natural conditions (fish and uncultivated pastures).

Combustion was the second largest source of fixed nitrogen, altogether 70 Gg N yr^{-1} (including small amounts from industrial processes). Most emissions were in the form of nitrogen oxides (NO_X), derived mainly from oxidation of N_2 in the air. NO_X reacts further to produce nitric acid or particulate nitrate which is deposited, thus NO_X-N is equivalent to mineral fertilizer in terms of being available as a nitrogen source for plants (and as a pollutant).

The third main source of reactive nitrogen was fish from the sea, altogether 63 Gg N yr^{-1} in (1988-1991), probably up to 70 Gg N in 1994. Since more than half of sea catch was exported abroad, the net input to the Norwegian economy[2] was 27 Gg N yr^{-1}.

Other imports were about 9 Gg N yr^{-1} in commodities for human alimentation and for pets. This estimate does not include by-products recycled as animal feed. Harvested timber contained about 5.6 Gg N yr^{-1} (including bark).

The amount of nitrogen in synthetic products used in Norway, either imported or produced locally, was relatively modest although not negligible, approximately 12 Gg N yr^{-1}. About 1.7 Gg N yr^{-1} was emitted from primary chemical industries directly into waters[3].

In conclusion, the total amount of reactive nitrogen related to the Norwegian economy was about 270 Gg N yr^{-1}, of which 55% was used in agriculture, 26% was related to energy and transport (and is directly emitted), and about 4-5% was found in various synthetic products. The remaining 14% was related to fishery[4], to food import, and to a smaller extent to wood materials.

The N-flows through the food producing sector as a whole are presented in figure 2.2. The only final outputs included are municipal waste, sewage, and trade export commodities.

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[2] Including waste from processing of fish for export, but excluding waste dumped in pelagic waters.

[3] Not shown in figure 2.2, since it is immediately emitted outside the economical system.

[4] Exported fish and fish products used in agriculture excluded.

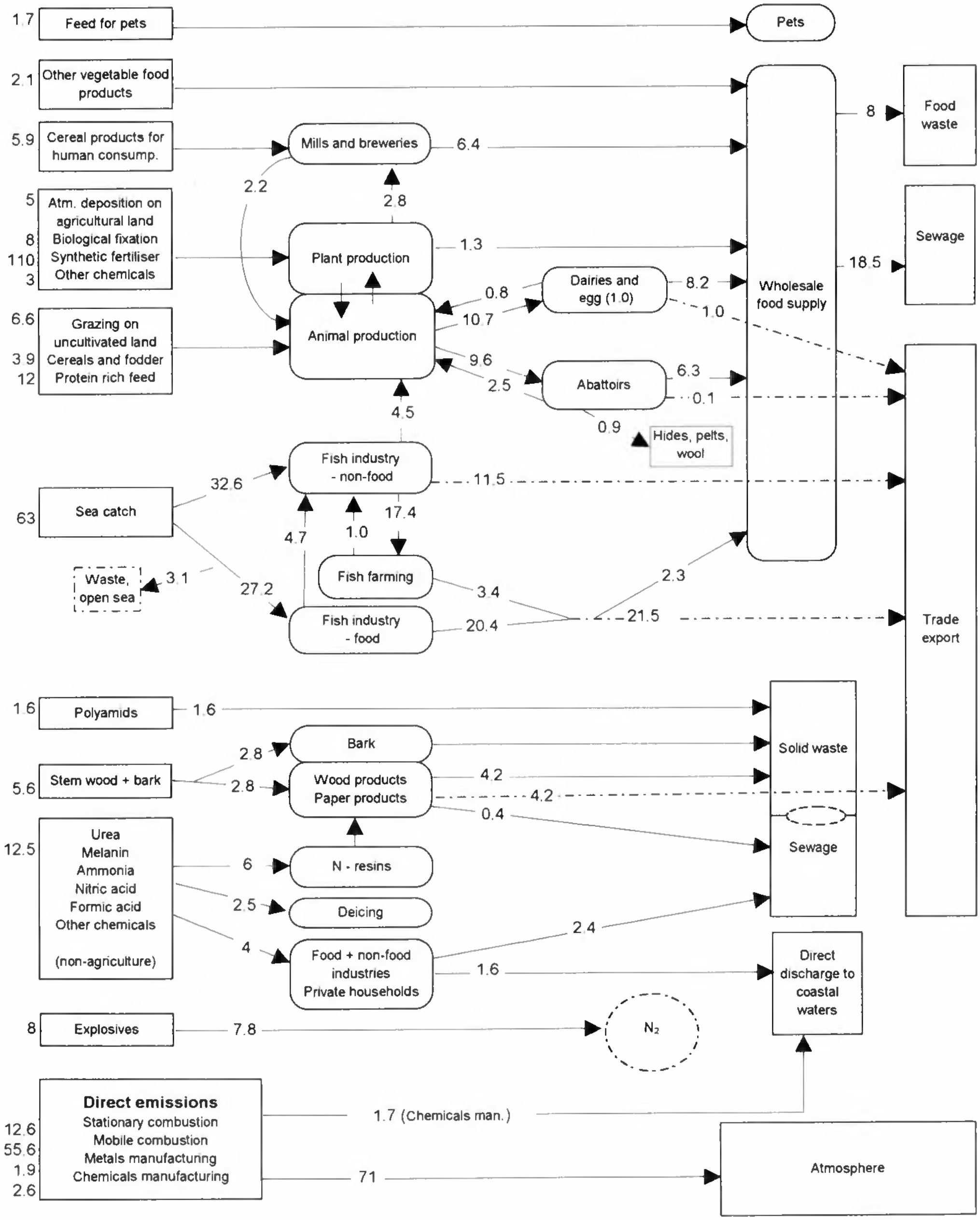

Figure 2.2: Nitrogen flows through goods produced and/or consumed in Norway, and direct nitrogen emissions, in Gg N yr^{-1} (Gg: 10^9 g). Boxes on the left hand side represent inputs into the Norwegian economy, those on the right hand side represent outputs.

2.2.3 Nitrogen losses

The difference between inputs and outputs at each joint in figure 2.2 represents the potential nitrogen loss from that sector or process. This is not the actual leaching to the environment, but a maximum amount which could eventually be lost (by deposition or denitrification) unless accumulated in the system. Accumulation may occur as biomass or "humus-N".

The total difference between input and output to agriculture was 130 Gg N yr^{-1} (input: 149 Gg N yr^{-1}, sum of plant and animal production, including animal growth but not pastured plants from ranging outside cultivated land). Since most products must be processed by primary agricultural industries before they can be available for wholesale market, we have measured the output (19 Gg N yr^{-1}) at this level, namely delivery from slaughter houses, dairies and mills. In the case of vegetables, the border between farmers and wholesale marked is less clear, but since vegetables contribute very little to the total nitrogen delivery to human consumption, the consequences are minimal. The primary agricultural industries are usually relative large units in Norway, from which by-products are collected relatively easily and recycled as animal feed. This choice of the sector borders avoids including recycled materials as agricultural outputs. Known losses from abattoirs and dairies are only about 1.2 Gg N yr^{-1} in whey, intestinal contents and sewage waters from abattoirs. Thus the surplus at the farm level was about 130 - 1 = 129 Gg N.

In comparison the highest estimate[5] of nitrogen load to the sewage system was ca. 22 Gg N yr^{-1}, and the total production of solid waste contained at most 19 Gg N yr^{-1}, of which almost 9 in non-easily decomposable materials (bark, wood, paper, polyamides). The nitrogen loss from fish cages to coastal waters was 13 Gg N yr^{-1}. Other emissions to waters from industry and losses on land from non-agricultural activities accounted altogether for around 5 Gg N yr^{-1}. This clearly identifies the agriculture production site as the sector with the largest overall potential nitrogen loss. This is an order of size larger then dissipation from the sewage or the solid waste renovation systems. Only emissions from combustion (70 Gg N yr^{-1}) are comparable to losses from agriculture. We need to take a closer look at the possible mechanisms of nitrogen losses (or accumulation) at this level.

A well known loss is NH_3 evaporation from animal excrements. The estimated ammonia losses from manure and from chemicals was about 25 Gg N yr^{-1}. Present estimates suggest that denitrification from agricultural soils is unlikely to exceed 10-20 Gg N yr^{-1} on a national scale (equivalent to 10-20 kg N ha^{-1}, total cultivated: 10^{10} m^2). Large scale monitoring of nitrate leaching from agricultural areas to drainage water is usually in the range of 20-50 kg N ha^{-1} yr^{-1}. Taking the upper level of these ranges, we find an average N surplus at the farm

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[5] Excluding background nitrogen concentration in waters

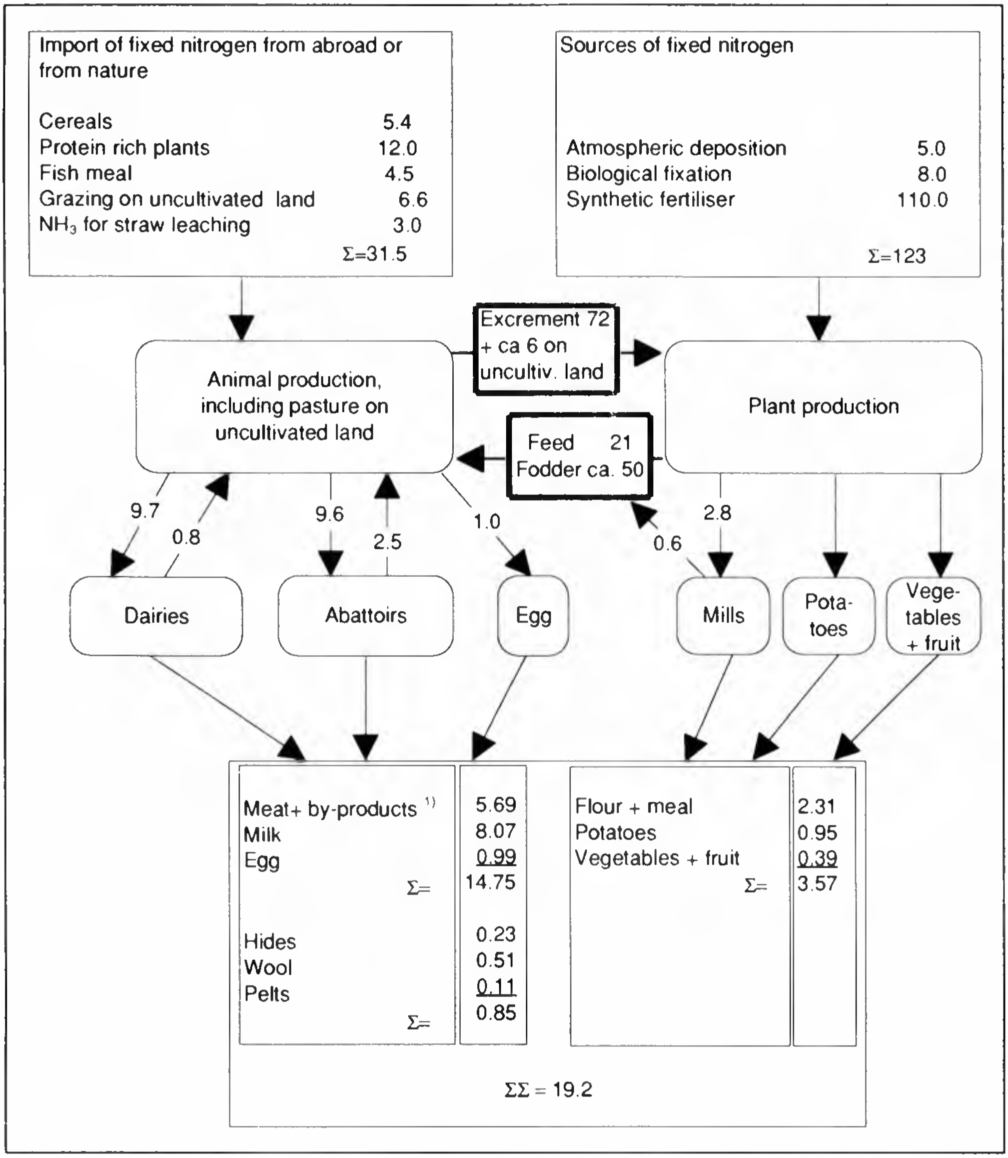

Figure 2.3: Major nitrogen flows through the agricultural sector, in Gg N yr^{-1}.

level of 129 - 25 - 20 - 50 = 34 Gg N yr^{-1}, equivalent to 34 kg N ha^{-1} yr^{-1}. This could hypothetically indicate a net accumulation of nitrogen in the system, possibly as soil organic matter. However, a net annual increase in the soil organic nitrogen pool does not seem plausible. Rather, one would expect a gradual decline in the overall soil organic matter in the

Norwegian agriculture due to a gradual increase in the area of plowed versus permanent pasture systems. Our estimate indicates a relative low nitrogen recovery from soil, compared to nitrogen budgets of field trials. In particular fodder production estimated by means of average animal consumption was less than what we would expect from field trials. Losses during harvesting and storage of roughage, and incomplete utilization in years with unexpectedly high yields are likely reasons. But even assuming losses as high as 25% of the total roughage production, these would account for only 16 Gg N of the total losses from agriculture.

In conclusion, present estimates of nitrogen losses through denitrification, nitrate leaching and ammonia volatilization from the plant/animal production system are inadequate to account for the total nitrogen emission from agriculture. Accumulation in soil organic matter and losses during fodder conservation can explain only part of the unaccounted loss. The relevance of losses from the plant/soil system, and the need for further studies of the agricultural system as effected by farming is evident.

2.2.4 The "nitrogen-cost" of food production

Wholesale food supply was about 26 Gg N yr^{-1} including imported plant products. About 2/3 of that was estimated to end up in the sewage system and 1/3 as solid waste. This shows that sewage and solid waste represented large N outputs from the human N-cycle, although their share was small compared to the losses from the agricultural sector.

We can divide the whole sector so as to separate the most important processes: plant production, animal production, processing of the main products: milling, slaughtering, dairy production. In the case of meat production, also partitioning of carcasses. The nitrogen flows through these processes are illustrated in figure 2.4. The estimates in this figure are based on the assumption that all the feed and fodder is produced in Norway. It is further assumed that no recycling occurs. The purpose of the figure is to illustrate the inherent N-cost of the various components of the agricultural system.

Based on I/O ratios for plant products ($2.34*1.27 = 3$), milk ($2.34*4.9*1.2 = 14$) and meat ($2.34*1.24*1.5*4.9 = 21$), we can calculate the "nitrogen saving" obtain by recycling at different trophic levels. For example chicken liver is hardly used for human consumption in Norway. Recycling as animal feed saves an input of 2.3 kg N to soil per kg N in liver. Used for human consumption it would save 21 kg N. This also illustrates the importance of increasing nitrogen recovery during food processing on the total nitrogen load to the environment. The overall recycling of by-products from mills and abattoirs reduced the need of total nitrogen input by 13 Gg N yr^{-1}.

The importance of the human diet composition is obvious. While it is important to make the production of food more N-efficient to reduce environmental stress, one also observes that a change to a more vegetarian diet would reduce the overall N-input significantly, and hence N-loss to the environment.

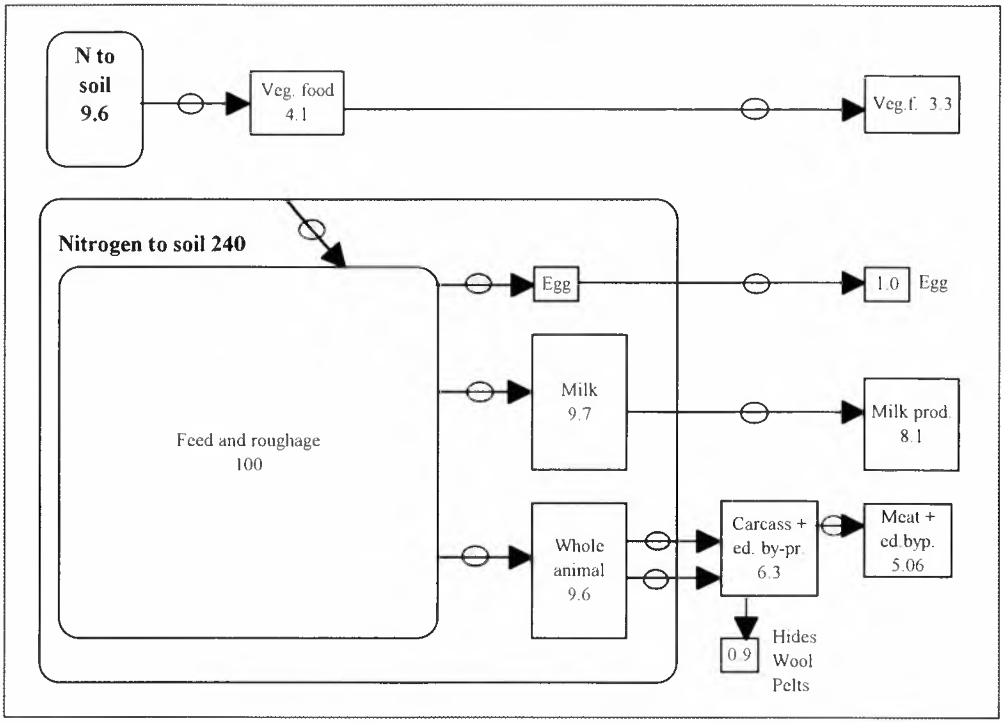

Figure 2.4: Nitrogen demand for production of various food items. The boxes on the far right show the nitrogen amount in whole sale food commodities produced by the Norwegian agriculture. The shaded boxes illustrate the necessary amount of fertilizer N (manure + mineral fertilizer + atmospheric deposition) if all the feed and fodder was to be produced by the Norwegian agriculture, and no recycling of animal products occurred.

2.3 Processes involved in P and N losses

Weather conditions and soil characteristics are crucial factors which determine the losses of N and P from the soil plant system; but agronomic practice is a strong modulator. The purpose of this chapter is to give a brief summary of the processes involved.

Phosphate binds strongly to soil colloids, and losses occur primarily as particle bound P through surface runoff. P-losses from the system are therefore primarily controlled by factors that determine the surface runoff of soil material (erosion). Soil erosion is typically an episodic phenomenon, occurring during heavy rain, freeze/thaw, snow melt etc. The soil properties (infiltration capacity, surface roughness, aggregate stability etc) may modulate the effect of such weather events. The steepness and lengths of the slopes are decisive factors for erosion and transport of the eroded soil material. Soil tillage is the most important agronomic factor that affects soil erosion. Plant cover efficiently protects the soil against erosion, and will also reduce the transport of particles with surface runoff. In contrast, the fertilizer level and P-uptake by the crop are of minor importance as factors regulating the P-losses.

The episodic character of the P-losses and the decisive role of physical factors, demands a modelling strategy that emphasizes the hydrology with a high resolution in time. But for the modelling to yield reasonable predictions of average P losses, long time series must be used to ensure inclusion of a representative number of erosion episodes.

The N-losses from the soil plant system occur primarily as nitrate leaching. In contrast to P-losses, the nitrate leaching is controlled by a complex set of factors which regulate the nitrogen transformation in the soil (Johnsson et al. 1987). Nitrate leaching as such is a simple physical phenomenon, linearly related to the concentration of nitrate in the soil profile.

The concentration of nitrate in the soil fluctuates throughout the season, and is strongly influenced by sinks and sources of mineral N in the system. These sinks are again profoundly affected by the agronomic practice. The sources and sinks of mineral N in soil are illustrated in figure 2.1.

Plants represent the most important N-sink in the system, assimilating N either ammonium or nitrate (depending on the availability of the latter). Any agronomic practice that affects plant growth will affect the nitrate dynamics and hence nitrate leaching from the system. Another important sink for mineral N is the microbial N-assimilation (immobilization in figure 2.1). Transient periods of net N-assimilation by the soil biota occurs during initial decomposition of plant litter with low N-contents (e.g. straw and dead plant roots). Apart from fertilizer N, the microbial mineralization of organic N is an important source of nitrate (via ammonium). The soil contains large reserves of organic N (N humus in figure 2.1) which are slowly mineralized (1-2% per year). The humus N pool is stabilized by a continuous supply of "fresh" material through litter and metabolic products. The size and the stability of the humus pool functions as a "buffer" in the N-dynamics of the system. If an agronomic practice is introduced which increases the supplies of humus N, the soil may function as a net accumulator of nitrogen (as humus N) for decades. And vice versa, a "soil mining" agronomic practice may go on for decades before the supplies in the soil are seriously depleted.

For more detailed information about N cycling in the soil system, readers are referred to text books and reviews (see for example Bacon 1995). To sum up, the following factors are considered the most important for determining the nitrate leaching from the soil-plant system:

- Plant uptake of mineral N
- Mineralization of old humic material
- N-mineralization/immobilization dynamics as affected by various types of litter.
- Denitrification (i.e. reduction of NO_3 to N_2O and N_2)
- Nitrification (oxidation of NH_3 to NO_3)
- The regulation of the process rates by soil temperature and moisture content
- Vertical transport of nitrate by percolating water

The agronomic practice has a profound influence on most factors. Hence predictions of the nitrate leaching as a function of agronomic practice demand a careful consideration of how each factor is influenced by the agronomy, and how this in turn affects the nitrate leaching. This is the task of the N modelling in the present study, described in more detail in chapters 4.4 and 6 (and references therein).

3 How to reduce nutrient losses?

The relationship between the levels of inputs and emissions of nutrients from an agro-ecosystem depends, as we have seen, on the transformations, circulations and storage within the system. The targets for policy measures to reduce emissions can either be the input levels, the internal processes, or the emissions. The efficiency properties of such measures depends on the relationship between the three. For an input factor that causes a single type of emission with invariant spatial effects, the effects of input targeted and emission targeted policy measures are equal (Vatn 1995). In such a case the policy measure with the least transaction costs – i.e. the costs of information gathering, contracting and controlling/enforcing established deals or contracts (Bromley 1991; Niehans 1987) – should be utilized.

Given the general dissipative and diverse nature of emissions from agricultural production systems, transaction costs normally will be far lower on the input as opposed to the emission side. Thus lower levels of monitoring and control costs favor input regulations. Such regulations tend to have low precision, however, due to the diversity of emissions and their dependency on the ecosystem's internal processes and storage functions, as previously discussed. In conclusion, input regulations are favorable due to their low transaction costs, but may fail because of low precision. Emission oriented regulations have the opposite qualities. For nonpoint-source pollution in agricultural systems, there appears to be prohibitively large monitoring costs, favoring input regulations.

A third alternative would be regulations oriented towards the internal processes in the agro-ecosystem, i.e. regulations on the production methods. To evaluate this issue, two questions have to be answered. First we need to know which alterations in input levels and agricultural practice that will have a favorable effect on the nutrient emissions. Secondly, we have to search for policy measures motivating farmers to make such changes and analyze the costs related to abatement, production changes and to implementation and maintenance of a certain policy.

3.1 Changes in the agricultural practices

As described in chapter 2, nutrient losses are affected both by the agronomic practices, soil characteristics, and weather/climatic conditions. Intuitively, the fertilizer levels will affect the emissions, but the internal sinks (plants and soil) have a profound influence on the emissions. Hence, reduction of fertilizer levels and manipulations of these sinks may be equally effective measures to obtain reduced emissions.

In the case of phosphorus, the efficient sorption to soil colloids makes the relationship between fertilizer levels and emissions very weak (at least on a moderate time scale). P-emissions occur mainly through runoff of soil colloids, and is controlled mainly by other factors than fertilizer level. For nitrogen there is a stronger case for fertilizer reductions as a measure against pollution, but the dependency of the internal sinks (plants and soil micro flora) on agronomic operations (including N fertilizer) may interfere. In extreme cases, i.e. at very low N-levels, a moderate input of N may actually reduce nitrate leaching due to its stimulation of plant growth (Uhlen 1989). This serves to illustrate the complications involved, although a successful farming regime is expected to operate at N-levels where a positive relationship between N-levels and nitrate leaching is anticipated.

The emissions vary from year to year in response to changes in weather conditions and the interaction between weather factors and agronomic practices. This annual variability of emissions holds a clue to understanding the relationship between agronomic practice and emissions. For a given practice, annual emissions may principally be characterized by the probability density function in figure 3.1.

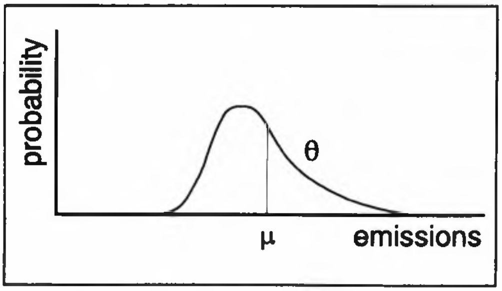

Figure 3.1: Distribution (θ) and mean (μ) for yearly nitrogen leaching and/or erosion. Principal relationships.

The skewed distribution function has implications for the effects of various agronomic measures. The average emission level (μ) can be lowered either by reducing the overall emission level equivalent to shifting the whole frequency distribution (figure 3.2 (a)), reducing the annual variability (figure 3.2 (b)) or both (figure 3.2 (c)).

Let us use nitrogen leaching to exemplify the alternative mitigation strategies illustrated in figure 3.2. *Reduced N-fertilizer levels* can be assumed to shift the whole distribution function to the left (a), but empirical data strongly suggest annual variability of the fertilizer effect: In years with high nitrate leaching (due to unfavorable conditions for plant growth), the nitrate leaching may be proportional to fertilizer levels; in contrast to more favorable years in which nitrate leaching is insensitive to N-levels over a wide range (Uhlen 1989).

The introduction of *crop types with a higher potential nitrogen uptake potential* has similar effects as reduced fertilizer levels, but the effect on the distribution function is strongly dependent on the ability of the new plant species to tolerate drought stress and other unfavorable conditions. *Improved soil structure* has the potential of reducing the overall emissions, since the nitrogen uptake *and* the drought tolerance of the soil plant system may be improved.

Strategies targeted directly on the *variability* (figure 3.2 (b)) must focus on its causes. *Irrigation* is a candidate, since high nitrate leaching may be caused by drought-limitation of plant growth. But irrigation may in fact result in higher nitrate leaching if heavy rain occurs just after irrigations early in the season. *Crop protection* against any other damages than drought (diseases and insects) will similarly reduce nitrate leaching in years when such factors potentially reduce crop growth. Due to its effects on other environmental relations, this may still be a somewhat disputable strategy. *Split fertilization* is an alternative strategy which may be effective: A second or third nitrogen dose, dependent on the crop performance each year, may thus cut the edge off the nitrate leaching in particularly unfavorable years.

Some strategies may actually work both on the overall leaching level and the annual variability (figure 3.2 (c)). The growing of *catch crops* (after the cash crop) may indeed fulfill this criterium. The catch crop will necessarily affect nitrogen emissions both in "good" and "bad" years – since the catch crop takes its nitrogen mainly from that mineral N pool which is most prone to leaching (i.e. mineral N in the soil after harvesting of the main crop). But the effect is potentially larger when the mineral N level in the soil throughout the autumn is high, which is the case in years with risk of high leaching losses. Thus, catch crops may reduce μ through reduction in the overall leaching levels and through a more dramatic effect in years with potentially high nitrate leaching (figure 3.2c).

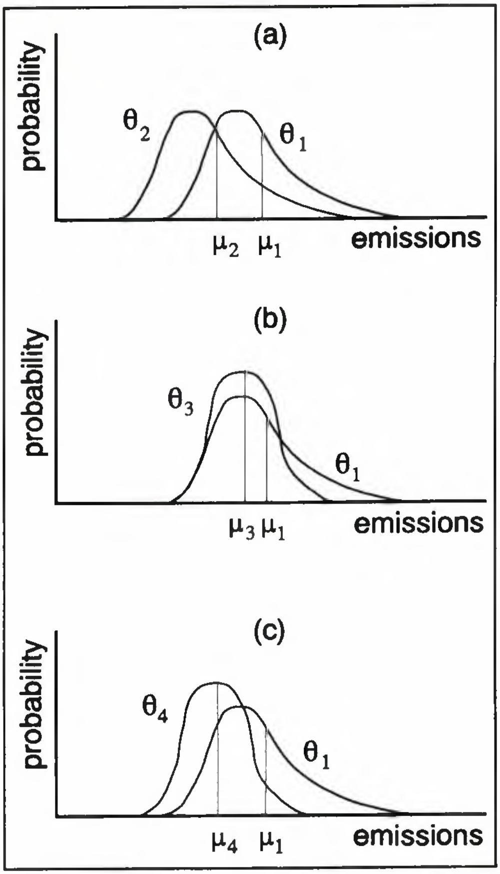

Figure 3.2: Distribution density (θ) and mean (μ) for yearly losses of nutrients.

The above points illustrate some basic relationships as they will occur in specialized plant production with the use of mineral fertilizers only. On animal farms, an optimal use of organic fertilizers is crucial. Ammonia is lost through volatilization from the animal house, the manure storage and in connection with manure spreading on the fields. Insufficient storage capacity for the manure may force the farmer to spread some of it in the autumn, necessarily causing nitrate leaching. Insufficient acreage per animal will result in excess levels of manure and large losses of N; either to the atmosphere as ammonia or to groundwater/streams through nitrate leaching. New techniques for manure storage and spreading may reduce the ammonia volatilization to a minimum, however.

New feeding practices, particularly for ruminants, may reduce the nitrogen concentration in the manure (Bolstad 1994), allowing a higher animal density without excess manure to be applied. This is clearly an interesting strategy, since it combines potential environmental benefits and economic gain for the farmer. On the other hand, a lower content of ammonium-N in the manure makes it less profitable to minimize losses of ammonia through new manure storage and handling technology; thus the result is not necessarily a reduction in the total emissions.

The greatest losses of nutrients occur inn fall and mild winters. The time for *soil tillage* affects *plant growth* and the amount of *plant cover* in these periods. Plowing late in fall or in the spring may thus shift the probability density function to the left as it also will affect the variance, in similarity with catch crops. If the altered tillage routines affect the growth of the main (cash crops) negatively, the overall effect on nitrate leaching is hypothetically neutral or may even be negative. In contrast, the P-runoff through soil erosion would probably be more consistently lowered by reduced or postponed tillage.

As is easily observed, there are few measures that are unequivocally favorable in environmental terms. Measures that minimize nitrate leaching may increase the risks for P losses. This is a risk connected with perennial crops and catch crops from which substantial amounts of P may be lost by surface runoff of plant-derived P solubilized by frost damage (Uhlen 1988; Øgaard and Krogstad 1995). Reduced tillage may be favorable for both N-losses and soil erosion, but requires an increased use of herbicides. We thus need to pay attention to the different trade-offs. Even more important, the complexity revealed thus far shows that it may become a difficult issue to motivate farmers in ways that combine the above measures in a cost-efficient manner.

On the background of the above reasoning, we have chosen to analyze P and N emissions as affected by a number of relevant physical measures as listed below:

Reduced N-levels
Split fertilization
Changed cropping
Catch crops
Reduced tillage, delayed/spring tillage
Changes in manure handling/spreading techniques

Timing of manure application (storage capacity)
Changes in feeding practices

Considerations of ecological damage cost functions strengthen the view that the *variability* of emissions should be focused. Marginal damage costs are often convex. Thus greater damage is attached to emissions with high variability as compared to those with low, even though the expected means may be equal. This is illustrated by figure 3.3.

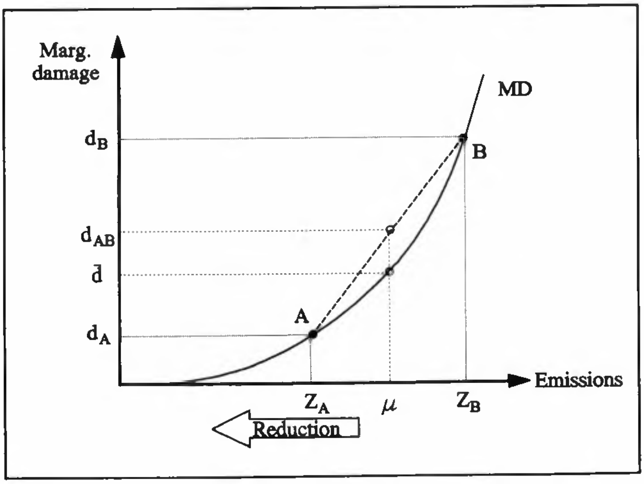

Figure 3.3: Emissions with the same expected level of μ, with and without variation.

Assume two stylized types of emissions – both with an expected mean = μ. Let one type have zero variance while the other has a bimodal emission pattern (Z_A- Z_B). Due to the convexity of the function, the zero variability scenario has a lower average damage ($\bar{d}$) compared to that for the bimodal case (d_{AB}):

$$(d_A+d_B)/2 = d_{AB} > \bar{d} \qquad [3.1]$$

In cases where the damage function has a threshold level, only the higher levels of emissions are of importance. In such cases the damages are negligible up to a certain level of emission and detrimental beyond that point.

3.2 Policy measures

3.2.1 Motivating farmers to change agronomic practice

In the abatement literature, both taxes and marketable quotas on emissions are proposed as measures to motivate economic agents to reduce emissions. In a world of certainty these two policy options are equivalent as measured against the standard efficiency criterion even though they have different distributional effects. With uncertainty these policy measures differ except in cases where the slopes of the expected marginal environmental cost curve and the expected marginal abatement cost curve are equal. If the environmental costs rise more sharply than abatement costs around the expected optimum, marketable quotas are to be preferred. The conclusion favors taxes if abatement costs are expected to rise the most (Weitzman 1974).

The above conclusion can be transformed to the case with regulations on inputs too, even though the question becomes more difficult to handle due to the additional uncertainty caused by the relation between input use and emissions. As to changes in farmers adaption, the two systems creates equivalent incentives. We start our discussion with input taxes.

For a profit maximizing farmer the following relation holds for the use of the input N – nitrogen in mineral fertilizer – in production of y = f(N):

$$\frac{\partial f(N)}{\partial N} = \frac{v}{p} \quad (= vp^{-1}) \qquad [3.2]$$

where input price is v and product price is p. Assuming that f(N) is concave and twice differentiable, increasing v with a tax t makes it profitable to reduce input of N to the point where the gradient of the production function f(N) is $(v + t)p^{-1}$ as shown in figure 3.4.

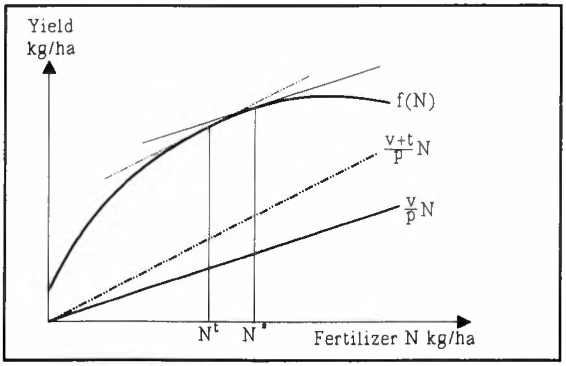

Figure 3.4: Change in the optimal use of N following from a tax t.

If emissions of N are environmentally harmful and increasing in N, such a tax would *ceteris paribus* lead to less environmental damages. The increased production cost would, under standard market assumptions, increase the market price of y. While this must be taken into consideration when calculating the level of t, it forwards the right type of signals to the rest of the economy as it changes the relative price in disfavor of products based on N.

From [3.2] we see that the same effect on N use could be obtained by reduced producer prices. In markets with product price subsidies this is advocated as an interesting strategy as emphasized for example in the McSharry plan of the EU. There are some differences if we compare with an input tax, however, that should be observed. Certainly, if there are other reasons to remove the subsidies, reduced input and emissions would follow free of charge. If the aim is to reduce emissions, lower product prices is equivalent to taxing inputs only in cases with no relevant substitution effects in the production. Such effects may be important, as is emphasized in much of the literature. A relative increase in the price of N will enhance the value of all sources of nitrogen, and make it more costly to lose the nutrient at different stages of the production process. In relation to the previous discussions, we can make the following observations:

- A tax may motivate farmers to utilize N in manure better. They may find it economical to increase storage capacity to be able to spread all N in the growing season and thus substitute for purchased N. They may also find it profitable to change to spreading techniques with less losses directly to air and/or water.

- A tax may induce a shift to increased use of legumes due to their N fixation capabilities. In grass production, this will most probably have positive environmental effects, while the effect is more uncertain with legumes used as green manure.

- A tax may motivate a change to split application of nitrogen. Increased N price will *ceteris paribus* make it more profitable to use technologies that supply N more precisely to the actual plant growth potential each year than is possible with standard rules of application.

- A tax may motivate farmers to use catch crops since less N is leached and instead incorporated into the organic soil component. This N may be released in later seasons and in this way made available for plant growth.

The above described potentials imply that an input tax may make regulations like requiring certain technologies, less warranted. The magnitude of the various changes are inversely related to their costs. To analyze the environmental effects, the effects of changed farming practices on plant growth and soil processes need also to be considered.

Looking more specifically at the different possibilities, analyses made by Simonsen, Rysstad and Christoffersen (1992) indicate favorable effects of an N tax on manuring practices under Norwegian conditions. Their study shows that there are substantial possibilities for changes even at tax levels of 100 % and lower. The effect was rather large reductions in the use of mineral fertilizers. The results are, however, sensitive to small changes in the assumptions made.

Clover is the most interesting legume under Norwegian conditions. It is normally part of the seed mix used when establishing meadows. The high fertilizer levels used reduces their competitiveness, and the clover mostly dies out after a short period. Since lower N levels may have a substantial effect on the capability of clover to survive and grow, the loss of plant mass may be modest even if the use of N diminishes. This may make N use in grass production rather sensitive to changes in the N price – i.e. we may observe large substitution effects. In the case of green manure the situation is somewhat different. Here the land is used to produce N with the help of legumes in one period, while this N/plant mass is incorporated into the soil as fertilizer in the next period. In such a case the capacity to fix N must most probably be rather high for an N tax to induce shifts.

Split fertilization becomes relatively more profitable as the N price increases. In years with dry conditions in the early part of the growing season and low yield potential, farmers may save fertilizer by practicing split fertilization. Additionally, profits may be increased in years where the potential yields are high (nearly ideal growing conditions in the spring/early summer). These advantages need to be compared to the additional costs of split fertilization. The farmer will have costs related to the extra round of fertilizer application at least in some years. There will further be some losses in yields due to extra trafficking in standing crops. Finally, if the first round application is low, costs may arise that are associated with plant growth stagnation early in the growing season.

The greater the difference in the profit maximizing fertilization levels between "good" and "bad" years, the greater the expected benefits of split fertilization. In this connection it is important to note that split fertilization may not lead to any reduction in the total use of N. If practiced optimally from a profit maximizing point of view, split fertilization would lead to lower fertilization levels in years where growing conditions indicate low yields, and to higher levels when growing conditions indicate high yields. Simonsen, Rysstad and Christoffersen (1992) point out that the total use of N need not to be reduced, while a higher precision still should result in reduced average leaching.

For a tax to induce the use of catch crops, the increased mineralization in the growing season – due to a larger N pool in the soil – must pay for the extra costs created by sowing the catch crop (normally rye grass) and letting it compete with the main crop for water and nutrients. The higher the tax, the greater the chance for this to happen. Note that there is a time delay before the net change in mineralization becomes positive. Thus costs and gains will occur at different times, and the level of the interest rate will influence which tax rate, if any, will make it profitable to grow catch crops. Based on existing knowledge of the dynamics of incorporating organic matter in soils (Christensen and Johnston 1995; Jenkinson 1990; Uhlen 1991), we expect the time delay to be considerable.

The above reasoning shows that even if there is a large potential for a tax (or tradeable quota system) to induce various N saving substitutions, it is uncertain at which rate they will occur. Thus it is necessary to analyze the effects of policy measures that more directly motivate the use of practices like the ones listed in section 3.1. Such measures include mandatory catch crops, certain storage facilities etc.

As we turn from nitrogen to phosphorus and soil losses, the argument for using policy measures other than input taxes is even stronger. Here losses are only weakly connected to input levels as it is the type and duration of plant cover, time and form of soil preparation etc., that are most important. Certainly the average fertilizer level will over time influence the amount of P in the eroded soil. Still, the yearly uptake in grains corresponds to a small fraction of the total amount of P in the top soil. Thus the effect will only be significant in the very long run, though as such important enough.

In the case of phosphorus we want to analyze different systems of prescribed or subsidized changes in tilling practices. Further, we expect that policies favoring the use of catch crops and manure spread in the growth season, also will be positive as to reducing surface runoff of P.

3.2.2 Transaction costs, environmental costs and precision

As emphasized earlier, going from emission directed policies to input related ones will in many cases imply loss of precision because it is more difficult to adapt such policy measures to local pollution characteristics. Moreover, we will have less precision since the type and form of emission often varies between the different uses of the input. The expected reduction in transaction costs may still favor input measures. Turning to measures like regulating the production process more directly, is a way to reimpose increased precision, while enhancing transaction costs.

Transaction costs are often neglected in studies of policy measures. If accounted for, we tend to find an implicit conception that they are zero when the policy instrument is constructed as a market incentive like a tax or tradeable quota. But as Coase (1937) showed a long time ago, if that was the case, the command system of a firm should never exist. Thus no analyses can escape the issue. Transaction costs are, however, very difficult to measure. In policy evaluations we often need to make an a priori evaluation without any other empirical foundations than possibly those of "similar" cases.

Our study provides an assessment of the level of precision gained or lost by different policy measures. This forms a basis for discussing whether gains in precision may cover the additional costs associated with more complex systems of information gathering, administration and control. The expected level of transaction costs will be evaluated in a more qualitative way.

In this study we have assumed that farmers are profit maximizers. If they do not maximize – either because their way of making decisions is less rational or because the informational needs are so high that they largely will follow "rules of thumb" – it may be that prescribed practices or using input quotas may compete well with more incentive compatible measures.

3.2.3 Distributional effects

Different policy measures have specific distributional effects as they have different efficiency properties. Given the *ex post* implementation of policy measures as in our case, the gains to be obtained are of the potential Pareto improvement type (Vatn and Bromley 1995). Thus distributional effects are an inherent part of the issue as is also clarified by Hammond (1990), who like Mishan (1981) and Bromley (1989) further emphasizes that efficiency and distribution can in general not be kept apart.

For the implementation of certain policy measures, distributional effects seem to be as important as the efficiency properties. It will be especially hard to get support for changes where some groups will experience substantial losses. As to taxes, the levels needed to make the desirable changes often turn out to be very large, while on the other hand the social costs related to the induced changes in production may be low. This creates a special mix of both strong positive and negative attributes attached to the policy.

This problem is often magnified by going from emission to input taxes. As in the case of N, earlier analyses show that under Norwegian conditions there are no increases in emissions observed for the first 50 – 60 kg used per ha for grains (Uhlen 1990; Sødal and Vatn 1990). Thus no emission tax would have been demanded in cases with such low use. But with an ordinary input tax, even this volume would be taxed. For those practicing "low input" agriculture already, this kind of tax may appear unfair. Such relations certainly increase the problem of gaining public support for certain policies.

Hence it is relevant to measure both costs and distributional effects of the various policy regimes studied. It may be of interest to try to search for solutions that both score high on cost-efficiency and have modest distributional effects.

4 Modelling principles and practices

To be able to analyze and evaluate the different types of policy options discussed so far, we need to combine insights about processes driving nutrient turn over in soils, leaching, erosion, plant growth and farmers choice of agronomic practices. While weather and soil conditions are important factors in understanding the different natural science elements, cost relationships drive the choice of agronomic practice. These costs are in turn partly dependent upon the natural processes mentioned. They rely, however, also on the institutional set up, technology and existing production structure.

Earlier analyses have mainly been devoted towards studying one or a few of the above interrelationships. The idea underlying our research is that especially in policy analyses, we need to work at a systems level and concentrate on the dynamics between otherwise fairly well understood individual processes. Disciplinary research is certainly important, but must be complemented with more systems oriented studies focussing on the interactions.[6]

This chapter is divided into four parts. First, we present the basic choices made as to how the different processes studied are integrated. Second, we give an overview of the structure of the model framework. Next, we present and discuss the principles for the economic part of the modelling. We finish the chapter by a similar presentation for the natural sciences involved. A more technical and complete presentation is given in appendix A.

4.1 Integrating economics and natural sciences

4.1.1 Integration and system levels

The main challenge for our study has been to develop a firm basis for handling the interaction between the very diverse set of relevant processes. With the given complexity, we found mathematical modelling to be the most constructive way to cooperate across disciplines. Further, we chose to start from the systems level. Too many projects have illustrated the difficulties and failures that occur when starting from the parts or disciplines, trying to integrate their analysis towards some (hopefully) common objective. Thus we began by defining the boundaries of the system, its main parts and the dominant interactions between

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[6] This kind of research is obviously important also for the disciplinary oriented activities in clarifying the relevance of different types of more narrowly defined specialist research and in developing hypothesis that otherwise would be hidden as "blind spots" between disciplines.

these parts. In a second phase we went on to describing the internal dynamics of each element.

Since our main focus is on nutrient and soil losses to water, we defined the watershed as our system of study. At the same time we realized that a watershed is not easily connected to existing societal units. First, it may include a set of farms that are only partly demarcated by the boundaries of the watershed. Most important, no political unit is normally demarcated this way. Still we found these problems to be minor and mainly related to the possibility of differentiating the policy between subregions of a country.

We further limited the study to the cultivated part of the watershed, i.e. losses from other types of land use and the question of what happens with the different emissions as they leave the soil, is mostly kept at the level of background information and not modelled explicitly so far.

To establish a common ground to handle the dynamics between the different processes and to secure consistency, the following simple model of the main parts of the system was constructed:

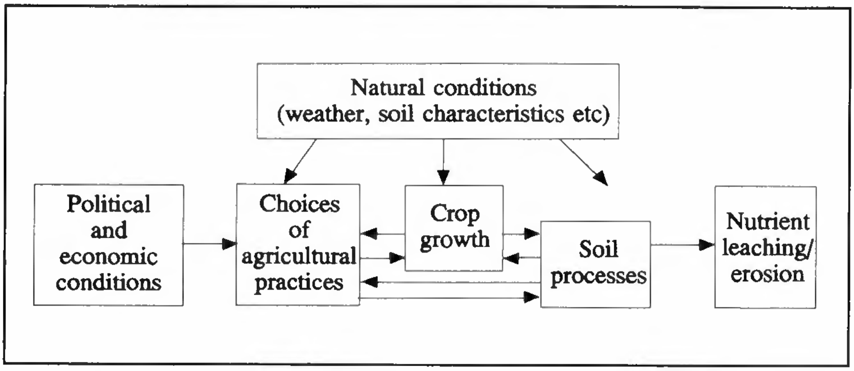

Figure 4.1: The main elements of the studied system

While the aims of the project focuses on the relations between the left and right parts of the figure, most of the communication between the economic analyses and the study of nutrient leaching and erosion goes through the interface between *choices of agronomic practices*, *crop growth* and *soil processes*. For the farmer, maximizing expected net returns from crop production is the interesting issue in our case. Correspondingly, plant growth plays an important role in explaining the level especially of residue N and thus emissions. Similarly, soil processes are influenced by the farmer's choices as these in turn influence both crop growth, leaching and erosion.

The various processes in figure 4.1 operate at different levels. A way to overcome the problem of varying scales is to utilize the fact that both social and natural systems tend to be organized in hierarchies as previously emphasized. The different levels are nested, with processes at one level becoming elements of higher level processes. In our analyses the following levels were chosen:

1. *Landscape/watersheds*. Partitioning criteria: Demarcated to cover types of climate, topography and production. Modelling: Aggregated emissions to air and water.
2. *Farm*. Partitioning criteria: Size, type of production and stocking rate. Modelling: Farmers choices of agronomic practices.
3. *Farm field*. Partitioning criteria: Soil properties and chosen agronomic practice. Modelling: Crop growth and farmers choices of agronomic practice.
4. *Point/farm field*. Partitioning criteria: Soil properties and agronomic practice. Modelling: Hydrology, nutrient turnover and leaching.
5. *Plot/grid cell*. Partitioning criteria: Topography, soil properties and agronomic practice. Modelling: Erosion.

4.1.2 Partitioning and interaction – crop growth as an example

Crop growth is an important cross road between the disciplines involved. It can thus be used as an example of how various interactions are taken care of in the modelling. Plant yield can be defined as a function of different agronomic variables in the following way:

$$y = f(w, i, g(j, l, N_{1,T}, N_{2,T}, N_{3,T}, p, k, d, m, o)) \qquad [4.1]$$

where y denotes yield, plant mass in dry matter,
w denotes weather,
i denotes type of soil, and
the elements in g are all agronomic in the sense that they may be influenced by the farmer's choices:
- j is type of crop(s),
- l denotes crop succession,
- $N_{1,t}$ is nitrogen in mineral fertilizers applied at time t,
- $N_{2,t}$ is nitrogen from manure in mineral form applied at time t,
- $N_{3,t}$ is mineralized N from the different organic components of the soil at time t,
- p denotes phosphorus in fertilizers,
- k is soil preparation methods,
- d is sowing date,
- m denotes soil compaction, and
- o denotes competition effects of catch crops.

In making the relationships in [4.1] operational in a mathematical programming framework, the varying scales and resolutions needed for the different sub-studies becomes important. Here the necessities and perspectives are clearly different both in relation to subsystems and scientific traditions. Still, in both biology, soil science and economics there is a need to preserve fine-scale variability in more coarse-scale modelling. Rastetter et al. (1992) discuss four methods by which to accomplish this:

a. Partial transformations using an expectation operator to correct for (the most severe) aggregation errors.
b. Moment expansions using truncated Taylor series expansion of the expectations operator to approximate partial transformations.
c. Partitioning – separating the coarse scale objects (aggregates) into a manageable set of relatively homogenous subgroups.
d. Calibration – recalibrating fine-scale data to coarse-scale information.

Methods (a) and (b) are actually variations over the same basic solution. Incorporating fine-scale variability by a statistical expectations operator may yield good results, but is often complex and difficult to utilize in systems with many elements and dimensions of variation. Partitioning – (c) – may be a good alternative in such cases, utilizing the increased capacity of computer technology. The prospect of (d) rests on the availability of data both at the fine and coarse scales. Costanza, Wainger and Bockstael (1995) find (c) to yield a good solution for analyzes of land based systems. It offers a good platform for linking analyses that must be undertaken at different levels and studied with variable resolutions and is utilized throughout this study.

In the case of crop growth we chose to partition [4.1] by the factors w (weather), i (soil type) and j (crop), i.e. we have developed separate production functions for each subgroup of these variables (Romstad 1995; Vatn 1994). The only arguments in the final yield functions are the different elements of N as the other variables in [4.1] are taken into account by influencing the parameter values of the separated functions, mostly in a multiplicative fashion. On the basis of this, [4.1] is reformulated:

$$y = f_{ijt}[(N_1, N_2, N_3)\ \Omega_{lkdmo}\ \mid\ p] \qquad [4.2]$$

where the subscripts follow the variable definitions of [4.1]. The weather is covered by the time factor t and Ω is an operator for the different elements of agronomic practice except fertilizing. The level of phosphorus (p) is fixed, assumed to be given at a level not constraining the growth of the different crops.

In the case of N leaching, it is not plant mass in itself, but the level of N-uptake in plants and roots that is of importance. This level is estimated separately as a function of both dry matter yield and plant available N in the soil:

$$NH = h(y, N) \qquad [4.3]$$

where NH denotes total N uptake by plants,
y denotes dry matter yield, and
N denotes plant available N (= $\Sigma_{q=1}^{3} N_q$).

For more details see appendix A5.5.1 and Vold, Bakken, Vatn (1995b).

The choices implicit in [4.2], reflect partly the character of available data. The method used makes it possible to utilize existing experimental field data that most often are produced with the help of factorial trials. Further, using a regression strategy at this level simplified the communication between disciplines and interaction between parts to a level possible to handle. The technique applied made it feasible to both preserve the necessary details and secure consistencies throughout the study as a whole.

As to the levels of resolution, it has been important to capture the essential dynamics of each process while avoiding overload of details at the systems level. The differences in needs between economics and the natural sciences involved appears already at the first argument of [4.1]. While the plant processes follow *actual* weather, the farmer must make his decisions mainly on *expectations* about the weather and subsequent plant growth. This distinction is taken care of by producing yearly production functions – f_{ijt} – to be used in the natural science part of the modelling and an average function – f_{ij} – representing the expectations of the farmer. To cover variation in weather conditions, a 20 year period with weather data from 1973-92 is used in the analyses. Information about the estimated functions, methods and functional forms are given in appendix A5.

Yearly specified information about weather is also utilized in the economic analyses in cases where it proved important and relevant. Thus, sowing date is modelled as an optimizing problem partly based on expectations (choice of equipment used) and on information about actual soil water content as it evolves (choice of sowing sequence of fields and determination of sowing date each year).

Moving to i – the soil quality – resolution is the same throughout most of the study. Production functions are estimated for clay, silt and sandy soils. The different soil processes are also modelled for standard profiles of these soil types, reflecting a given agronomic history. In the erosion study and the module choosing soil preparation method, we found it necessary to partition the three main types further. In other parts of the economic study, relations are undifferentiated over soil types and instead maybe differentiated by farm size, type of preparation etc. as these factors are of greater importance.

When it comes to j – i.e. type of crop – separate yield functions for barley, oats, spring wheat, winter wheat, grass (with clover) and legumes have been estimated. The functions estimated are based on plot trials with standard treatments like autumn plowing, use of mineral fertilizers only (i.e. $N_2 = 0$) and with N mineralization (N_3) given from such an agronomic history. Thus the functions are estimated dependent upon the actual level of N_3, whose effect is captured in the year specific yield functions f_t. This implies that N_3 in [4.2] is really ΔN_3 measuring the difference in mineralization following from changes in agronomic practices as compared with the standard treatment. Such changes may be use of catch crops or animal manure with its organic N components. The way [4.2] is structured, changes in ΔN_3 modifies the optimal use of N_1 and/or N_2, securing consistency as to the farmers choice variables.

4.2 The structure of the modelling system

On the basis of the above principles, a system of mathematical models has been constructed – ECECMOD. Some models are developed from scratch. In other cases it has been possible to use already existing models while adjusting them to Norwegian conditions. Finally, it has been necessary to reconstruct models initially developed outside the project. Figure 4.2 (next page) gives an overview of the main structure of ECECMOD.

In the figure it is differentiated between external inputs, (process based) models, and modelling results (intermediate and final states). The level of resolution (scales) for the spatial dimension is also given. As we see, *crop growth* is placed at an "intermediate" level between external inputs and the model level. This reflects the methodological choices previously explained.

As to the different models, we would like to emphasize the following:

- *ECMOD* is an optimizing model, consisting of a set of modules related to different choice problems. The optimizing procedures are mainly non-linear. The model chooses agronomic practice for each farm field at the levels necessary for the rest of the modelling (day, season, year). Optimizing is to a large degree based on *expectations* – expressed in the terms of mean figures – with expected yields as the most important relation. The model also calculates measures to evaluate the cost-efficiency of different strategies on the basis of data on changed emissions from the landscape models and cost data from previous runs of ECMOD.
- *SOIL* is a deterministic one dimensional hydrology model which simulates soil water content, water flows and soil temperature, based on daily weather and soil characteristics (Jansson 1991; Botterweg 1992). The information produced here is used both as driving data for nutrient turnover and erosion modelling and to determine sowing date (ECMOD)

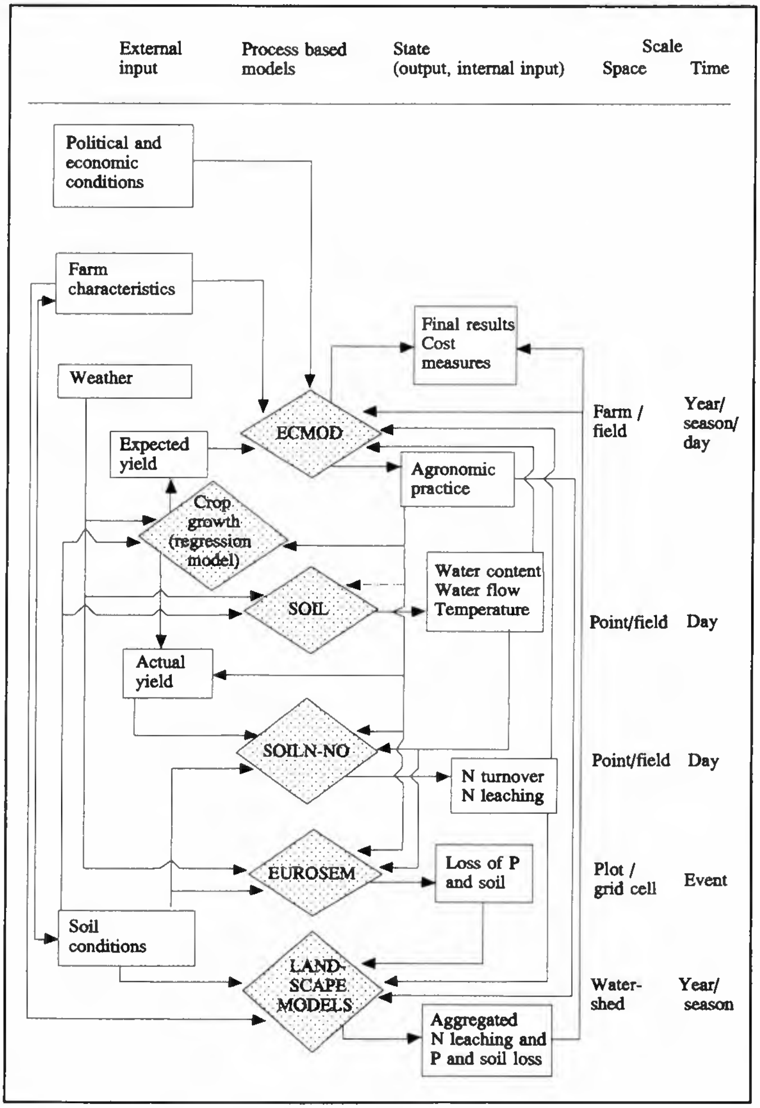

Figure 4.2: The structure of ECECMOD.

- *SOILN-NO* (reprogrammed version of SOILN) is also a one dimensional, layered deterministic model describing nitrogen turnover (Johnsson et al. 1987; Vold, Bakken and Søreng 1994). It produces information about loss of N as a function of chosen agronomic practice, plant growth, soil hydrology, temperature, and soil characteristics (soil type and agronomic history) expanded from point to field level assuming homogenous fields (ECMOD).

- *EUROSEM* is a new model describing erosion as a function of agronomic practice, weather, soil characteristics and topography. It is an event oriented, process based model substantially diverging from the more dominating tradition of regression based analyses (Morgan et al. 1996; Botterweg 1996).
- *Landscape models*. Finally there are developed two systems or models for aggregating data from plot and/or field level to the level of watersheds. The aggregation of costs and N leaching estimates is a fairly simple weighing based on the relative distribution of productions, soils etc. in landscapes. As to erosion, GRIDSEM (Leek 1993) is used. It is a model handling the movement of matter in landscapes and capable of aggregating erosion losses over larger areas.

The chosen structure has made it possible to divide the analysis into manageable parts, that can be sequentially analyzed in a consistent manner. First ECMOD is run and farmers' choices of agronomic practice are modelled on the basis of information about political and economic conditions, farm characteristics and cost relationships. Further the relevant information given by f_{ij} and Ω in [4.2] and some pre-estimated parameters from the natural science modelling like soil water content and changes in the level of mineralization (ΔN_3) is used. Then the different natural science processes are run in sequence given the choice of farming practices. The level of resolution varies between the different stages of the analysis according to relevance and need for precision. The choices of agronomic practices are modelled on the basis of information at a lower resolution than the different soil processes. This is consistent since farmers must make their decisions on a coarser scale than is needed to adequately model the natural processes determining emissions.

The are some problems with the chosen sequencing, in our case relating especially to the level of ΔN_3 which is dependent both on farmers' use of organic nutrients (manure, catch crops etc.) and on soil processes. Taking this fully into account would have demanded analyses where the economic and natural science analyses were fully integrated step by step – i.e. updating the model determining farming practices with consecutive information about the development of the various soil processes. This type of integration is very demanding, as it also would have over-estimated farmers possibilities to adjust. We have chosen a solution where average effects of various levels of organic fertilizers on N_3 are pre-estimated for the period studied. These estimates are made with the help of SOILN-NO. This separate and fairly coarse scale estimation of ΔN_3 may, as new equipment measuring mineral N in the soil becomes available, make this solution less adequate in the future.

ECMOD works at the farm level. The connections to the chosen landscapes go through the system of model farms. These farms cover the variations in the studied landscapes/watersheds in a representative way. The system demands each model farm to be divided into a set of specifically defined fields. Parallel to this, the landscape is divided into series of plots (fields) homogenous in soil. To be able to transmit information about agronomic practices to the landscape level, each plot is attached to a model farm field. This link is established through the process of constructing the model farms, basing them on information about size, production, soil conditions etc. on the existing farms in the actual landscapes (for details see appendix A4.2).

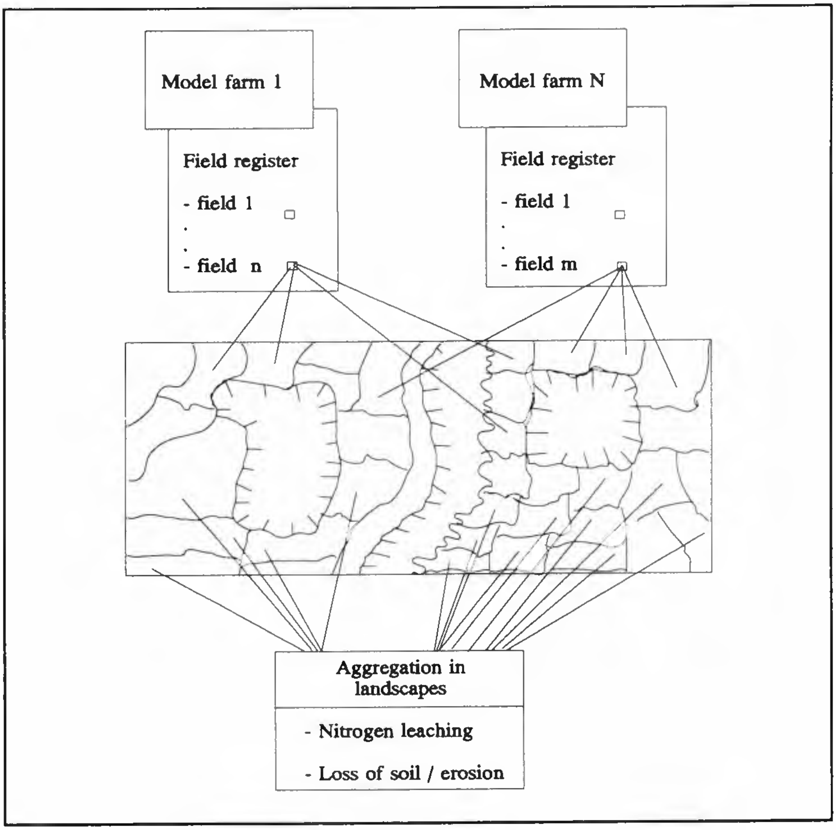

Figure 4.3: The connection between model farms and landscapes.

The N-leaching estimates are initially developed at the model farm field level. All necessary information is known here as long as each farm field is presumed to be homogenous in soil characteristics. Total estimated emissions at landscape level is found through weighing. As previously stated, total losses through erosion are calculated by also taking into account topographical and mass transport processes.

4.3 Basic principles for the economic modelling

The primary objective of ECMOD is to model economic responses to changes in environmental policies pertaining to agriculture. Principally, one could choose among econometric simulation or mathematical programming methods. Further, there is a choice to be made whether to undertake the modelling at the sector or farm level.

As already emphasized, we have chosen to focus at the farm level implying that mathematical programming is the only relevant tool. In our mind it is extremely important to be careful about getting the choices of agronomic practices right and producing information at a level of resolution that connects well to the natural science modelling. A sector modelling approach has serious disadvantages in this respect.

The drawbacks with a farm level approach are two fold. First, it does not explicitly take account of structural changes potentially induced by the analyzed policy measures. Second, it is not capable of modelling feedbacks of farm level decisions on product prices. These are important limitations, but of minor importance for the studies undertaken here, since most policy measures studied will have minor effects on farm structure and prices. This conclusion is also due to the fact that prices on agricultural products in Norway are set in negotiations and realized through a complex system of market regulations. Thus the market influences prices in a very indirect way in Norway. Modelling these feedbacks or changes in farm structure would further have required a partial equilibrium approach. This would have made it more difficult – if not impossible – to get the necessary details for the natural science modelling.

The decision to construct ECMOD was based on two factors: (a) existing models did not contain the flexibility needed to model the effects of all the relevant policy measures on agricultural practices, and (b) communication between the economic model(s) and the natural science models demanded a type of output very different from those produced by existing models be it sector or farm level models.

4.3.1 Behavioral assumptions

The "farmer" in ECMOD is assumed to maximize expected profits. To some extent the profit maximizing assumption is controversial (see for example Simon 1956; 1959), in particular applied to the way decisions are made in small firms. Norwegian farms belong to the category of small farms. In that connection, Vatn (1991) studied 650 farm households using data from the period 1975-90, and found that other factors than profits – in particular leisure time – were important for farmers' production decisions. A recent study on factors affecting tillage practices among Swedish farmers ranked the relative profits of the various tillage practices as the most important factor (Widabeck 1995). Even the most ardent critics of the profit maximizing hypothesis admit that profits play an important role in the decision making process in the firm.[7] Despite this controversy, profit maximization has some very desirable attributes relative to other assumptions about the decision making process:

- The decision parameters are generally observable (like prices), or manifested in some technical relationship (like production functions).
- It is more readily incorporated into mathematical programming models.

Two important features of farming are (i) the stochastic nature of the production process, particularly caused by the weather, and (ii) a considerable time delay from production decisions are made to the realization of the production results. In such cases farmers need to make their decisions based on their expectations. According to the rational expectations hypothesis (see Scheffrin (1983) for an introduction) optimal use of information occurs when the forecast errors are unbiased and identically independently distributed, and the orthogonality condition is met (it is not possible to improve the forecast by utilizing more available information).[8]

In ECMOD the informational problems can be divided into two categories:

(1) *Incomplete prior information.* The farmer has incomplete information when decisions are made. These decisions are therefore made on the basis of his/her expectations. An example of this kind of decision is crop selection, where crop selection is decided before the growing season starts, and the modelled farmer is well aware that the decision made may be sub-optimal when evaluated *ex post*.

(2) *Sequential information and sequential decisions.* As the growing season progresses, the farmer acquires more information regarding the possible outcomes of the growing season. This information is utilized in decisions that are made through the growing season. The effect of sowing date on the optimal fertilization level (see A2.6) is one example of such a decision.

4.3.2 Model structure

ECMOD incorporates these two types of decision problems through its structure and the solution sequence of the various modules. Each model farm is set up with a standard machinery, based on the model farm size and type of production (based on 1992 figures for

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[7] For a thorough discussion of the profit maximizing hypothesis see for example Becker (1981), Bunn (1984) or Simon (1959).

[8] For a thorough discussion on the use of information, see Simon (1959).

comparable farms). The sequence in running the modules are:

- The *crop selection module* is specifically tailored to the cropping pattern of the model farms (separate module specifications for model farms that only grow grains, farms with grain/grass rotation and contract crops). Based on product and input factor prices, and possible environmental regulations – like catch crop requirements – crop rotation is determined for each year for non-corrected *ex ante* fertilization levels.
- The *manure handling module* determines optimal manure storage/handling for the 20 year analysis period, and how much manure to spread on each field, conditional on the non-corrected fertilization levels obtained in the crop selection modules. Important factors in this module are ammonia losses and the soil compaction effects due to trafficking (see A2.4 for details).
- The *tillage practices module* consists of two routines: (a) choosing the optimal tilling equipment, and (b) choosing the optimal tillage practices for each field and year – given (a) and the results from the above modules. Decisions under (a) involve investments, and are therefore fixed through the 20 year modelling sequence for any given scenario. These decisions are then used as restrictions when year-to-year tillage is modelled in (b).
- The *spring time management module* determines the optimal sowing date on each field in every year, given the solutions to the above modules. An important attribute of this module is that it increases the value of labor for late sowing dates, resulting in the farmer working more hours per day. The reason for this adjustment in the module is that the later the sowing date, the larger the expected yield loss.
- The final *adjustment/optimization module* adjusts fertilization levels based on the solutions to the above modules. These adjustments are due to:
  - the soil compaction effects caused by any heavy manure spreading equipment,
  - expected yield effects from the chosen tillage practices, and
  - expected yield effects from the chosen sowing dates.

  The module also makes adjustments in fertilization levels due to lagged effects of previous crops on each field, and competition effects (from catch crops). Finally this module calculates the actual yield from the year specific yield curves.
- In addition to transferring data from ECMOD to the natural sciences modules, the *natural sciences transfer module* sets certain parameters used in the natural sciences modules, like sowing date(s) for crops sown in the fall (when labor constraints on the farm are less severe than in spring), harvesting dates and root depth through the growing season.

A more detailed presentation of the various elements of ECMOD is given in appendix A2.

4.4 Modelling the natural processes

4.4.1 Choice of models

The overall structure of ECECMOD discussed in section 4.1 and summarized in figure 4.2 sets criteria for the performances of the natural science models. They should be able to keep a high resolution in time to cope with temporal variability, and should also differentiate adequately between soil types (texture). Frost and snow cover represent an important challenge to modelling for Norwegian climatic conditions, and the models must be able to simulate these phenomena properly. No existing single model handles hydrology, nutrients

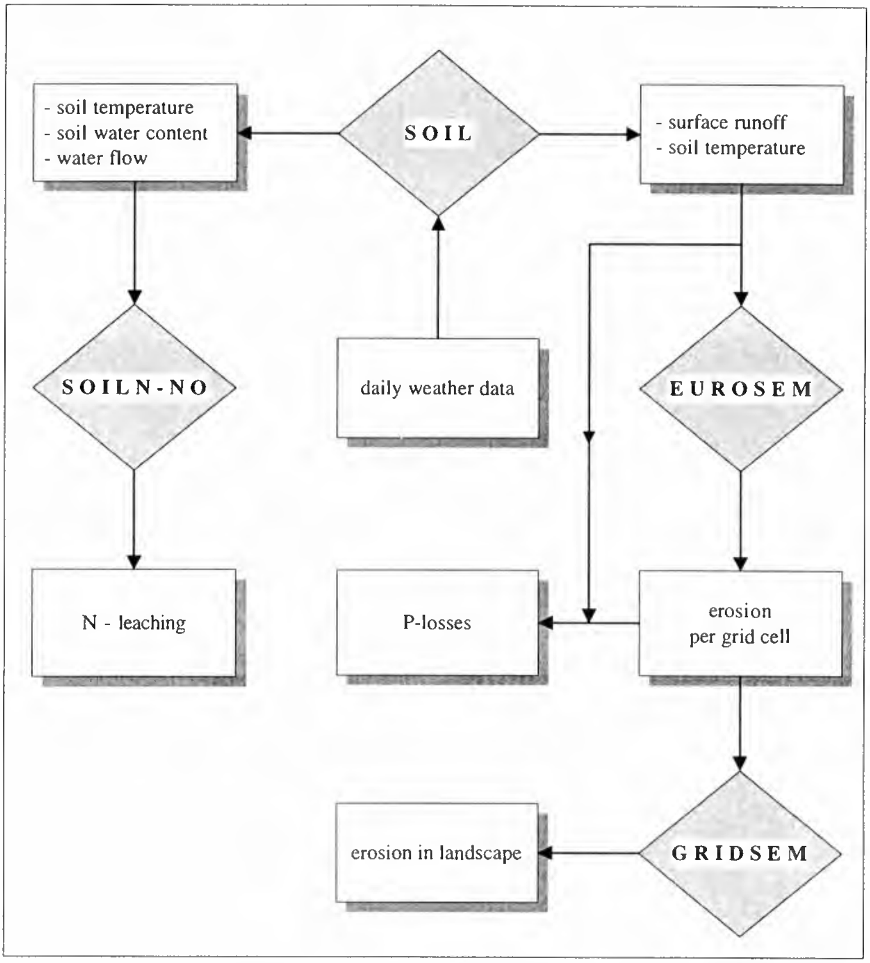

Figure 4.4: The information flow between the four natural science models.

turnover as well as erosion at a satisfactory spatial and temporal resolution level for ECEC purposes. As a consequence, the different models chosen had to enable easy exchange of input and output data between them, and deliver data back to ECECMOD with the appropriate resolution in time and space. Thus, the choice of one model has consequences for the choice of the other models. Further, the existing expertise of the research team had implications for the choice of models as well. It is a general experience that the performance of complex models is strongly dependent on the user's level of experience with that particular model.

Taking into account the aspects mentioned above it was decided to use SOIL for modelling the hydrology processes, and SOILN for modelling nitrogen dynamics. EUROSEM in combination with GRIDSEM was selected for modelling erosion. For phosphorus losses no model was available with the degree of resolution demanded, and it was decided to calculate P-losses from simulated runoff and soil erosion. The information flow between the four natural science models is schematically presented in figure 4.4. A short presentation of the models and methods is given in this section. For more detailed information the reader is referred to chapter A3.

4.4.2 Hydrology processes in the unsaturated zone modelled with SOIL

An independent simulation of the hydrology processes in the soil was needed to produce necessary information for the other modules in ECECMOD. The hydrology model SOIL simulates the physical transformation of weather factors into flows and states in the terrestrial sphere. The output from the soil hydrology simulations is used as driving input for other process simulations such as N-dynamics and leaching simulations with the SOILN-NO model. In the application of EUROSEM snowmelt runoff as estimated with SOIL is used as driving input when simulating winter erosion.

SOIL is a continuous, process based, one-dimensional hydrology model that simulates water and heat flow through a layered soil profile. Water flow is assumed to be laminar and solved with Richard's equation for unsaturated flows. Heat flow in the SOIL model is the sum of conduction and convection. Compartments for snow, intercepted water and surface ponding are included to account for processes at the upper soil boundary. Different types of lower boundary conditions can be specified, including groundwater flow. Weather input variables needed by the model are daily values for temperature, precipitation, wind velocity, relative humidity, and cloud cover. The time resolution of the input data determines the time resolution of the output and can vary from 1 minute up to years. SOIL has been shown to simulate adequately the hydrology of a wide range of soil types and vegetation covers in different climatic zones (Jansson 1994). The first version of the model appeared in 1987 and it has been improved continuously since then. The model routine for calculating surface runoff has been improved following a proposal made by Botterweg (Jansson 1994).

For the application in ECECMOD, a time resolution of 1 day was used in accordance to the resolution of the available standard meteorological data. Soil profiles for clay, silt and sand were selected from a soil data-base and adjusted with local soil survey information. The model has been calibrated for the three main soil types by adjusting model output to field data provided by JORDFORSK, Center for soil and environmental research, Ås, Norway (Øygarden 1989; Geest 1993; Ludvigsen 1995). In cases where no data for calibration were available, the model output has been evaluated by comparison with other outputs previously calibrated, and with consensus expectations in accordance with expertise on hydrological processes in soil. Details of the calibration process are described in A3.

Plant growth is not simulated dynamically in ECECMOD and the influence of plants on the hydrological cycle through evapotranspiration is realized by user defined time series of the plant cover depending variables. Two such series were made for ECEC, one for perennial plant cover and one for annual cropping.

4.4.3 Nitrogen transformation and losses

To estimate nitrogen transformations and nitrate losses from the soil, it was decided to use the Swedish model SOILN. The model is moderately complex, and was considered adequate for the ECEC purposes. Further, it works well in concert with the hydrology model chosen for our erosion and P-loss predictions. However, it soon became clear that some essential changes were desirable for our applications, and we therefore decided to reprogram the model. Further modifications and improvements were implemented throughout the ECEC project, and the final version was named SOILN-NO (previously NESIM). The processes and transports involved are illustrated in figure 4.5.

The SOILN-NO model is one dimensional with layered structure, which means that an independent simulation of the processes illustrated in figure 4.5 (left part) is done for each layer, and transport between the layers is driven by water movements (and soil tillage in top layers). The model needs hydrological data (heat and water status and transport), which is provided by the SOIL model. This utilization of output from a SOIL model simulation as driving variables in a SOILN-NO model simulation requires the specified depth and soil characteristics of layers in the SOILN-NO simulation to be in accordance with the SOIL simulation. The driving variables are water content and temperature in each layer, and water transport between layers, to drainage tiles and ground water.

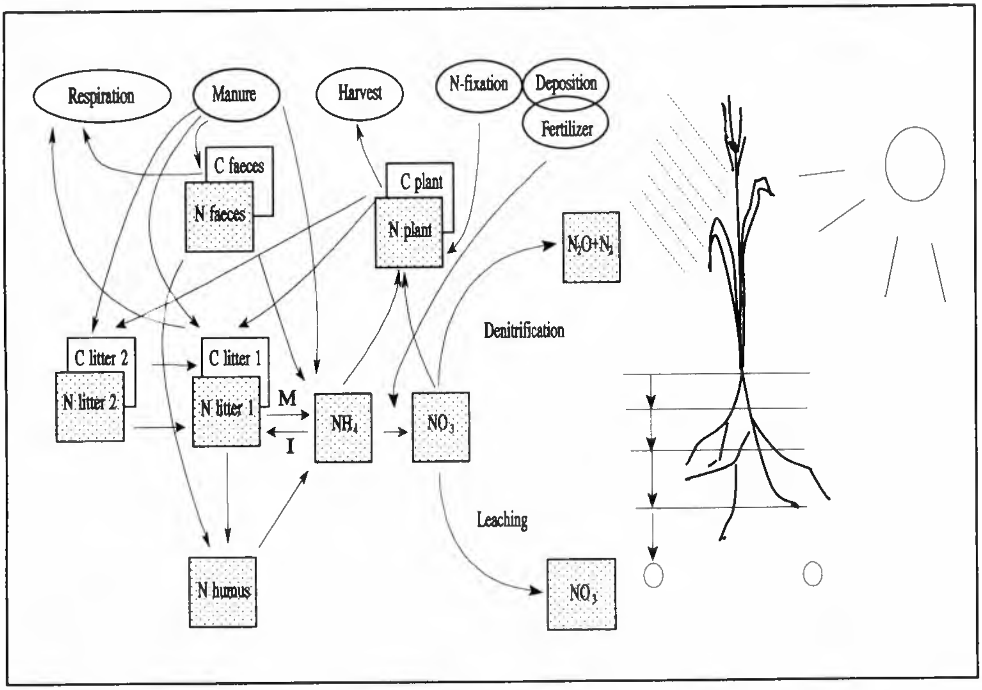

Figure 4.5: C and N transformations and N-transports in the SOILN-NO model.

The SOILN-NO model describes nitrogen transformations in the layers by a system of ordinary differential equations for each layer. Nitrogen mineralization/immobilization by microorganisms is governed by litter carbon decomposition and the C/N ratio of the total substrate available to microorganisms. The diversity of litter substrates encountered in an agricultural system is secured by setting individual C/N ratios and stabilities (here expressed as the percentage of "light litter") for each category. Figure 4.5 illustrates the transport and N-transformation processes involved in the SOILN-NO model as used in the ECEC project.

The daily N-uptake by plants is distributed between the soil layers according to the root distribution and a compensatory uptake from layers with excess nitrogen if there is lack of nitrogen in other parts of the profile. This compensatory N uptake in depth is often not sufficient to secure that simulated plant uptake equals the potential N uptake. In the original SOILN model, daily potential N-uptake is calculated according to a logistic growth function, and periods with lack of nitrogen are not compensated by extra uptake in later periods of the growth season. This N-uptake model was not satisfactory in light of the model application requirements of our project, where the nitrogen contents of harvested yields are considered as driving variables. A new approach to N-uptake modelling, with the possible action of having compensatory uptake over time, was exploited in the SOILN-NO model.

For the specific ECEC tasks of scenario modelling, we needed an efficient system for reading model inputs in order to implement the wide range of agricultural operations. Input data with information of agricultural operations includes manure application, plowing, yield types and nitrogen contents of yields, root distribution, fertilization and green manuring. We found that the original system for handling such inputs was unsatisfactory, and developed a more efficient ECEC-tailored system. A full description of how input of agricultural practice is organized, is given in Vold, Bakken and Søreng (1994).

Model inputs also include parameter values and initial values of model variables. Various methods exist for parameter estimation. Parameters with a clear physical interpretation are often estimated by direct measurements or taken from the literature. Other parameters are estimated by partial (regressive) considerations. In SOILN as in any other models, some parameters remain which cannot be determined by such simple approaches. Such parameters are most often chosen through "trial and error" exercises, where model performance is judged by visual comparisons between model and measurements. Alternatively, such parameters may be estimated by application of an iterative solution algorithm for solving non-linear least-squares problems. This option was not available in the original SOILN model, but was integrated in the SOILN-NO model (Levenberger-Marquardt algorithm). The algorithm was used for parameter estimation (Vold, Breland and Bakken 1994) and to calculate the effect of certain agricultural practices on the appropriate fertilization level (Vold, Bakken and Vatn 1995a).

The many parameters of the model and the complex pattern of interdependency as to how they influence the model performance requires a careful consideration of the order in which the parameters are determined. A first part of a stepwise strategy for this parameterization was suggested by Bakken and Vold (1995) and used to determine a part of the parameters for the ECEC modelling. A more thorough discussion of the choice of model, model extensions, driving variables, parameter values and model input and output is given in section A3.3.

NO_3 leaching shows large variation between years (Uhlen 1989). Such annual variability, even under controlled experimental conditions (ibid) are primarily due to variation in crop growth (hence nitrogen uptake), precipitation and possibly in off-season (winter) temperatures. Thus, nitrate leaching needs to be modelled for long time periods in order to ensure the inclusion of a representative number of extreme years.

As a consequence, our simulations of nitrate leaching (and P-losses) were based on real weather data for a 20-year period, which were used to simulate water and heat transport through three differently textured soil types, using the SOIL model. These simulations were then used as driving variables for predicting P-losses and N-leaching. The models are described in more detail in Chapter 4 and A3, and other chapters referred to therein.

4.4.4 Modelling soil erosion with EUROSEM and GRIDSEM

Both the hydrology and nitrogen model described above are point models which are independent of the landscape. However, for erosion and related phosphorus losses, the landscape topography has to be taken into account. The one dimensional hydrology model gives the amount of surface water generated, but for erosion the flow paths and slope dependent flow velocity has to be known. An erosion model that can handle a complex landscape at a resolution in time and space as applied in ECECMOD does not exist. It was decided to use the event based erosion model EUROSEM, simulating erosion for small homogeneous areas, in combination with GRIDSEM, which is a GIS based system with gridcells, covering whole landscapes. Potential erosion for gridcells is simulated with EUROSEM and the GRIDSEM system distributed over the landscape. Net erosion per grid cell was estimated and added up for the whole landscape.

The European soil erosion model (EUROSEM) is a process-based erosion prediction model designed to predict erosion for individual events and to evaluate soil protection measures (Morgan 1994). The model uses a mass balance equation to compute sediment transport, erosion and deposition over the land surface. The rate of detachment of soil particles by raindrop impact is computed as a function of the energy of the direct throughfall and leaf drainage, the detachability of the soil and the depth of surface water. The detachment of soil particles by runoff is determined as a function of the difference between transport capacity and existing sediment concentrations in the flow, simultaneous deposition of sediment from the flow and the cohesion of the soil. EUROSEM accounts for soil protection measures by describing the soil microtopographic and vegetation conditions associated with each practice. EUROSEM is not built to simulate snowmelt erosion. However, it is possible to take that into account by selecting adequate parameter values and giving snowmelt runoff as driving input variable instead of precipitation, combined with an infiltration rate of zero (Botterweg 1996). Daily values for snowmelt runoff are calculated from SOIL output.

The method used here demands EUROSEM to be run beforehand for each of the possible combinations of precipitation events / snowmelt runoff events, agricultural practice dependent variables, soil type and slope class. EUROSEM was run for plots of 30*30 m, the grid cell dimension in GRIDSEM. Each plot is homogeneous with respect to soil type, slope and agricultural management. For the annual crop systems given by ECMOD, daily values for plant height, plant cover and soil surface conditions were derived. Precipitation events were divided into 9 classes depending on total amount of precipitation. Each class was then divided into 3 sub-classes (low, medium or high precipitation). Snow melt events were divided into 8 classes based on total amount. Each snowmelt class was split in two, one series with soil surface temperature above 0°C and the other series with temperature at 0°C or below, for simulating runoff over thawing soil and still frozen soil. Finally, for each day with runoff from a farm field, erosion values were selected from the created database with potential erosion levels, based on precipitation and surface conditions for that day for each soil type and slope. This information was used as input for GRIDSEM.

The GRIDSEM modelling system (Leek 1993) consists of a data management and general computation "platform". It applies the principles of various erosion models or erosion values to individual grid cells in a catchment while it also takes account of some of their global interdependencies. In ECECMOD's application potential erosion values estimated by EUROSEM are transposed directly as a grid cell factor.

The digital elevation model, or DEM, in GRIDSEM represents the landscape surface, and forms the basis for several parts of the modelling process. An overlay is made of DEM and the soil map used by ECECMOD where farm and farm field borders are included, too. Finally, the location of the flow paths in the landscape are estimated and stored. Daily potential soil loss values for one event as estimated by EUROSEM, are transposed to all the grid cells with the same agronomic practice slope class and soil type. Net erosion is then calculated in GRIDSEM taking into account the flow path in the landscape and deposition as a function of the distance between a cell and the nearest down hill flow channel.

4.4.5 Calculation of phosphorus losses

Losses of phosphorus from agricultural areas are first of all related to soil loss because of the strong binding of P to soil particles. In addition P-losses can occur in connection to application of manure on fields. Despite the strong binding between P and soil particles, P-losses with drain water occurs (Øygarden 1989). No models covering all these pathways for P are available and in ECECMOD the three ways for losses have been calculated. The calculation is based on plant available P in soil (P-Al) and the empirical relationship between total P and P-Al as found by Øgaard and Krogstad (1995):

Silty and sandy soils: $\text{Total-P} = 5.5 * \text{P-Al}$ [4.4]

Clay soil: $\text{Total-P} = 14.5 * \text{P-Al}$ [4.5]

Losses of particulate P with erosion was calculated from the Total P (TP) concentration in the soil, the amount of eroded material and an enrichment coefficient (=TP in eroded sediment/TP in soil>1) , according to an empirical relation given by Sharpley (1980).

For situations where an equilibrium existed between dissolved P and particulate P, the amount of dissolved P in runoff was calculated as a function of P-Al and sediment concentration in the runoff.

Phosphorus concentration in snow melt runoff from fields with perennials may be higher than that from tilled fields due to frost released plant P, but there are large variations between years (Uhlen 1988; Ulén 1995). In ECECMOD, this effect on P losses with snow melt has been taken into account by setting a 25 % higher P concentration in early spring runoff from fields with perennials compared to other fields.

For non-equilibrium conditions existing a short period after the application of manure, another method had to be used. The amount of dissolved-P and adsorbed-P in manure and fertilizer was given by ECMOD (for each fertilizer application). The amount of the different P-fractions available for transport with surface runoff was calculated on the basis of soil type and a technology and soil type dependent infiltration rate. On the days following fertilization, the amount of P-fractions on the surface was reduced by transport with infiltrating water and surface runoff (kg ha^{-1} mm^{-1}). At tillage all the P-fractions were presumed to be mixed into the top soil, and with equilibrium established.

5 The structure of the analyses

5.1 Analyses at different levels

Our analyses are oriented towards studying the effects of different policy measures on emissions from different landscapes. This implies an aggregation of emissions over varying spatial elements (fields, soil type distribution etc.), socioeconomic parameters (farm categories) and for a large time scale (20 years simulation period). Analyses at this level are necessary in policy evaluations since they give the appropriate aggregated effects of certain policies on emissions. The aggregation, however, precludes a more detailed interpretation of the results with respect to the dynamics involved. The aggregation for whole watersheds also precludes an inspection of the general validity of the model with respect to its response to the relevant agronomic challenges.

To compensate for such shortcomings, we have supplemented the analyses of watersheds with analyses at more disaggregated levels. Due to the high priority of the nitrogen analyses motivated in chapter 1, these studies are restricted to N emissions. There are two types of supplementary studies:

(1) We have undertaken a series of systematic tests of the model output while varying some relevant agronomic operations one by one. This is done for different combinations of soil types and crops, over a range of N-levels and agronomic practices, by constructing an "artificial" model farm with all main soil types represented. The results allow an inspection as to whether the model gives reasonable outputs when compared to empirical data (for the few cases where such data exists). Predictions for which the empirical data are not available, can be critically examined for the same purpose (reason/common sense replacing empirical data). Finally, an experimental approach in modelling, where one factor is altered at a time, is a necessary step to establishing a basis for interpretation of more complex model runs for whole watersheds.

(2) We have constructed the analyses of watersheds so that it becomes possible to inspect the results at lower levels of aggregation. Here the farm level is of special interest since it reveals variation between different productions and between farm sizes that are hidden in the landscape analyses. There are reasons to believe that the efficiency and distributional properties of most policy measures vary between production and farm size categories. Information about this variation is crucial in the evaluation of the quality of different measures.

The analyses undertaken follow the above structure. In chapter 6 the results from the "factorial" analyses are presented. Chapter 7 and 8 cover the landscape and farm level analyses respectively. Before looking at the results from the different steps, we shall take a closer look at the landscapes and model farms.

5.2 The landscapes and the agricultural conditions

Three landscapes are chosen for this study. They cover important variations, especially with respect to soils and topography, but also to some extent in weather conditions. All areas are chosen within the larger catchment area relevant for the North Sea Convention (Miljøverndepartementet 1992). Two of them are part of the Auli watershed in Vestfold county – here denoted Auli A and Auli B. Auli A covers approximately 5.100 ha, out of which 1.300 ha is arable land. Auli B is about 3.200 ha, with roughly the same amount of arable land as Auli A. The two areas are adjacent to each other. The partitioning is made to capture some variations, especially in topography. Auli A is a somewhat more hilly landscape than Auli B, which is to be considered rather flat by Norwegian conditions.

The third area covers the watershed of the Mørdre stream, with only 450 ha arable land out of a total area of 680 ha. This area is characterized by a very flat plateau falling fairly

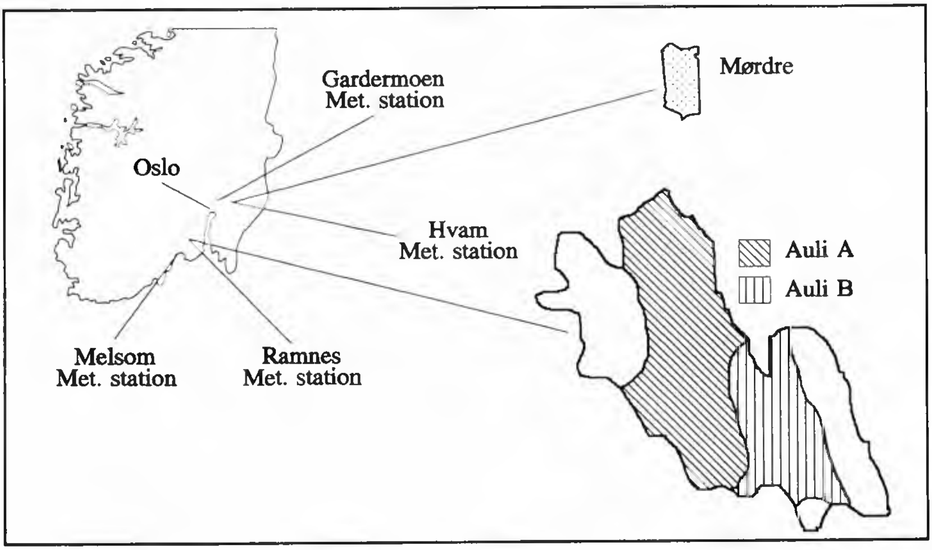

Figure 5.1: The location of Auli (A and B) and Mørdre and the relevant meteorological stations.

steep down to the streams. The area is partly leveled and stream are partly put in pipes. Appendix A4.2 offers a more complete documentation of the different areas.

While clayey and sandy soils are dominating in both areas in Auli, silty soils dominate in Mørdre. This is documented in table 5.1. This table gives information also on the distribution of arable land in slope classes.

Table 5.1: Distribution of the arable land in Auli A, Auli B and Mørdre in soil and slope classes, percent of total acreage.

Area	Soils			Slope classes					
	Clay	Silt	Sand	1 0-2%	2 2-4%	3 4-10%	4 10-16%	5 16-25%	6 >25%
Auli A	57	4	39	14.1	18.2	42.7	16.2	6.6	2.2
Auli B	64	8	28	31.6	24.4	33.2	7.9	2.6	0.4
Mørdre	24	75	1	63.4	11.0	10.3	6.7	7.8	0.8

The Mørdre area has a colder and dryer climate than Auli, with a longer period of snow cover. Average temperature for Gardermoen (Mørdre) for the 20 year period 1973-1992 has been 4.2^{0}C, while the corresponding figure for Melsom (Auli) is 6.3^{0}C. Average precipitation for the same period was 809 and 1009 mm respectively. The plant growth season lasts from late April/early May to September in both areas, but is on average shortest in Mørdre. More comprehensive data about weather conditions are given in appendix A4.3.

Looking at the production patterns, we observe that grain is the dominating crop in all three areas. Still Auli has a fairly large proportion of farms with animal husbandry. The amount of manure N per ha varies substantially between the areas, with an average of 75 kg/ha in Auli and 18 kg/ha in Mørdre. In Auli we also find a group of farmers combining grain farming with the production of grass seed or peas ("other").

Table 5.2: Distribution of farms according to type of productions in Auli A, Auli B and Mørdre, percent of total number of farms. 1992.

	Specialized grain	Pigs/poultry/grain	Milk/beef	Other
Auli A	47	14	28	11
Auli B	39	30	20	11
Mørdre	63	28	8	0

Source: Lundeby and Vatn 1994.

Comprehensive empirical studies are presently running in the two areas, gathering data on hydrological processes and losses of nutrients and soil, in itself an important reason for choosing these landscapes. This material have been made available for us by the Center for soil and environmental research (Jordforsk) and has been significant in calibration of the models.

5.3 The model farms

To cover the variation in agronomic conditions, a system of model farms has been developed. The farms in each area are divided into groups on the basis of dominant production, acreage and the stocking rate/amount of manure per ha. These are considered to be the most important factors in our case. The model farms represent an average of each group, but the production on each farm is simplified. On farms dominated by milk/beef production, other types of animals are converted to cow/calf equivalents on the basis of relative manure excretion. Similar procedures are undertaken for the other groups.

The system of model farms is separate for Auli and Mørdre, while we found no reason to differentiate between the two parts of Auli. An overview of the characteristics is given in table 5.3. A more complete documentation is presented in appendix A4.2.

Table 5.3: Overview of the system of model farms.

Area	Model farm	Production	Size ha	% of total area	Manure N kg/ha	Number of fields
Auli:			2.598.0	100.0		
	1.1	Milk/beef	13.0	3.9	64	5
	1.2	Milk/beef	31.0	14.1	94	7
	1.3	Milk/beef	18.0	6.0	182	5
	1.4	Pigs/poultry	14.0	13.9	70	4
	1.5	Pigs/poultry	28.5	5.2	91	6
	1.6	Pigs/poultry	9.5	3.2	336	4
	1.7	Grain	11.0	31.3	0	4
	1.8	Grain	32.0	11.7	0	6
	1.9	Grain and grass	14.0	5.6	0	5
	1.10	Grain and peas	13.0	5.2	0	4
Mørdre:			446.5	100.0		
	2.1	Milk/beef	38.5	8.2	76	7
	2.2	Pigs/poultry	48.5	28.4	41	6
	2.3	Grain	11.0	30.4	0	4
	2.4	Grain	47.5	33.0	0	6

There are all together 14 model farms in the constructed system. These farms are split into about 80 farm fields of different sizes and with varying soil characteristics depending upon the situation on the farms they cover. In the Auli area, model farm 1.7 dominates, representing about 1/3 of the area. Model farms 1.2, 1.5 and 1.8 follow, none of them representing more than 15 % of the total acreage. In Mørdre model farms 2.2, 2.3 and 2.4 cover about an equal part of the land, while milk/beef production is rather insignificant in this area.

In addition to the above system, a model farm 1.0 for Auli has been constructed to facilitate the factorial analyses previously discussed. It consists of altogether 12 fields. For each main soil type – clay, silt and sand – there is a field for each of the dominating grain species (barley, oats and spring wheat) and a field with grass in rotation with barley.

5.4 The scenario structure

To evaluate the effects of various changes in agronomic practice and/or policy measures, a baseline scenario was constructed. Our *Base* scenario has two important properties:

(1) It is based on the situation in 1992 concerning the political and economic conditions. There is one exception to this. Environmentally motivated taxes and subsidies that existed in 1992 are removed. This way we have established the best basis for comparing various measures. It must be added that the type of policy measures eliminated had existed only for a very short time period before 1992.

(2) The analyses were undertaken assuming that farmers have time to adjust fully to the new conditions. This implies that they were not bound by previous investment decisions. Here it should be added that most investments modelled related to changes in machinery or enlargement of manure storing facilities.

The results from the Base scenario were compared with a set of scenarios where various environmental measures were added. All these analyses have been undertaken under the long run adaption conditions described in point (2) above. Details about the various scenarios are given in chapters 6 and 7 and in appendix B. Key information is given in infobox 7.1 (section 7.3).

One scenario was run where a short run adaption criteria was applied. To test how well the model predicts choices of agronomic practices, a scenario named S-1992 was run where the modelled results was compared with the actual situation in the three areas in 1992. In this analysis the costs of previous decisions have been taken into account, since we assume capital to be relatively fixed in the short run. We will give more details about how this was done in chapter 7.

Each scenario analysis was run for a 20 year period to cover variations in the weather conditions. The economic and political conditions were fixed for the whole period. The time period chosen was 1973-1992.

6 Modelling the effect of agronomic operations on N-dynamics

As stressed in the previous chapter, the performance of the model (SOILN-NO) is difficult to judge by inspecting its predictions at farm and landscape levels. This is one reason for studying nitrate leaching from our "experimental farm", i.e. *model farm 1.0*. On this farm, experiments can be done by manipulating the agronomic components one by one, and in a direct manner (not via economic/legislative measures as elsewhere in this study). Thus, *model farm 1.0* is like an experimental farm, where large scale and long lasting (20 years) experiments can be run. The exercises with the *model farm 1.0* serves many purposes as outlined in the previous chapter:

- Validation by comparison/judgment against empirical data and general experience.
- Inspection of single factor effects to increase the understanding of the system's response.
- Creating a basis for interpretation of predictions at larger scales.
- Generate new hypotheses for experimental research and for design of economic measures against pollution.

The *model farm 1.0* experiments comes in addition to a number of exercises at an even more detailed level during the construction (Vold, Bakken and Søreng 1994; Vold and Søreng 1995) and parameterization of the model (see also appendix A3.3). Examples are the testing against laboratory data of various N-transformations (Bakken and Vold 1995), field measurements of C and N-transformations (ibid), plant N uptake by field grown crops (Vold, Bakken and Vatn 1995b), ammonium and nitrate transformations during decomposition of clover materials (Vold, Bakken and Søreng 1994) and nitrate leaching from field lysimeters (ibid).

6.1 Methodology

We used the same hydrological drive data as for one of our research areas (Auli, appendix A3.2) for a 20 year period. The *model farm 1.0* contains all combinations of the three soil types and grain crop types (as continuous monoculture). The parameter values for SOILN-NO, the plant yield functions and the N-uptake estimation routines were identical to the ECEC standard routines (appendix A3.2).

Infobox 6.1: Experiments descriptions

- Base

		Barley	Oats	Wheat
N-levels	clay	11.6	10.3	12.8
(gNm^{-2})	silt	11.6	10.3	12.7
	sand	11.6	10.2	12.2

Plowing date: October 5 (all soils)
Weed N = N-uptake by weeds and germinating shed grains: average = 0.45 g N m^{-2}, which is 11% of a normal catch crop. It changes from year to year however, according to weather conditions (appendix A5.5.3). The C/N ratio of "weed" biomass is 30.

- Fertilizer N Increasing N-levels: 0, 3, 6, 9, 12, and 15 g N m^{-2} (identical for all grains and soil types).
- Weed-kill Weed-N = 0, i.e. all green plants eliminated at harvest (NB plowing date is still October 5).
- Early plow Plowing date September 1 (immediately after harvest) => Weed-N=0.
- Catch crop Rye grass grown as a catch crop (CC) after the main crop. Potential N-uptake in CC (whole plant) was on the average 4 g N m^{-2}, but varied from year to year according to weather conditions. Alternative regimes: *Catch100* = CC every year and *Catch50* = CC every second year. N-levels in CC-scenarios are as for Base, but an extra doze of 0.6 g N m^{-2} is given to the crop following a season with CC in CC100, and 0.5 g N m^{-2} in CC50 (for explanation see Vold, Bakken, Vatn 1995a).
- Spring plow Soil tillage in spring (around May 1, depending on weather). The grain crop yield (hence also its potential N uptake) was altered compared to Base depending on soil type: +4% for silt, -4% for clay & sand. This was based on agronomic experimental results (appendix A5.4).

As a point of reference, we ran *model farm 1.0* under the conditions given in the Base scenario as defined in chapter 5. This Base for *model farm 1.0* differs from the watershed Base scenarios, however, in having continuous monoculture of each grain type throughout the 20 year simulation period and in having autumn plowing on all soil types. The Base represents a benchmark for comparison with new scenarios where specific agronomic operations are implemented in a scenario which is otherwise identical to the *Base* The Base scenario for *model farm 1.0* also represents a conventional type of farming practice, in terms of continuous monoculture of grains, a constant mineral fertilizer level (optimal according to the 1992 prices exclusive of fertilizer taxes), a fixed plowing date (October 5) and no catch crops or green manure. The plant uptake of N is determined by the year-specific production function and the N-uptake functions (Vold, Bakken and Vatn 1995b).

Alternative agronomic practices were then implemented, alone or in combinations. In addition, we ran an N-fertilizer experiment, where all parameters were identical to those in the Base, except for the fertilizer level. A minimum information about the Base scenario is shown in the box above, followed by a list of the other experiments for which the only information given is that distinguishing them from Base. Other parameter values are shown elsewhere (appendix A3.2). For most scenarios (including Base), two extra experiments were run, where fertilizer levels were increased and decreased with 1 g N m^{-2}. Thus for most treatments, the sensitivity to a small change in fertilizer N level was investigated.

6.2 N-levels

The nitrate leaching in response to increasing N-levels for barley is shown in figure 6.1. The values for oats were very similar (not shown). These predictions are similar to data from field lysimeters by Uhlen (1989). It is interesting to note that the model predicts higher nitrate leaching for 0 than for 3 g N m^{-2}. Similar phenomena are often observed experimentally (Uhlen et al. 1996). This decline may be of academic interest only, since grain cropping without fertilizers is relatively rare. But the shape of the curve at moderate N-levels is of practical interest. At levels above 6 g N m^{-2}, the nitrate leaching is seen to rise substantially with increasing N-levels, with a positive second derivative. The marginal increase in nitrate leaching thus reaches about 0.5 g N per g extra fertilizer N added, at a fertilizer N level of 15 g N m^{-2}. The leaching from wheat fields (figure 6.2) was much lower than from the other two grain species. This reflects the steeper production function (hence N-uptake function) for wheat. This difference in growth between the grain species is well known agronomic experience, but to our knowledge its effect on nitrate leaching has not been tested systematically. Although plausible, we are inclined to consider this a working hypothesis, well worth to be tested experimentally. The root/shoot ratio is a critical factor. In our modelling, we have assumed the same root/shoot ratio for all grain species. If the ratio is lower for wheat than for the other species, the three grain species may have more similar leaching patterns. Since the low predicted leaching from wheat fields compared to that from the other grains may have consequences for future policy (if correct), an empirical testing of this phenomenon would be worthwhile.

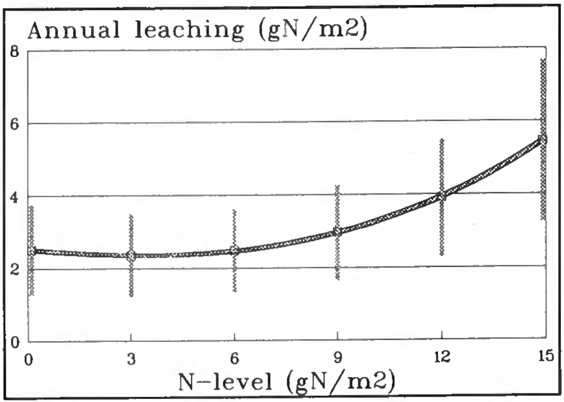

Figure 6.1: Predicted nitrate leaching as a function of N fertilizer levels, barley on clay.

The model predictions of soil organic matter level in response to fertilization ("humus N" in figure 6.3) shows a gradual decline at low and moderate fertilizer levels, but a stable level is obtained around 15 g N m^{-2}. Similar results were obtained for oats, while wheat (figure 6.4) appears to sustain a stable humus level at a lower fertilizer N level (in agreement with the higher productivity and lower leaching). The response of humus-N to N-fertilization implies that the marginal response of humus-N to fertilizer N represents 30-50% of the added fertilizer N. These estimates are within the ranges observed in field trials (Uhlen 1989).

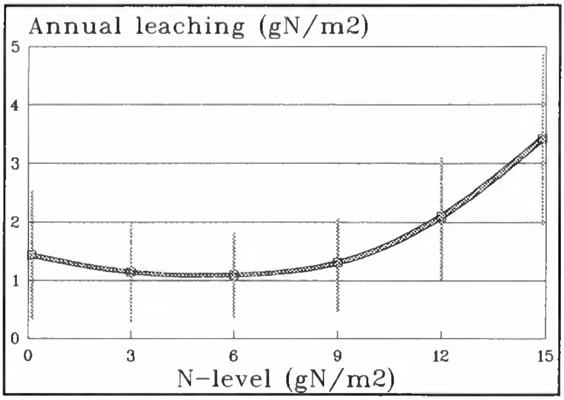

Figure 6.2: Predicted nitrate leaching as a function of N fertilizer level, wheat on clay.

The SOILN-NO model has two pools of litter, a recalcitrant type (=*heavy litter*) and an easily decomposable type (=*light litter*). The decay rate of the two litter pools was kept constant throughout the scenario modelling, but the different plant materials (and manure material) had different C/N ratios and relative amounts of heavy and light fraction, so as to match empirical C- and N-dynamics during their decomposition in soil (Bakken and Vold 1995, Vold, Bakken, Søreng 1994). The resulting N-contents in the *heavy litter* pool was in equilibrium (although fluctuating according to yield levels) at moderate (9-12 g N m^{-2} y^{-1}) fertilizer levels (see figure 6.5). Since we are dealing with pools with first order decay rates, the stability depends on inputs and initial levels (which are inputs to the model). Thus the decision on initial values is in fact an implicit part of the parameterization of the model, particularly for the humus pool (due to its stability). The decay rate of humus had been determined according to net mineralization patterns in fallowed and cropped clay loam (Bakken 1983, Uhlen 1989).

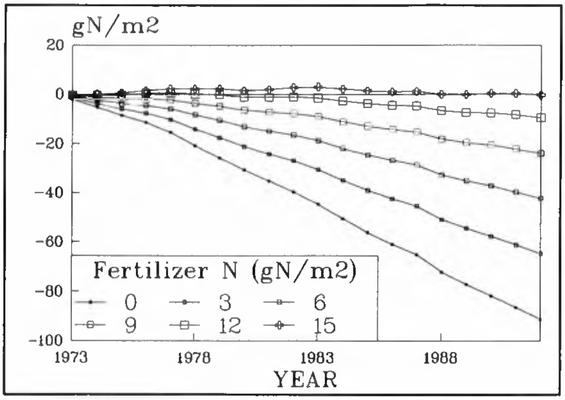

Figure 6.3: Predicted humus N in soil throughout the 20-year simulation period, at different N fertilizer levels, barley on clay.

The parameters determined for clay (Bakken and Vold 1995, Vold, Bakken and Søreng

1994), regarding the C- and N-dynamics of the soil biota, have also been used for sand and silt. We are aware that this is clearly wrong for a number of parameters. For instance, it is unlikely that the soil organic N in sand should be as high as in clay (0.3%). However, one cannot change this value (based on factual differences) without taking all the others into new consideration (this could only be done in truly mechanistic model, but no soil organic matter models fulfill this criterium).

Instead, we decided to retain all the parameters regulating the microbial C and N-dynamics for all the soil types, which ensures two essentials:

(a) The *short term microbial N-dynamics* in response to inputs of fresh organic materials will be identical for the three soils.

(b) All soils are in a pseudo-equilibrium situation (regarding soil organic N) at moderate N-levels given to monoculture of grain crops.

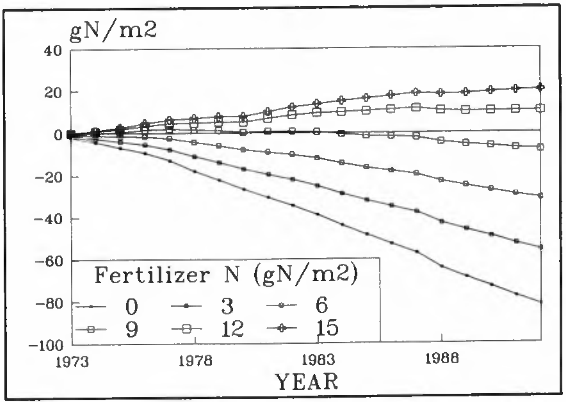

Figure 6.4: Predicted humus N in soil throughout the 20-year simulation period, at different N fertilizer levels, wheat on clay.

There are few certain evidences that texture seriously affects the short term nitrogen turnover in soil, thus point (a) should be reasonably sound. It is worth mentioning, though, that the differences in hydrological properties will create differences in the soil organic N dynamics and nitrate leaching (see table 6.1), but this is not due to differences in the internal microbial processes *per se*. There is evidence that the long term changes in soil organic matter (SOM) is profoundly influenced by soil texture. But it is also a fact that all soil types approach a pseudo-equilibrium situation regarding their soil organic matter content, if cultivated with the same agronomic regime for some decades. The level of SOM, and in particular its dynamic change in response to new agronomic practices, depends on the cultivation history. Thus, by using the same parameters (and the initial pool sizes) for the three soils, we are implicitly assuming that they have an identical cultivation history.

One could argue that reparameterization according to texture would be absolutely mandatory if the modelling was to be used to predict long term changes in SOM. The continuous decline in humus-N of the unfertilized soil (figure 6.3 and 6.4) may be indicative of a weakness of the model or parameter setting. One would assume that the rate of net change would slow down if unfertilized for 20 years. This illustrates that even for such a short period of time, there are limitations as to the validity of the model (or parameter values) if taking the agronomic practice to the extreme. A more adequate response to the continuous zero fertilization could be secured by reducing the initial amount of humus-N, and increasing the decay rate accordingly (so as to obtain a stable pool, but at a lower level), which would then deplete more rapidly under a zero fertilization regime.

6.3 Weeds

The weeds and germinating shed grain (collectively called weeds) growing after harvest represent a net N-sink in the system, which takes its nitrogen at a time of the year when the nitrate pool is prone to leaching. The weeds will also function as an N-sink when mixed into the soil, due to its relatively high C/N ratio (=30). Weeds are in some cases eliminated by herbicides or early plowing. We were interested to see what effect weeds have on the nitrate leaching, and compared nitrate leaching with and without weed growth. The results for barley and wheat are shown in table 6.1

Table 6.1: Simulated annual nitrate leaching with or without weed growth. Average potential uptake of N by weeds was 0.45 g N m^{-2}. Data are for barley and wheat, fertilized as for the Base scenario.

		Barley			Wheat	
	Clay	Silt	Sand	Clay	Silt	Sand
Base (weeds present):	3.77	4.39	5.11	2.38	2.73	3.43
Weeds absent:	4.45	4.98	5.67	2.92	3.14	3.80
Effect of weeds:	0.68	0.59	0.56	0.54	0.41	0.37

The results for oats were very similar to those for barley. Test runs at two other N-levels (+ 1 and -1 g N m^{-2}) also gave similar effects of weeds (the effect being slightly weaker at lower N levels than at high N-levels). Inspection of nitrogen uptake by the crop plants indicated only a slight reduction as a result of weed growth. The reduction in leached nitrate N was largely recovered as an increase in humus-N. The weed effect on nitrate leaching was somewhat larger than the N uptake by the weeds, reflecting the net N-immobilization during the early phase of weed decomposition (after incorporation).

6.4 Early plowing

In SOILN-NO, the decomposition of above ground plant residues (stubble and straw) does not start before plow date, hence the plowing date determines the timing of incorporation of this potential N-sink (high C/N ratio in stubble and straw). Plowing also affects the weed growth. We compared two scenarios: One with a regular plow date October 5, and one with plow date September 1 (immediately after harvest). The N-uptake in weeds was 0,45 g N m^{-2} for the regular plow date (October 5) and zero for the early plow date. The results for wheat are shown in table 6.2.

Table 6.2: Modelled annual nitrate leaching in field with wheat, affected by plowing date. Average potential uptake of N by weed was 0.45 g N m^{-2} for plowing October 5, and 0 g N m^{-2} for plowing September 1.

	Clay	Silt	Sand
Early plowing (1/9)	2.87	3.12	3.82
Base (plowing 5/10)	2.38	2.73	3.43
Effect of early plowing	0.49	0.39	0.39

The early plowing gave consistently higher leaching than the regular plowing date; similar but somewhat larger effects (0.5-0.65 g N m^{-2} y^{-1}) were found for the other grains (not shown). When inspected for each single year, we found a positive correlation between the leaching in Base and the effect of early plowing (barley on sand: $r^2=0.31$, df=18), in other words early plowing increases the leaching more in years when nitrate leaching is high compared to years with a low leaching (EP = 0.05 + 0.1*NLba, where EP is the increase in leaching due to early plowing, and NLba is the nitrate leaching in the Base scenario, data for barley on sand). This is a plausible result, since the N-uptake in weeds and the immobilization of N during the early phase of weed decomposition will be N-limited in years when the grain crop has depleted the pool of mineral N in the soil.

6.5 Catch crops

The average potential N-uptake in catch crop was 4 g N m^{-2}. Scenarios were run with catch crops plowed in October 25, or the next spring, and at three different N-levels. We also tested the effect of reducing the potential N-uptake in the catch crop by 25%. Scenarios with catch crop every second season were also run.

The reductions in nitrate leaching due to catch crops are 2-3 g N m^{-2}, which is substantially lower than the potential N-uptake by the catch crop as modelled (= 4 g N m^{-2}). This indicates that the potential N-uptake exceeds the supply of mineral N. This was confirmed by the test run where the potential N-uptake by the catch crop was reduced from

4 to 3 g N m^{-1}: This resulted in a slight (0.1-0.3 g N m^{-2} y^{-1}) increase in the nitrate leaching, i.e. only 10-30% of the reduction of the potential N-uptake by the catch crop. Adding more fertilizer N (+1 g N m^{-2} y^{-1}) increases the leaching for both treatments, but the increase is steeper without catch crops (0.5 g N per g extra fertilizer N) than with catch crop (0.3 g N per g extra N).

Table 6.3: Modelled annual nitrate leaching (g N m^{-2}) as affected by catch crops every year (Catch100), plowed October 25. Results for sandy soil. Variation between years shown as standard deviation.

Treatment•	Barley		Oats		Wheat	
	mean	st.dev.	mean	st.dev.	mean	st.dev.
Base-1	4.65	1.53	3.90	1.36	2.93	1.04
Catch100-1	1.90	0.80	1.51	0.77	1.21	0.67
Base	5.11	1.72	4.41	1.54	3.43	1.19
Catch100	2.19	0.91	1.78	0.85	1.42	0.74
Base+1	5.69	1.94	5.02	1.75	4.06	1.39
Catch100+1	2.51	0.99	2.19	0.95	1.73	0.83

• Codes: +1/-1 means that the N level is increased/decreased by 1 g N m^{-2} y^{-1}, Catch100=catch crop every year.

The catch cropping reduced the N-uptake in the main crop by around 0.2 g N m^{-2}. This was unexpected, since the extra N-doze of 0.6 g N m^{-2} was assumed to compensate for the catch crop-effect (Vold, Bakken and Vatn 1995b). Catch cropping resulted in a substantial increase in soil organic N. This is shown for barley on clay in figures 6.5 and 6.6. Figure 6.5 shows the changes in the heavy litter fraction throughout the 20 year modelling period. A slight reduction takes place in the Base scenario, whereas the Catch100 scenario shows a rapid accumulation during the first three years, followed by small fluctuations (reflecting catch crop yields) thereafter. The heavy litter pool is unlikely to hold more extra nitrogen than a few g N m^{-2}, considering its relatively rapid decay rate: $63*10^{-4}$ d^{-1} at 15 °C. This decay rate is equivalent to a half life of about 1 year under our field conditions (decay rate constants for average outdoor conditions are about

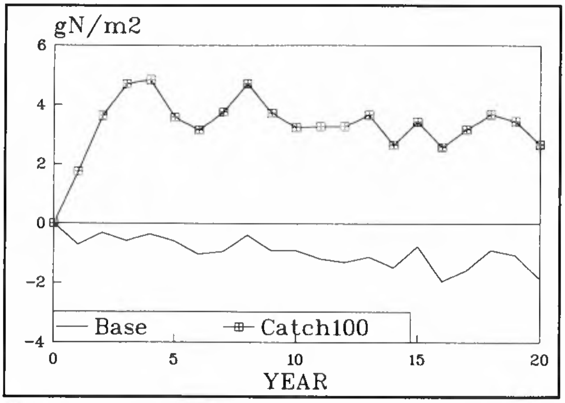

Figure 6.5 Fluctuations in "heavy litter N" as affected by catch crops, initial content=0. Catch100 and Base scenario, barley on clay.

1/4 of those at 15 °C and optimal moisture).

The humus N shows a different trend: In the catch crop scenario, humus N is steadily -increasing throughout the whole modelling period (figure 6.6). Again, this is a very plausible result, considering the slow decay rate of this pool: $9*10^{-5}$ d^{-1}, which is equivalent to a half life of 70-80 years under our field conditions. This illustrates the model's predictions regarding the residual fertilizer effect of nitrogen captured by the catch crop: One would have to grow catch crop for a very long time before soil organic N level reaches a new equilibrium level.

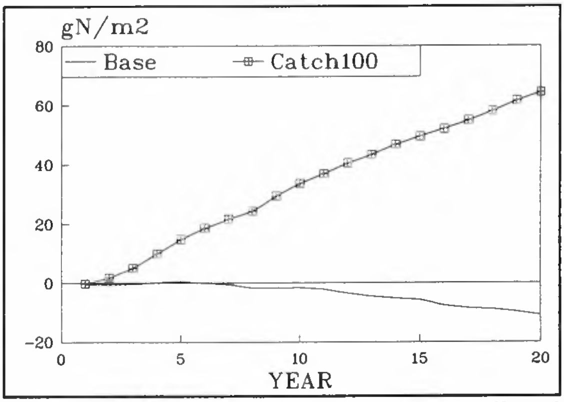

Figure 6.6: Changes in humus-N levels as affected by catch cropping, initial content=0. Catch100 and Base, barley on clay.

6.6 Spring plowing

Spring plowing was tested with and without catch crop. Field experiments have demonstrated a difference between soil types regarding crop yields as affected by spring plowing: On silt soils, spring plowing results in improved crop growth, whereas the opposite has been found for sand and clay soils (appendix A5.4). The spring plow effect on potential N uptake by the crop was estimated to be +4% on silt, and -4% for the types of clay and sand dominating in Auli. Spring plowing versus autumn plow (October 5) was estimated to give an extra potential uptake of 0.17 g N m^{-2} in weeds. These plant production estimates (which are inputs to the model) are based on experimental data (appendix A5.4).

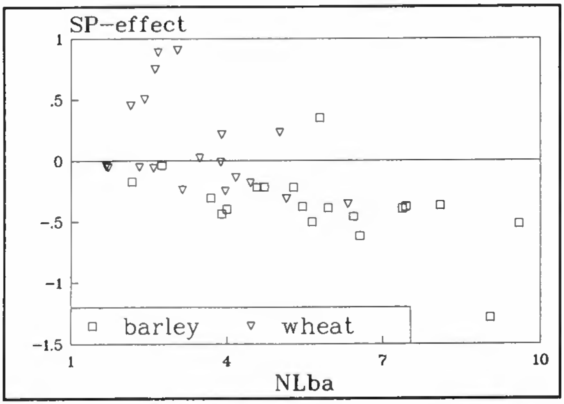

Figure 6.7: The effect of spring plow (SP) on nitrate leaching (SP-base), plotted against leaching in base (=autumn plow). Single year results for wheat and barley on sand.

The results for the spring plowing scenarios are shown in table 6.4.

Nitrate leaching on clay soil was hardly affected at all by spring tillage, except for a slight increase for wheat. The harvest N was reduced, but the relative reduction was lower than the "prescribed" 4% yield reduction, except for wheat. This reflects that for a significant fraction of the years, the N uptake for barley and oats must have been N-limited.

Nitrate leaching on silt was consistently reduced, which is not surprising since two factors play in concert (increased N uptake both in main crop and in weeds). The relative increase in plant N uptake was less than 4 % (zero for wheat), reflecting again that for most of the years, plant N uptake has been N-limited. On sand, the nitrate leaching from barley and oats was reduced by spring plowing, the same was true for the plant N uptake. Wheat deviated from this pattern.

Table 6.4: Modelled effects of spring tillage and autumn tillage on nitrate leaching and N in harvest.

			Leached NO_3			Harvested N	
Soil	Scenario	Barley	Oats	Wheat	Barley	Oats	Wheat
Clay	Base	3.77	3.14	2.38	8.73	8.44	10.6
Clay	Spring plow	3.74	3.18	2.56	8.55	8.23	10.2
Silt	Base	4.39	3.67	2.74	8.70	8.43	10.6
Silt	Spring plow	3.73	3.12	2.43	8.91	8.61	10.6
Sand	Base	5.11	4.42	3.43	8.30	7.94	9.7
Sand	Spring plow	4.79	4.27	3.61	8.10	7.70	9.2

The result as presented are bewildering, and require a closer inspection. The two main effects (at least in the model) are the changes in potential N uptake by the main crop and the weeds. When inspecting the leaching data for single years, we found that the spring plow effect was significantly negatively correlated with leaching in the Base scenario (r^2=0.5 for barley on sand) and positively correlated with the harvested N. The correlation is illustrated for barley and wheat on sand in figure 6.7, where the spring plow effect on nitrate leaching is plotted against nitrate leaching in the autumn plow scenario (=Base). The data demonstrate that the net result of spring plowing depends on the strength of the crop as an N-sink, and how spring plow affects this sink (through yield decrease or increase). If the main crop (wheat or barley) is a weak N-sink (which is the case in years with high nitrate leaching in the Base scenario), the SP-effect on the weed N-uptake dominates, resulting in "negative" SP-effects (reduced leaching in SP versus Base). And vice versa: when the main crop is a strong N-sink, the 4% reduction in the main crop N uptake is more important for the N-leaching, hence the SP effect tends to be positive (higher leaching in SP than in Base). This "explains" the negative correlation shown in figure 6.7. The confusing patterns in table 6.4 is more understandable. A discussion of this kind may seem futile, since the effects are so small anyway. But it may be legitimate as an exercise to demonstrate a complex pattern of interaction between sinks.

Substantial reductions in nitrate leaching as a result of spring plowing versus autumn plowing has been observed in lysimeter experiments at Apelsvoll Experiment Station (Ragnar Eltun, pers comm). These results, however, were ascribed to a reduction in percolating water, however (increased surface runoff). In our case, we used the same hydrological drive data for both treatments. We may therefor have underestimated the effect of spring plowing on the nitrate leaching. The contrast spring plow versus early plow (september 1) shows consistently lower leaching for the former though, due to the modelled N uptake by weeds.

6.7 Marginal changes in N-fertilizer levels

Most scenarios with *model farm 1.0* were run in three versions, one with a fertilizer N level as listed earlier, and two others were the N-fertilizer level was reduced or increased by 1 g N m^{-2}. In general, these exercises added little information, apart from confirming a positive second derivative of the N-leaching response to N-fertilization (figure 6.1 and 6.2). It may be worthwhile to use the results to illustrate the model behavior. In figure 6.8, we have illustrated the annual recovery of an extra doze of 1 g N m^{-2} given to barley on clay.

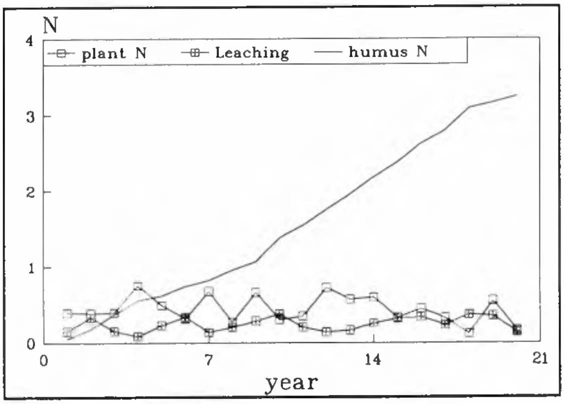

Figure 6.8: Recovery of extra fertilizer N as an increase in plant N, leached nitrate and as accumulated humus N. Barley on clay.

The recovery in the three pools (leached nitrate, plant N and accumulated humus N) are estimated as the difference between the Base and the Base+1 (i.e. fertilizer level for the Base scenario + 1 g N m^{-2} y^{-1}).

Table 6.5 Interaction between catch crop (Catch100) and N fertilizer level on the average annual nitrate leaching (gN m^{-2} y^{-1}) from silt. Variability indicated by the standard deviation.

	Barley		Oats		Wheat	
Treatment	Mean	St.dev.	Mean	St.dev.	Mean	St.dev.
Base	4.39	1.43	3.67	1.37	2.74	1.08
Base-1	3.96	1.30	3.19	1.20	2.31	1.00
Base+1	4.84	1.57	4.20	1.51	3.20	1.20
Catch100	1.34	0.77	1.02	0.75	0.75	0.59
Catch100-1	1.08	0.68	0.84	0.65	0.64	0.51
Catch100+1	1.65	0.87	1.30	0.89	0.95	0.67

The recovery of the Δ fertilizer N as Δ plant N (Δ = the marginal change as shown in table 6.5) showed large variation, and the recovery as Δ leached nitrate was negatively correlated with it. The recovery as Δ humus-N represented around 15% of Δ N. The negative correlation between N recovery in plants and in leached nitrate is illustrated in figure 6.9, where the data for wheat on clay has been used to illustrate the recovery of Δ fertilizer-N (+/- g N m^{-2} y^{-1}) as Δ plant N and Δ leached N.

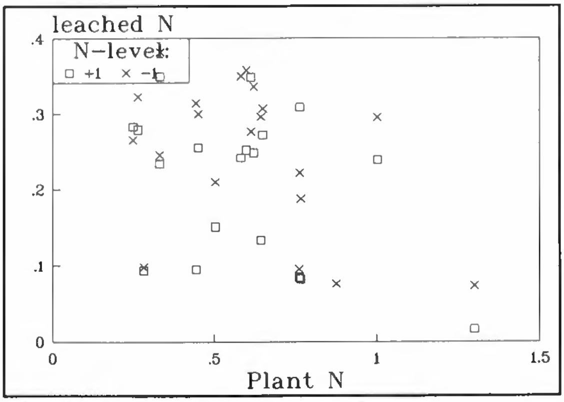

Figure 6.9: Annual data for Δ plant N and Δ leached nitrate. Negative values for -1 plotted as positive. Base scenario (+/-1) for wheat on clay.

The figure efficiently illustrates the range of values, and the negative correlation, none of which are particularly surprising. Catch crops had a profound influence on the recovery of an extra doze of N. The results for silt, with and without catch crops are shown in table 6.5.

6.8 Concluding remarks.

Model predictions cannot replace empirical data, but may be a useful tool for interpolation and extrapolation. One should bear in mind though, that empirical data on nitrate leaching have limited value as well, due to the high "noise" level in such experiment (both temporary and spatially variability). Particularly if interpreted according to the rule that the absence of evidence (null hypothesis not rejected!) is taken as an evidence of absence ("..nitrate leaching is not reduced by lowering the N-fertilizer level"). This is of course a perversion of a sound skepticism which is one of the virtues of true empiricists.

In general, the SOILN-NO model, as parameterized for the ECEC modelling, responds adequately to fertilization when compared to experimental results and consensus opinions. The simulation over a 20 year period demonstrated the large variability in annual nitrate leaching, and the variability in specific agronomic effects on this leaching. The experiences support the view that the model, as used, can be utilized as a tool for "extrapolation" to "new" scenarios for which no empirical material is available. This is not to say that the model is "validated" once and for all!

As has been repeatedly experienced, the nitrate leaching is strongly influenced by the performance of the crop plants. This was clearly demonstrated to be the case when using the SOILN-NO model. We decided to use crop performance as an input variable in the model, and have thus been able to draw heavily on a number of agronomic experiments under a variety of conditions (appendix A5). When transforming such yield data to plant N uptake estimates, we used a nonlinear Michaelis Menton type of function, which ensured the plant N uptake to be an adequate function of both N fertilizer level and the harvest level (Vold, Bakken, Vatn 1995b).

The presented exercise with *model farm 1.0* also serves as a tool for interpretation of prediction for the different landscapes studied by the ECEC project, since many of the agronomic factors studied are the same as those implemented (in the economic models) in response to the political/economical measures.

7 Scenario analyses at watershed level

We will now expand our analyses from factorial changes in the agronomic practice to look at the effects of a set of various political measures at the watershed level. Compared with chapter 6, two important real life complications enter the analysis. First, we have the problem of constructing policy measures that successfully induce farmers to make desirable changes. Secondly, a measure may motivate the farmer to simultaneously make several changes, of which some may even be undesirable from an environmental point of view. This makes the analysis realistic, but more difficult to interpret.

We will present the main results for each scenario in this chapter. A more complete presentation is given in appendix B. Before we start comparing various policy measures, a quality check is needed also at the watershed level. To assess how well ECECMOD predicts the choices of agronomic practices, we have run the modelling system for the political and economic conditions of 1992. We will start by presenting the results of this analysis.

7.1 Modelling the 1992 agronomic practice – scenario S-1992

In scenario S-1992, the existing price, tax and support system of 1992 is used. In our case, a newly introduced support scheme for farmers reducing fall tillage and a 20 % fertilizer N tax ought to be mentioned. One cannot suppose farmers to be able to adjust momentarily to changes in the political and economic conditions. This is taken into account by the way capital costs are modelled in scenario S-1992. The value of all existing capital assets on the model farms are set to 50 % of their non-depreciated value. The farmer has to bear these costs if changing to other types of equipment made favorable by the scenario specific political and economical conditions. In later scenarios the choices are not thus bound.

Some support schemes that existed in 1992 were subject to individual farm considerations. This was the case with subsidies given to enlarge manure storage facilities and to induce spring tillage/reduced tillage. These kinds of systems are difficult to model within a mathematical programming framework since the rules are object to detailed farm specific evaluations. We have chosen not to put efforts into modelling such elements, since the policy measures analyzed in the scenarios studied later are of a more general kind. This implies that no support for increased storage capacity is incorporated while subsidies to reduced tillage is given without any kind of farm specific considerations.

Even though the policy framework is related to one specific year, it is important to remember that the modelling is conducted for a 20 year period when comparing "observed 1992" with "modelled 1992." We consider it most important that the model produces good estimates for fertilizing intensity, the level of yields and the choice of crops. As to the first relationship, comparing the model results with observations concerning 1992 is most relevant. The farmers choose fertilizer levels on the basis of given prices and expectations about yields. The actual yield levels, however, are heavily influenced by weather factors, and we have to compare average observed levels with average modelled results for the whole period. As to the choice of crops, the relative prices of the year may be considered most important, speaking in favor of comparing the average modelled pattern with the observed status of 1992.

Table 7.1 shows the observed and estimated figures for fertilizer levels in grain production. The model estimates are lower than the observed levels, but the error is marginal for the dominant group of specialized grain farms. It should be mentioned that the census data cover about 20 % of all farms and is based on farmers own ex post reporting. As far as the observed values are correct, the model will *ceteris paribus* underestimate N leaching in grain production. The statistics only cover mineral fertilizer levels. Census data show, however, that farms with animal manure apply about the same amount of mineral fertilizers to grain as the specialized grain farmers. The effect of animal manure is estimated on the basis of data about the total volume of animal manure and the farmers' own estimate of the distribution between crops (Statistics Norway 1994). The calculation assumes 40 % effect of manure N, which is standard, but may be too high (Lundeby and Vatn 1994).

Table 7.1: Observed and modelled nitrogen fertilizer levels in grain production

	N fertilizer kg/ha
Observed:	
- All grain producing farms:	
- Vestfold county	131
- Akershus county	124
- Specialized grain farms:	
- Vestfold county	119
- Akershus county	116
Model estimates:	
- Auli	113
- Mørdre	114
- Per grain species:	
- Barley (clay)	114
- Oats (clay)	101
- Spring wheat (clay)	125
- Winter wheat (clay)	128

Sources for observed levels: Statistics Norway (1994); Lundeby and Vatn (1994)

The most disaggregated official agricultural data for 1992 are publicly available at the county level. Special analyses made for us by Statistics Norway at lower levels show that the areas in which our landscapes lie, do not differ from the average (Lundeby and Vatn 1994). The census data do not cover the fertilizer levels for the different grain species. Data from the model analyses are given to indicate some of the variation in the model estimates – in this case for clayey soils.

Table 7.2 gives the corresponding data for grass production. In this case the model estimates fit very well for Auli/Vestfold while the model overestimates fertilizing levels somewhat for Mørdre/Akershus. Some farms with grass production are run very extensively. This kind of practice is not well handled in the modelling. Tests done on the underlying material show a much greater variation in fertilizer levels in grass than in grain production (Lundeby and Vatn 1994). This is to some extent captured in the model too. The need for roughage is partly made dependent upon the number of animals on the farm – i.e. we assume a "non-perfect" market for roughage. This makes it optimal to use more fertilizer on farms with a lot of cattle per unit of land. Thus the estimated fertilizer level for grass on model farm 1.1 is on average 169 kg/ha, and 194 kg/ha for model farm 1.3.

Table 7.2: Observed and modelled nitrogen fertilizer levels in grass production.

	N fertilizer kg/ha
Observed:	
- All farms with meadow:	
- Vestfold county	186
- Akershus county	146
- Specialized milk farms:	
- Vestfold county	168
- Akershus county	149
Model estimates:	
- Auli	181
- Mørdre	174

Source for observed levels: Statistics Norway (1994); Lundeby and Vatn (1994)

Turning to yields, we have used yearly data from Statistics Norway to modify the experimentally based production functions (see appendix A5). The differences observed in table 7.3 are thus very small and mostly reflect the effect of differences in soil distribution at the county level as compared with the modelled areas. Since the same yield functions are used for both Mørdre and Auli, we have not differentiated between the counties in table 7.3. Further, data on the actual situation does not exist at lower aggregation levels than the county.

Table 7.3: Observed (Akershus and Vestfold) and modelled (Auli and Mørdre) yield levels for grain and grass production, kg/ha.

	Barley1)	Oats1)	Wheat1)	Grass2)
Observed	3610	3680	4000	6230
Modelled	3640	3750	4160	6190

1) Normalized water content, average for 1973 - 1992

2) Dry matter, observed cover 1984-1992 while modelled cover 1973-1992.

Sources for observed yields: Statistics Norway (1974-1993), Lundeby and Vatn (1994)

For grains, the observed data cover the average for the period 1973-1992, which is identical with the modelled period. For grass the census provides data only for 1984-1992. The method used handles the variation between years, with an equally good fit between observations and model estimates as for those presented in table 7.3.

The distribution of crops is difficult to model, since we are facing a discrete choice problem where small variations in initial conditions, the chosen field structure, distribution of soil types etc., influences the results. The fit for Auli is still very good, while the results for Mørdre diverge more from the observed situation. In this case we have data for exactly the same areas as the ones modelled. This is important since production patterns may vary substantially within a county.

Table 7.4: Observed and modelled distribution of crops, % of total cultivated land area.

	Barley	Oats	Wheat	Meadow	Other
Auli:					
Observed	28	27	27	13	5
Modelled	30	24	28	17	2
Mørdre:					
Observed	31	46	17	4	2
Modelled	34	28	33	5	0

Sources for observed results: Lundeby and Vatn (1994)

The deviations in Mørdre relate especially to the distribution within the group of grains. The fact that the area is small may partly explain this lack of fit (crop rotation, etc.). The model estimates give the average results for the whole crop rotation system repeated over a 20 year period, while the observed data cover 1992 only. More important, we believe, is the dominance of silt in Mørdre. Trial data for silty soils are very scarce, and we suspect oats to compete better on that type of soil than our production functions indicate. We further note a tendency towards increased wheat production at the expense especially of oats throughout the 1990's. From 1992 to 1993 the wheat area increased with 50 % in Akershus while we observe a change of about 25 % in Vestfold. We may thus observe a lagged response to price changes and the fact that new varieties and milder falls have produced increased interest for especially winter wheat.

As one would assume from the way the existing support system is modelled, we obtain predicted storage capacities for manure which are too low. Similarly, too much spring tillage is estimated compared with practice. Average storing capacity for the S-1992 scenario is 8 months while the census data indicate an average of nearly 10 months (Statistics Norway 1994). All model farms chose to use tank trailers, which is dominating in practice too. Looking at reduced tillage/spring tillage, ECMOD predicts that 46 and 54 % of the total area will be thus treated in Auli and Mørdre respectively. In the census data, the figures are given for the grain area specifically, with Vestfold at 35 % and Akershus at 30 % (Statistics Norway 1994).

If the soil is tilled in the fall, the model chooses a date in early October. This date is mostly the same in all scenarios. Divergences from this will be reported as they occur.

7.2 The Base scenario

This scenario differs from S-1992 in that all environmentally motivated measures existing in 1992, like taxes and subsidies, are removed. Further, we evaluate the adaption in a long run perspective. The history still counts, since the structural features of the industry as they were in 1992 are captured by the model farm system.

Running the model under these condition, we obtain the following results:

Table 7.5: The Base scenario. Estimated agronomic practice and nutrient losses. Mean over 20 years.

	N fertilizer kg/ha	Spring tillage %	N leaching kg/ha	N air[1)] kg/ha	P loss kg/ha	Soil loss kg/ha
Auli A						
Total	127.3	1	**40.4**	**6.5**	**4.97**	**1180**
Grain	114.1	1	40.8	4.7		
Meadow	189.0	..	41.4	15.0		
Other	89.7	..	19.3	0.0		
Auli B						
Total	124.2	2	**41.2**	**7.8**	**4.64**	**1058**
Grain	115.5	2	42.2	6.1		
Meadow	192.1	..	38.8	19.0		
Other	53.4	..	22.4	0.0		
Mørdre						
Total	119.2	47	**29.4**	**1.9**	**0.56**	**281**
Grain	116.0	49	29.5	1.8		
Meadow	184.1	..	27.9	10.0		
Other	..	..	..	..		

1) Ammonia-N loss in connection with manure spreading.

Concerning agronomic practices, there are some deviations of interest compared with scenario S-1992. The fertilizer level is estimated to increase with about 3 kg per ha on average due to the removal of the 20 % fertilizer tax. We further observe a switch to fall tillage since the subsidy for spring tillage is removed. In Auli fall tillage is almost non-existent in the Base scenario, while the reduction is much smaller in Mørdre. The persistence of spring tillage in this landscape is due to the positive effect of this practice on the dominating silty soils. Thus the increases in yields from scenario S-1992 to Base are larger in Auli. Still, they are within a range of 0 - 3 % (see appendix B). Changing from a short to a long run perspective has some influence on the choice of manure spreading practices, but no estimated influence on storing capacity which is continued at the level of 8 months.

As to the environmental variables, we observe that N-leaching is somewhat higher than the levels presented in chapter 6 for Auli. The reason is mainly related to the use of manure – inducing extra losses. While the amount of manure is not high on average, we have already seen that model farms 1.3 and 1.6. have rather heavy loads.

The levels of leaching are on average about 30 - 40 kg N ha^{-1} yr^{-1}, which is comparable to measured leaching under similar conditions (Ludvigsen 1995). The lower levels in Mørdre are explained by differences in soil characteristics, precipitation and the fact that the amount of manure is lower. Variation between years, soils and production are substantial as indicated by figures 7.1 and 7.2.

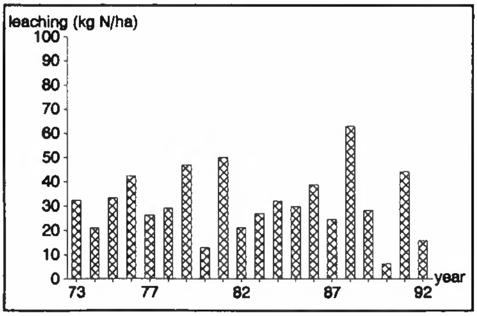

Figure 7.1: Simulated N leaching (kg/ha) on a clayey soil, specialized grain farming, Auli.

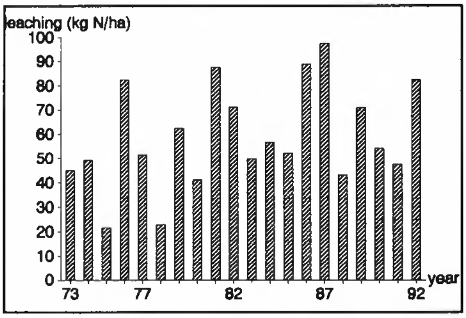

Figure 7.2: Simulated N leaching (kg/ha) on a sandy soil, grain in combination with pig farming, average animal stocking rates, Auli.

The ammonia losses estimated in the Base scenario cover only losses in connection with manure spreading. On top of that comes *a loss of about 15 % of total ammonia while storing the manure.* This loss is only marginally influenced by the changes in agronomic practice that are covered by this project and is thus *not modelled.*

The average levels of soil losses lie in the interval 300 - 1200 kg/ha, while the losses of P vary between a half and 5 kg. The level of soil and P losses is more difficult to evaluate than losses of N since variations in agronomic practice, local soil and topographical conditions are extremely important. The measures cover losses to streams and no observations exist for the specific conditions modelled. Observations for smaller areas and a subsection of years

(Eltun 1990; Ludvigsen 1995) are utilized to validate the results, which are found to be reasonable, although somewhat high in Auli, especially for P. A test for Auli A indicates that only about 50 % of what is eroded, finally reaches the streams. The rest is estimated to be deposited in the landscape.

The fairly large difference between Mørdre and the two areas of Auli is partly explained by soil type and slope conditions. Silty soils dominate in Mørdre. These soils have a large infiltration capacity. Furthermore, over 60 % of the area in Mørdre is in slope class 1 (0-2 %), while the figures for the two Auli areas are about 15 and 30 % for A and B respectively. The most important factor is the fact that about 50 % of the area in Mørdre is tilled in spring. Plant cover heavily influences erosion. The differences between the areas are even higher for the estimated P emissions than for soil losses. There are two main reasons for this. The level of P is higher in clayey than in silty soils. Furthermore, there is more P lost from manure in Auli due to the higher stocking rates.

Moving to Auli, clayey soils dominate. Auli A is more hilly than Auli B, but it also has more sandy soils and grass land, explaining why the differences between these two areas are rather modest. The highest losses of P from manure are found in Auli B. This is due especially do rather substantial manure amounts spread in the fall on some of the farms. Still it is only some years that contribute with losses of manure P. Even in Auli B this source counts for less than 10 % of all P losses.

7.3 Comparing different policy measures

To analyze the potential for reduced emissions and the costs thereby invoked, we have formulated a set of scenarios. Infobox 7.1 gives an overview. Each scenario represents a defined class of policy measures differing from the Base scenario in distinct ways. We would like to discuss the results in three steps. First, we present the results from a selected set of scenarios, showing some main tendencies at the landscape level. Second, we will discuss the results obtained in these scenarios more thoroughly by varying the level or type of policy measures used and look at different combinations (section 7.4). Again the discussion will mostly be undertaken at the landscape level. Finally, we offer some further insights into the different patterns of variation (section 7.5 and chapter 8).

Four scenarios are run to analyze different main strategies as discussed in chapter 3:

- Tax100: 100 % tax on N in mineral fertilizers.
- Price33: A 33 % price reduction on grains (also reducing the value of grass).
- Catch50: 50 % arable land requirement on catch crops/grass cover.
- Soil-Sub: Subsidy to abandon fall tillage.

Infobox 7.1: Scenario descriptions

S-1992	1992 political and economic conditions – short run adaption
Base	1992 political and economic conditions except environmental taxes/ subsidies
Tax50	50 % tax on N in mineral fertilizers
Tax100	100 % tax on N in mineral fertilizers
Tax200	200 % tax on N in mineral fertilizers
Tax100M	100 % tax on N in mineral fertilizers, including a market for manure
Price33	33 % price reduction on grains
Catch50	50 % arable land requirement on catch crops/grass cover
Catch100	100 % arable land requirement on catch crops/grass cover
Catch50Tax100	Catch50 and Tax100 combined
Catch100Tax100	Catch100 and Tax100 combined
Storage12	12 months manure storage requirement
Catch50Storage12	Catch50 and Storage12 combined
Split100	Split fertilization generated by seasonal, tradeable N-quotas
Soil-sub	Subsidy to abandon fall tillage
Soil-50	Mandatory requirement: < 50 % of the acreage with fall tillage
Soil-subTax100	Soil-sub and Tax100 combined
Soil-subStorage12	Soil-sub and Storage12 combined
Soil-subTax100Storage12	Soil-sub, Tax100 and Storage12 combined
FeedingB	Changed feeding practices reducing excretion of N and P in manure
Early-Plow	Plowing shortly after grain harvest

The main results from the modelling are given in table 7.6. Before we discuss these, some comments need to be made on the kind of measures used. The various emissions are presented as deviations from those obtained in the Base scenario (the highlighted figures in table 7.5). The deviations are provided both in absolute terms and in percent. Four emission categories are covered, N-leaching, loss of ammonia-N, P and soil losses. In reality we also have the losses of nitrous oxide (N_2O). This type of loss however is impossible to model with any accuracy at our level.

Three cost measures are used. Again we measure the deviations from the Base scenario. First, the table gives the change (reduction) in net income per ha for the farmer ("Costs farmer"). Second, we present two social cost measures – i.e. measures where we follow standard procedure and remove subsidies or taxes from the income/cost calculation since they do not represent real costs (income effects disregarded). We have formulated two measures here. One measure is social abatement costs per ha (Soc.abatem. costs A). The other is social abatement costs per kg reduced N leaching (Soc. abatem. costs B).

It is important to note that the costs are average costs. Estimating reliable/precise marginal costs is a difficult task both concerning the actual cost structure and the complexities of ECECMOD. Estimates of the marginal costs are made on the basis of average cost measures and will be reported later.

As to the social cost measures, Norwegian prices are used. This is certainly not an obvious choice. One may argue that the higher prices, especially on agricultural products reflects a higher willingness to pay for Norwegian produced food. However, at least as far as changes in production volumes are rather marginal, as is mostly the case here, the argument goes clearly in favor of using world market prices. Using such prices would have created some consistency problems, though. Not only product, but also input prices are heavily influenced by the structure of Norwegian agricultural policy. Being unable to determine a consistent alternative price scenario, we have chosen to use 1992 prices as observed. Even though there are uncertainties involved in the cost estimates, this implies that the costs are most probably overestimated given world market prices as basis. On the other hand, most scenarios involve rather small changes in production, so the importance of the chosen base line for prices is not highly important.

Policy measures increasing costs for farmers and changing the level of output, will in open markets induce changes in the prices for agricultural products. This mechanism is very different in administered agricultural products markets like the Norwegian, and we have chosen not to let output prices be influenced by changes in costs/output levels.

As already mentioned, table 7.6 differentiates between abatement costs per ha and per kg reduced N-leaching. There are four different types of emissions estimated, with varying environmental effects and no existing common standard for weighing them. Given that such a standard does not exist, it has been important to present the results in a way that makes it easy for the reader to evaluate the results obtained. Producing cost estimates for the same unit as the loss estimates – i.e. per hectare – makes it possible to compare by using any weighing the reader may prefer. Producing an estimate where all costs are carried by the change in N leaching, are motivated by the fact that most measures in this study are oriented towards reducing this type of loss. Other gains (or losses) may be evaluated as "extra" gains (costs). All emissions are given as the mean over the 20 year period 1973-1992.

The results in table 7.6 represent only a first indication of the tendencies in the material since we need to vary the levels of each policy measure to get deeper insights into their qualities. Further, the levels presented in table 7.6 are not strictly comparable. Still the table gives indications that will hold throughout the whole study. Looking at the social costs as defined above, the price cut and the N tax seem to offer the lowest cost per kg reduced N leached per hectare. On the other hand these measures only influence the N losses, and the effects are rather low – especially for the price measure – while the consequences on farmers' income are quite substantial. We will later discuss what may be obtained by an increase in the tax levels or further decreases in product prices.

Table 7.6: Results from a set of scenarios compared with the Base scenario. Estimated costs and changes in emissions (mean over a 20 year period).

Scenario	ΔN leaching Mean[3] kg/ha (%)	ΔN air[1] Mean[3] kg/ha (%)	ΔP loss Mean[3] kg/ha (%)	ΔS loss[2] Mean[3] kg/ha (%)	Costs farmer NOK[4]/ha	Soc.abatem. costs A NOK[4]/ha	Soc.abatem. costs B NOK[4]/kg N[5]
Tax100							
Auli A	-5.9 (15)	-2.5 (38)	-0.09 (2)	-9 (1)	570	77	13
Auli B	-5.3 (13)	-2.9 (37)	-0.05 (1)	-3 (0)	510	64	12
Mørdre	-4.4 (15)	-0.8 (42)	0 (0)	0 (0)	610	51	12
Price33							
Auli A	-2.7 (7)	+1.1 (17)	-0.13 (3)	-32 (3)	3030	22	8
Auli B	-2.4 (6)	+1.7 (22)	-0.11 (2)	-15 (1)	3090	20	8
Mørdre	-2.6 (9)	0.0 (0)	0 (0)	0 (0)	3100	31	12
Catch50							
Auli A	-10.8 (27)	0.0 (0)	-2.16 (43)	-520 (44)	199	199	18
Auli B	-12.0 (29)	0.0 (0)	-2.34 (50)	-553 (52)	217	217	18
Mørdre	-7.9 (27)	0.0 (0)	0 (0)	2 (1)	294	294	37
Soil-Sub							
Auli A	-0.4 (1)	0.0 (0)	-2.72 (55)	-676 (57)	-370	138	370
Auli B	-0.2 (0)	0.0 (0)	-1.71 (37)	-423 (40)	-310	117	710
Mørdre	+0.1 (0)	0.0 (0)	0.01 (2)	2 (1)	-510	30	..

1) Loss of ammonia-N in connection with manure spreading
2) Soil loss
3) Mean over 20 years
4) NOK = Norwegian kroner
5) Costs per kg reduced N leaching

According to the estimates, catch crops influence N-leaching, P- and soil-losses rather substantially. Catch crops are a more expensive abatement strategy per kg reduced leaching of N than the tax/price measures. Taking the gains related to less erosion into consideration, the differences may not seem that large, though. We further observe that Catch50 gives more varied results between the areas. The main reason for this is that we have assumed catch crops to demand fall tillage. Since Mørdre is dominated by silty soils, Catch50 both influences N-uptake by the main crop and the volume of spring tilled fields negatively. The farmers gain, however, from avoiding catch crops on silty soils. The negative effect is thus counteracted by private economic incentives as sandy and clayey soils will *ceteris paribus* be chosen first.

There are some extra uncertainties attached to the effect of catch crops on erosion. The reduction is mainly caused by increased soil cohesion, mainly due to an increased volume of fresh roots. The cohesion level is increased with 10 % compared to plowed grain fields without catch crops.

Catch crops deviate from the price/tax measures also along another dimension. While the marginal social costs are rather constant over fairly large intervals of acreage under catch crops, they rise much steeper for the two economic measures. At the margin the social costs per kg N reduced leaching are – as an example – fairly equal for a 100 % tax and a 50 % catch crop requirement. We will return to this issue later.

Subsidizing farmers abandoning fall tillage gives no or very small effects on N losses, while P losses and soil erosion are substantially reduced in Auli, as one would expect. As shown in chapter 6, the low N effect depends on rather late tillage even in the Base scenario (early October) and the fact that silty soils are tilled in the spring in both scenarios. However, as discussed in chapter 6, our analyses do not cover potential effects of spring tillage on the hydrological conditions throughout the fall. Thus the N-effect of spring tillage may be underestimated. Looking at P- and soil loss, the variations are largely explained by the amount of silty soils in the three areas (4, 8 and 75 % respectively).

If we turn to the costs faced by the farmer, we obtain to a large extent the inverse picture of the one described by the social cost measures. What seems societally cheapest, is most costly for the farmer. This certainly constitutes a challenge for policy makers. The pattern is mainly an effect of the substantial distributional effects of the analyzed price cut or tax. This is easily illustrated comparing column 4 and 5 in table 7.6. In the case with a 33 % price reduction, this cut counts for more than 99 % of the income loss the farmer faces. Even in the scenario with a 100 % tax, there are substantial differences between private and social costs. The tax counts for about 85 - 90 % of the expenses the farmer has to bear.

In the case with catch crops, the private and social costs are equal. Here farmers' costs are entirely related to increased resource use (seeds, labor and fertilizers) and yield losses. In practice, the social costs may actually be higher in this case than the private abatement costs. In table 7.6, the potential administration costs following the different systems are not incorporated. These costs are most probably not ignorable.

In the Soil-Sub scenario, the subsidy for spring tillage is set at the level of 1000 NOK per ha. This was the actual level used in 1992. According to the model analysis, it results in a net increase in farmers profits (negative costs), indicating that it should be possible to produce such a change with a lower subsidy. The costs vary between soil types, since the characteristics of the soil influences the effects on yields (see appendix A5.4). Actually, for silty soils, it seems like spring tillage has a positive yield effect, while it is opposite for the other soil types. Still, in our calculations the costs for the farmer lie most often in the range of 300 - 500 NOK per ha and year.[9] It must be emphasized that not all types of soils are present in the three chosen landscapes. This is especially the case for some types of clayey soils.

In chapter 3 we discussed the potential for a tax to induce split fertilizing and the use of catch crops. The analyses undertaken show that there is no reason to believe that farmers will change their practice more in these directions. Our analyses are made for tax levels up to 300%. The gains obtained with split fertilizing turn out to be too small to cover the extra costs, except for sandy soils where split fertilization seems profitable even with today's prices (see section 7.4.4 for a more extensive discussion). As to catch crops, it takes at least a couple of decades before the N mineralization reaches a level above what is the case without such a crop. The reduced leaching goes mainly to building a larger nitrogen pool in the soil, as already emphasized in chapter 6. The investment is thus not profitable for the farmer even with very low interest rates and/or high N taxes.

7.4 Diversifying the results

7.4.1 Lower product prices or nitrogen taxes?

Lower fertilizer levels result in less N leached. Reduced N input can be induced both by the means of an N tax or a reduction in the product price. As we remember from equation [3.2], the optimal fertilizer level is reached when the gradient of the production function with respect to N equals the relation between the N price and the product price. Thus a 50 % N tax and a 33 % price reduction should *ceteris paribus* give exactly the same reductions in fertilizer levels and thus in leaching.

As soon as other N-sources like manure N are available, the two measures work differently. While a product price change – i.e. in this case a lowered price on grain – will not have any effect on the use of such N sources, a tax on mineral N will make it profitable to utilize manure N better with positive side-effects on leaching and losses to air. Biologically fixed N may also become competitive, with a more uncertain outcome concerning N leaching.

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[9] The support system for reduced fall tillage was changed in 1995. The level was lowered on average and the subsidy was also differentiated – i.e. it is highest in areas where the erosion risk is largest. The lowest level is now 300 NOK and the highest 1200. Presuming that our cost estimates are correct, this should influence farmers' adaption only marginally. However, substantial decreases in fall tillage are observed (Nationen 1995), indicating that farmers evaluate losses differently from the results obtained in trials. However, the result may also indicate that farmers interpret the reductions as a signal to reduce the transition to spring tillage, or we may observe an example of what Tversky and Kahneman (1986) call "loss aversion."

Results from the following price and tax scenarios are given in table 7.7:

- Price33:	A 33 % price reduction on grains (also reducing the value of grass).
- Tax50:	50 % tax on N in mineral fertilizers.
- Tax100:	100 % tax on N in mineral fertilizers.
- Tax200:	200 % tax on N in mineral fertilizers.
- Tax100M:	100 % tax on N in mineral fertilizers combined with a manure market.

First of all, our analyses show that green manure is not a competitive N source at least with N tax levels up to 300 %. Thus on model farms with specialized grain production the modelling shows no substitution effects as to inputs. On the other hand we observe some substitution between crops especially in the Price33 scenario.

Comparing Price33 and Tax50 we observe that both measures result in a limited reduction in leaching, with Tax50 having a slightly larger impact according to the estimates. As to air losses we notice a larger difference, since Price33 even results in a negative development from an environmentally point of view compared with the Base scenario. The differences in leaching are caused by different substitution effects. Tax50 makes it profitable to utilize manure better, and time from spreading to incorporation of manure into the soil is reduced on several model farms. This also explains the positive effect on ammonia losses. In the case of Price33 an opposite tendency is observed as lower product prices make it less valuable to put efforts into converting manure N into N in grain or grass, especially increasing losses to air.

The reason why the differences in N-leaching between the two scenarios are not larger, relates to the fact that the price change induces a shift between the different grain species that does not occur likewise with a 50 % tax. The tendency is not strong, but it is observed in both areas. Since the manure substitution effect is low in Mørdre, due to small amounts of manure, the shift between grain species outweighs the manure effect.

We would suppose that in areas with more animal production than in Auli and Mørdre, the differences between a price cut and a tax would be much more distinct. The most important is still that both scenarios have rather small effects on N leaching – only 6-9 %. Reducing grain prices further, would most probably reduce leaching more. However, as earlier analyses show (Børve 1994; Moen 1994), we approaches a level where the main, long run reaction will not be changes in fertilizer intensity, but a transition away from grain to other land uses. ECMOD is not constructed to handle such structural changes. However, changes to extensive grass production or forest production induced this way, will have positive effects on nutrient losses. An increase in fallow areas will be negative, at least in the short to medium run.

Table 7.7: The effect of different price and tax measures. Estimated costs and changes in emissions as compared with the Base scenario.

Scenario	ΔN leaching Mean3) kg/ha (%)	ΔN air1) Mean3) kg/ha (%)	ΔP loss Mean3) kg/ha (%)	ΔS loss2) Mean3) kg/ha (%)	Costs farmer NOK4)/ha	Soc.abatem. costs A NOK4)/ha	Soc.abatem. costs B NOK4)/kg N5)
Price33							
Auli A	-2.7 (7)	+1.1 (17)	-0.13 (3)	-32 (3)	3030	22	8
Auli B	-2.4 (6)	+1.7 (22)	-0.11 (2)	-15 (1)	3090	20	8
Mørdre	-2.6 (9)	0.0 (0)	0 (0)	0 (0)	3100	31	12
Tax50							
Auli A	-3.0 (7)	-0.8 (12)	-0.05 (1)	-5 (0)	310	28	9
Auli B	-2.7 (7)	-2.0 (26)	-0.13 (3)	-17 (1)	270	24	9
Mørdre	-2.4 (8)	-0.8 (42)	0 (0)	-1 (1)	330	29	12
Tax100							
Auli A	-5.9 (15)	-2.5 (38)	-0.09 (2)	-9 (1)	570	77	13
Auli B	-5.3 (13)	-2.9 (37)	-0.05 (1)	-3 (0)	510	64	12
Mørdre	-4.4 (15)	-0.8 (42)	0 (0)	0 (0)	610	51	12
Tax200							
Auli A	-10.8 (27)	-2.6 (40)	-0.14 (3)	-13 (1)	1040	237	22
Auli B	-11.3 (27)	-2.8 (36)	-0.49 (11)	-72 (7)	930	227	20
Mørdre	-9.1 (31)	-0.9 (47)	-0.01 (2)	-8 (3)	1130	180	20
Tax100M							
Auli A	-7.3 (18)	-3.3 (51)	-0.13 (3)	-9 (1)	570	73	10
Auli B	-6.9 (17)	-3.8 (50)	-0.13 (3)	-3 (0)	520	63	9
Mørdre	-4.4 (15)	-0.8 (42)	0 (0)	0 (0)	610	51	12

1) Loss of ammonia-N in connection with manure spreading
2) Soil loss
3) Mean over 20 years
4) NOK = Norwegian kroner
5) Costs per kg reduced N leaching

Even if a price change seems to have rather limited potential for reducing N losses as long as grain still is the crop produced, one should acknowledge a potential for reduced losses through a change in *relative* prices. Certainly, there are uncertainties involved, and the differences in N leaching between grain species as presented in chapter 6, may be exaggerated. However, there seems to exist a potential for reductions of N-leaching by switching to more wheat production, even though there are limits to increasing one single crop without creating problems like increased frequencies of diseases etc.

We should also mention that there are some potential pitfalls in our case related to reducing product prices too far. Lower prices makes it less interesting for the farmer *ceteris paribus* to undertake efforts to increase yields. Here we have in mind investments in ditches, less use of pesticides etc. ECMOD is in its present form not capable of capturing these kinds of effects, but one general lesson from the modelling exercises undertaken is how extremely important the amount of N taken up by the plants is for the level of N leached.

While price reductions seem to have a low potential for reducing losses, except through the potential for reducing the amount of land tilled, there are further potentials for reducing losses by increasing the N tax beyond 50 %. Three levels are compared in table 7.7. Going from the lower to the higher level, we both observe decreased fertilizer intensities and better utilization of manure. We observe transitions from tank trailer to the use of a pipe system which results in both reduced leaching (higher yields due to less soil compaction), and reduced losses to air. In some cases 12 month manure storage becomes profitable.

In the Tax100M scenario, the consequences of a market for manure are explored. There is only a small group of farms – those covered by model farm 1.6 – that has more plant available ("effective") N in manure than the optimal fertilizer level even with a 200 % N tax. Given our scenarios, these farms are thus the only ones where a potential for sale exists. Our analyses indicate that sales become profitable somewhere in the interval between a 50 and a 100 % tax. The value of nitrogen is then increased to a level making it beneficial for both seller and buyer to engage in a trade of manure N. The costs to be covered by such a trade are related to manure transport and the losses the receiver faces since it is more difficult to distribute manure N evenly over the fields as compared with mineral fertilizers.

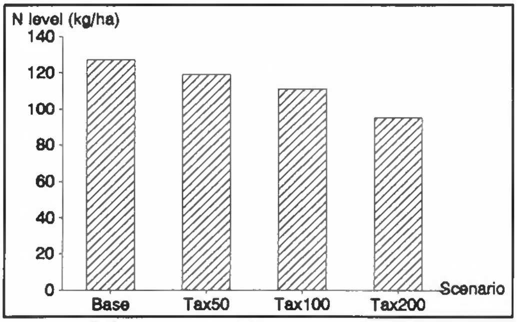

Figure 7.3: Average N fertilizer levels for different tax levels. Auli A, kg/ha.

In Tax100M the optimal sales level for all seasons is calculated. Sales will only take place in spring and it becomes optimal for model farm 1.6 to sell about 1/3 of its total manure nitrogen. The rather low level compared with the huge surplus on this model farm, is due to the fact that it is still not profitable to increase the storing capacity for manure beyond 8 months. Assuming that in spring effective N in manure substitutes mineral fertilizer N at the receiving farms in a one to one proportion, all effects on leaching comes on the farms represented by model farm 1.6.

Since Mørdre has no farms with very high animal densities, the potential market is only relevant for Auli. Here there is an estimated reduction in losses from Tax100 to Tax100M of about 20 to 30 %. Increasing taxes to 200 % will increase sales, but only marginally, because it will still not be optimal for model farm 1.6. to increase its storing capacity. Thus, with our model farms and assumptions, a market will not induce much extra reduced leaching going from a Tax200 to a Tax200M than what is already observed at the 100 % tax level.

Increasing the N tax induces a fairly linear reduction in leaching – doubling the tax means approximately doubling the reductions too. At the highest tax level, N-leaching is reduced with about 27 - 30 %. As shown in chapter 6, leaching is a non linear convex function of the N fertilizer level. Further, the response of an N tax on N use is fairly linear as illustrated with estimates from Auli A in figure 7.3.

From these observations one should expect a tendency to decreased reductions in N leaching as taxes increase. Only Auli A shows such a picture. The reason for this is the pattern of changes in the use of manure N, an issue that will be more fully dealt with in chapter 8. The changes in manure utilization is also the reason for the rather diverse picture of changes in losses of N to air.

According to table 7.7 social abatement costs per kg N reduced leaching is approximately doubled going from the lower to the higher tax levels. This indicates rather substantial increases in marginal costs. ECECMOD is not able to give precise marginal cost estimates. A quadratic function describing the relationship between reduced N leached and total costs is estimated on the basis of average costs. We got:

$$TC = \underset{(0.078)}{1.98} * A^2 \quad (F=644.6; \quad R^2 = 0.987) \qquad [7.1]$$

where TC denotes total costs and A reduction in N leaching. Thus marginal costs in NOK is about 4 times the level of reduced emissions given this estimate. There are two reasons for this pattern. Yield functions are concave while the loss functions are convex. Further, it generally costs more to achieve reduced losses through better manure treatment than through intensity reductions. Such changes therefore tend to occur only at higher tax levels.

The effects of the tax and price measures are negligible on soil erosion. The variation between the scenarios seems mostly to reflect changes in crop rotation patterns and coincidences in the combinations between soil factors, crop cover and weather patterns. They can thus not be considered as an effect of the measures with the exception that high tax levels increase the acreage of meadow slightly. As to the P-losses, we observe a slightly larger reduction than for soil losses if N taxes are introduced. This effect follows from less manure spread in fall and/or shorter time from spreading to incorporation in the soil.

7.4.2 Animal manure regulations

Reduced N losses from manure may be achieved by more direct measures than taxes on fertilizer N. Two policy measures are analyzed. First we have measures securing less excretion of N and P from animals. This can be obtained through reduced contents of N and P in concentrates and better composition of proteins and amino acids in the feed. A scenario called

FeedingB is constructed to analyze the effect of this option. Changed feeding practices is a much discussed measure due to expected low costs and the potential for solving the manure problem without substantial changes in the production structure.

Changed feeding practices of this kind may result in reduced production and/or increased stress for the animal. Changes proposed here are moderate, and kept within the limits of existing norms (Bolstad 1994). Policy measures may in this case be directed towards feed companies on the basis of mandatory standards. Desired results may also be obtained by a system of taxes on the N and P surpluses on the farm. This solution is under implementation in the Netherlands (Biewinga 1996). In our modelling a system with mandatory standards is used.

The second measure is mandatory full year manure storing capacity – the Storage12 scenario. This is presumed to have two effects. First it will secure that all manure – at least in cases where total levels are below optimal fertilizer levels – will be spread in the growing season. Thus the type of losses following fall spreading will tend to disappear. Further, such a change reduces soil compaction, especially in grass production, where compaction is rather high when spreading is undertaken in the fall. This way grass yields can be kept on a higher level, counteracting the loss of N. It should be emphasized that only about a half of the model farms with animals change to a 12 month storing capacity even with a 200 % tax as previously analyzed. Thus a mandatory solution may be warranted. The results of the analyses are given in table 7.8.

The effects on leaching turn out to be rather small for both alternatives. This is partly due to the small amounts of manure in the three areas. The effects on the animal farms will be discussed in more detail in chapter 8. For this group the effects are not negligible.

We observe that in the case of FeedingB, the costs are small. One might ask why we encounter any costs at all. Reducing the amount of expensive nutrients in the feed without reducing production, should decrease costs. Even if the farmer must compensate with increased purchase of fertilizers as an effect of the changed feeding strategy, the costs should in total be reduced. Since no price observations exist for this alternative, there are extra uncertainties involved. Our evaluation has been that the reduced amount of nutrients in concentrates, will most probably not reduce its price, while for most farms in our areas reduced N (and P) in manure must be compensated by increased fertilizer expenses. This explains the results obtained.[10]

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[10] If this were the case, one should have expected it to be utilized already by the feed firms. The situation seems rather to be to the opposite. As an example, the feed firms seem to add extra P through bone meal in concentrate because it is cheap. Changing protein content and the composition of amino acids does not seem to reduce prices either.

Table 7.8: The effect of changed feeding practice and increased storing capacity for manure. Estimated costs and changes in emissions as compared with the Base scenario.

Scenario	ΔN leaching Mean3) kg/ha (%)	ΔN air1) Mean3) kg/ha (%)	ΔP loss Mean3) kg/ha (%)	ΔS loss2) Mean3) kg/ha (%)	Costs farmer NOK4)/ha	Soc.abatem. costs A NOK4)/ha	Soc.abatem. costs B NOK4)/kg N5)
FeedingB							
Auli A	-1.2 (3)	-0.6 (9)	-0.07 (1)	-5 (0)	7	7	5
Auli B	-1.6 (4)	-1.0 (13)	-0.18 (4)	-18 (2)	14	14	9
Mørdre	-0.3 (1)	-0.1 (5)	0 (0)	0 (0)	8	8	26
Storage12							
Auli A	-2.3 (6)	+0.1 (2)	-0.15 (3)	-19 (2)	82	82	35
Auli B	-3.8 (9)	-0.2 (3)	-0.54 (12)	-69 (7)	88	88	23
Mørdre	-2.1 (7)	-0.6 (32)	-0.01 (2)	-6 (2)	0	0	0

1) Loss of ammonia-N in connection with manure spreading
2) Soil loss
3) Mean over 20 years
4) NOK = Norwegian kroner
5) Costs per kg reduced N leaching

There are some small effects on P- and soil loss. As to soil losses, we observe some increase in spring tillage on silty soils due to the effect of full year manure storage. The extra effects on P losses follow in both scenarios from less run-off of manure in the fall.

7.4.3 Catch crops

As we have already seen, catch crops seem to have a high capacity for reducing nutrient and soil losses. We will investigate this potential further, while we also will discuss the possibility to combine this solution with other measures. We emphasize that we consider the results for catch crops more uncertain than those for N tax/intensity reductions. This relates to the fact that the empirical underpinning is weaker.

Catch crops have two main deficiencies from our point of view. First, they have no effect on the utilization of manure. Second, they do not influence leaching from meadows. The first problem could be reduced by combining catch crops with mandatory 12 months storing capacity for manure. Both deficiencies could be counteracted by combining mandatory catch crops with a fertilizer tax.

We have investigated the following options:

- Catch50	50 % arable land requirement on catch crops/grass cover.
- Catch50Storage12	Catch50 + mandatory 12 months storage capacity for manure.
- Catch50Tax100	Catch50 + a 100 % tax on N in mineral fertilizers.
- Catch100	100 % arable land requirement on catch crops/grass cover.

- Catch100Tax100 Catch100 + a 100 % tax on N in mineral fertilizers.

Looking at table 7.9, we first of all recognize that the social costs per kg N reduced leaching are fairly equal in all scenarios presented. They further lie at the level of Tax200. The per ha measure naturally increases as more hectares are catch cropped or as the tax is added. All scenarios involving catch crops have a large potential for loss reductions. In the case of N-leaching, the effects are estimated to be 5 to 10 times that of Tax50/Price33 for areas like ours. The effect on soil losses are even larger.

If we compare with previously presented results (tables 7.6-7.8), we find as assumed, that a combination of policy measures gives a lower effect on leaching than the sum of each measure used individually. Still we see that an N tax or a mandatory 12 month storing capacity on top of a catch crop requirements has effect.

A 100 % catch crop requirement may be beyond what is practically attainable. What is interesting to see though, is that there seems to be a large potential for reductions at levels above 50 % in the case of N-leaching. It should further be mentioned that both scenarios with a 100 % catch crop requirement reaches the levels for N reductions as mandatory by the North Sea Convention. Whether this would hold for more animal dense areas is disputable.

Also in the case of P losses, the results show that a catch crop requirement may be sufficient to reach the 50 % goal in areas dominated by clayey soils (Auli) and grain production. Still we need to emphasize the extra uncertainties related to estimating the effect of catch crops on this type of loss. Further, the reductions in soil and P losses are only slightly increased going from Catch50 to Catch100. There are two counter-effects explaining this. According to the model predictions, Catch100 eliminates all spring tillage and all winter wheat. Thus concerning soil losses there exists a level of maximum potential reductions somewhere between 50 and 100 % in Auli. In Mørdre this point is reached at a much lower level due to the high percentage of silty soils.

The costs related to catch crops are largest in the Mørdre area. The reason for this is again the dominance of silty soils. While we have assumed that catch crops have to be plowed in the fall (late october), spring tillage is the most profitable soil preparation system for this type of soil. Thus there is an extra cost related to using catch crops in this area, also showing up in lower absolute reductions in N leached, since fall tillage reduces yields. It may not be necessary to plough fields with catch crops in the fall. However, we know little about the yield effect of using spring tillage in this case. Thus lack of data has made it impossible to pursue this line of inquiry.

Table 7.9: The effect of mandatory catch crops – singly and in combination with other measures. Estimated costs and changes in emissions as compared with the Base scenario.

Scenario	ΔN leaching Mean3) kg/ha (%)	ΔN air1) Mean3) kg/ha (%)	ΔP loss Mean3) kg/ha (%)	ΔS loss2) Mean3) kg/ha (%)	Costs farmer NOK4)/ha	Soc.abatem. costs A NOK4)/ha	Soc.abatem. costs B NOK4)/kg N5)
Catch50							
Auli A	-10.8 (27)	0.0 (0)	-2.16 (43)	-520 (44)	199	199	18
Auli B	-12.0 (29)	0.0 (0)	-2.34 (50)	-553 (52)	217	217	18
Mørdre	-7.9 (27)	0.0 (0)	0 (0)	2 (1)	294	294	37
Catch50Storage 12							
Auli A	-12.6 (31)	+0.1 (2)	-2.28 (46)	-517 (44)	279	279	22
Auli B	-14.7 (36)	-0.2 (3)	-2.67 (58)	-574 (54)	304	304	21
Mørdre	-9.5 (32)	-0.6 (32)	-0.06 (10)	-33 (12)	301	301	32
Catch50Tax100							
Auli A	-15.9 (39)	-2.3 (35)	-2.24 (45)	-521 (44)	780	282	18
Auli B	-16.5 (40)	-2.8 (36)	-2.42 (52)	-555 (52)	740	281	17
Mørdre	-11.8 (40)	-0.8 (42)	0.01 (2)	6 (2)	900	333	28
Catch100							
Auli A	-20.3 (50)	-0.3 (5)	-2.28 (46)	-529 (45)	495	495	24
Auli B	-23.4 (57)	-1.7 (22)	-2.55 (55)	-572 (54)	533	533	23
Mørdre	-19.1 (65)	-0.5 (26)	0.04 (7)	21 (8)	686	686	36
Catch100Tax100							
Auli A	-24.3 (60)	-2.4 (37)	-2.27 (46)	-522 (44)	1080	569	23
Auli B	-26.8 (65)	-2.9 (37)	-2.51 (54)	-559 (53)	1070	596	22
Mørdre	-21.5 (73)	-0.8 (42)	-0.04 (7)	21 (8)	1320	741	35

1) Loss of ammonia-N in connection with manure spreading
2) Soil loss
3) Mean over 20 years
4) NOK = Norwegian kroner
5) Costs per kg reduced N leaching

7.4.4 Split fertilization

As already indicated, our modelling shows that an N tax seems unable to motivate farmers to increase the use of split fertilization, maybe unless exceedingly high tax levels are imposed. To test the potential for such a change in practice, a system of seasonally defined tradeable quotas is therefore used.

As discussed in chapter 3, split fertilization makes it possible to adjust the total fertilizer level better to the plant growth potential each year, which should also gain the farmer. (S)he faces some extra costs though, both related to the extra round of application and yield loss because of the extra tractor traffic in standing crops.

The main challenge for this scenario is to determine the way the farmer will update his/her information set. (S)he will not be able to get exact information about the potential of each year before approaching harvest. Thus the farmer has to decide on a second application on the basis of restricted information. In the analysis presented here, we have chosen to model this by grouping the year specific production functions for grain into three groups, representing "good", "average" and "bad" years, assuming that this is the accuracy by which the farmer may be able to update information at the time the second fertilization is conducted. For each of these groups, new functions for expected yields are estimated. The results are certainly dependent upon the grouping, as they are vulnerable to the functional form of the yearly production functions.

The system of tradeable quotas is modelled in the following way. In the spring – when the quality of the year is unknown – a quota is distributed at the desirable level for "bad" years. If the year turns out to stay in that group, the model does not offer a quota for a second round application. If the year turns out to be better, such a quota is distributed, with the largest amount in "good" years. To be able to compare with other scenarios, the total level for the 20 year period is set equal to the one obtained by a 100 % N tax. It is thus named Split100. The nitrogen fertilizer is distributed differently between years and fields though. The assignment with split application is done in a way such that expected leaching (based on estimated N uptake in crops) is to be equal for all types of years.

ECMOD is currently not constructed to model N quota trade. Thus a quota is set for each model farm approximating the expected result from a trade regime[11]. Such a determination is in our case simplest to do for specialized grain farms. To test the potential for this strategy, an analysis restricted to these model farms was undertaken. Table 7.10 gives the results at model farm level for two of the four specialized grain model farms.

The results are not very encouraging. The estimated level of reduced leaching are about the same for Tax100 and Split100, while the social costs are clearly higher in the case with split fertilization, even though the extra transaction costs with such a system are not taken into account.

There seems to be two important reasons for this. First, the difference in optimal fertilization levels between types of years turns out to be rather small. Thus split fertilization *as modelled here* has only a limited influence on losses in "bad" years. Another grouping of years, with a stronger criterion for "bad" years, might have changed this. Second, split fertilization results in crop damages at a level of approximately 2 %. The isolated effect of this is an increased N loss of about 3 - 3.5 kg per ha actually eliminating the isolated gain from more precise N application as it also induces extra costs.

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[11] The research team is working on a more sophisticated N-trade regime to be reported elsewhere.

Table 7.10: The effect of split fertilization compared with general intensity reduction. Estimated costs and changes in emissions compared with the Base scenario.

Scenario	ΔN leaching Mean[2] kg/ha (%)	ΔN air[1] Mean[2] kg/ha (%)	Costs farmer NOK[3]/ha	Soc.abatem. costs A NOK[3]/ha	Soc.abatem. costs B NOK[3]/kg N[4]
Tax100					
Model farm 1.8	-5.6 (18)	0.0 (0)	640	28	5
Model farm 2.3	-3.4 (16)	0.0 (0)	660	50	15
Split100					
Model farm 1.8	-5.2 (17)	0.0 (0)	151	151	29
Model farm 2.3	-3.6 (17)	0.0 (0)	173	173	48

1) Loss of ammonia-N in connection with manure spreading
2) Mean over 20 years
3) NOK = Norwegian kroner
4) Costs per kg reduced N leaching

One could argue that in crops where herbicides or fungicides are used, there will be no or very low extra yield loss attached to an extra round of fertilizing. This is due to the fact that trafficking in such a case will cause little extra crop damage as the farmer will use already existing tracks produced while spreading the herbicides. If this is the case, split fertilization becomes a more favorable option.

Disaggregating the results, we observe that while split fertilization reduces profits for the farmer on clayey and silty soils, it is actually profitable on sandy soils even with N price as in the Base scenario. This creates a potential "win-win" situation on such soils where both the farmer and the environment would gain through reduced leaching.

7.4.5 Tillage oriented measures

Reduced fall tillage can be motivated by different types of policy measures. We have already looked at the effect of a subsidy at the level introduced in 1991/92. An alternative is to use a system with mandatory spring tillage on a certain percentage of the area. In the Soil-Sub scenario presented in table 7.6, the subsidy did not result in reduced fall tillage in cases where manure was spread in the fall. In a third scenario, the effect of this is analyzed through combining a spring tillage subsidy with mandatory 12 months storing capacity for manure.

The following three scenarios have thus been analyzed:

– Soil-Sub	Subsidy paid if an area is tilled in spring (1000 NOK per ha)
– Soil-50	Mandatory requirement: No more than 50 % of the acreage is allowed tilled in fall
– Soil-SubStorage12	Soil-sub combined with 12 month manure storage requirement.

The various measures induce the following changes in the amount of spring tillage in the three areas:

Table 7.11: The effect of various policy measures on the level of spring tillage in percent. Average over 20 years.

	Base	Soil-sub	Soil-50	Soil-SubStorage12
Auli A	1	50	36	66
Auli B	2	43	39	69
Mørdre	47	54	64	79

The effect of the various measures are substantial in Auli, while more modest in Mørdre since silty soils anyhow will be tilled in spring. There are two comments to be made upon the percentages in table 7.11. First, the model analyses only predict a change from fall to spring plowing. There are no scenarios where spring harrowing or direct seeding is chosen. The reason for this is the distributions of soils in the three areas, making these solutions uncompetitive.

Second, the results in table 7.11 are influenced by some deficiencies in the modelling that need to be highlighted. Due to the high complexities involved when modelling decisions about manure handling practices, we made some choices securing consistency in the N modelling, that induced some inconsistencies concerning tillage practices. These only affect farms with animal manure to be spread in the fall, which results in too high a volume of fall tillage. Thus the increase in spring tillage going from scenario Soil-Sub to Soil-SubStorage12, is as much an effect of the way the modelling is undertaken as of the enlargement of storage capacity per se. Estimates done indicate that more than 50 % of the difference relates to the modelling, implying that the percentage of spring tillage under the Soil-Sub scenario should be increased by about 10 % on average. In the scenario Soil-50 this error is of minor importance.

The low figures for Soil-50 in Auli are explained by the fact that a rather substantial part of the acreage is grass land which is plowed only every fourth year. The effects on emissions are given in table 7.12. In this case it is the consequences for erosion and P losses that are of interest.

While the effects compared with the Base scenario are substantial in Auli, they are insignificant in Mørdre. In Auli we observe that the impact of the policy measures are approximately linearly correlated with the ability they have to change the percentage of spring tillage. Similarly, for the policy measures with no requirements to secure that land with the highest erosion risk will be converted to spring tillage first.

The lack of effect on P and soil losses in Mørdre calls for some extra explanation. First, soil losses are already very low in this area due to the dominance of silty soils and the fact that a large proportion of the area is very flat. Further, the steepest parts of the agricultural land towards the stream is in permanent pasture. Thus the potential for reductions from the Base scenario is low.

Table 7.12: The effect of different measures directed towards reducing surface losses. Estimated costs and changes in emissions as compared with the Base scenario.

Scenario	ΔN leaching Mean[3] kg/ha (%)	ΔN air[1] Mean[3] kg/ha (%)	ΔP loss Mean[3] kg/ha (%)	ΔS loss[2] Mean[3] kg/ha (%)	Costs farmer NOK[4]/ha	Soc.abatem. costs A NOK[4]/ha	Soc.abatem. costs B NOK[4]/kg N[5]
Soil-sub							
Auli A	-0.4 (1)	0.0 (0)	-2.72 (55)	-676 (57)	-370	138	370
Auli B	-0.2 (0)	0.0 (0)	-1.71 (37)	-423 (40)	-310	117	710
Mørdre	+0.1 (0)	0.0 (0)	-0.01 (2)	-4 (1)	-510	30	..
Soil-50							
Auli A	-0.2 (0)	0.0 (0)	-1.79 (36)	-444 (38)	82	82	463
Auli B	+0.1 (0)	0.0 (0)	-1.56 (34)	-387 (37)	90	90	..
Mørdre	-0.4 (1)	0.0 (0)	-0.01 (2)	-6 (2)	5	5	12
Soil-subStorage12							
Auli A	-3.1 (8)	+0.1 (2)	-3.46 (70)	-824 (70)	-391	269	87
Auli B	-4.5 (11)	-0.2 (3)	-3.07 (60)	-695 (66)	-386	304	68
Mørdre	-2.0 (7)	-0.6 (32)	-0.02 (4)	-12 (4)	-700	90	44

1) Loss of ammonia-N in connection with manure spreading
2) Soil loss
3) Mean over 20 years
4) NOK = Norwegian kroner
5) Costs per kg reduced N leaching

Even though abandoning fall tillage is profitable under the scenario with a spring tillage subsidy, it still is profitable to continue with winter wheat in all three areas. This has a rather limited effect on erosion though, both since the area of winter wheat is fairly low and this crop has a substantial effect on erosion itself.

Throughout the 1990's, farmers have delayed fall tillage quite substantially. There exists no data documenting the extent of this transition. In the Base scenario fall tillage is set early October. A scenario – Early-Plough – has been constructed where the plowing date is set approximately one month earlier. This is assumed to have two effects. First, the amount of weeds and germinating grains will be heavily reduced, increasing the potential for N-leaching. Second, one would expect the erosion level to increase. The results are given in table 7.13.

The effect of this apparently minor adjustment in the agronomic practice is far from negligible. The effect on N-leaching of postponing fall tillage with one month is estimated to be at the level of 10 - 14 % which is similar to what was obtained by an 100 % N tax. The effect on soil and P losses are within the range 7 - 13 %.

Table 7.13: An early plowing regime compared with the Base scenario. Estimated emission levels, mean over a 20 year period.

Scenario Landscape	N leaching Mean kg/ha	 Change kg/ha	N air (ammonia) Mean kg/ha	 Change kg/ha	P loss Mean kg/ha	 Change kg/ha	Soil loss Mean kg/ha	 Change kg/ha
Base								
Auli A	40.4	..	6.5	..	4.97	..	1180	..
Auli B	41.2	..	7.8	..	4.64	..	1058	..
Mørdre	29.4	..	1.9	..	0.56	..	281	..
Early-Plow								
Auli A	44.9	4.6	6.5	0.0	5.57	0.60	1321	140
Auli B	46.6	5,4	7.8	0.0	5.28	0.64	1218	159
Mørdre	32.3	2.9	1.9	0.0	0.60	0.04	302	21

No cost estimates are given in table 7.13. This is due to the fact that postponing tillage with approximately one month does not induce any changes in costs, neither social nor private. Certainly, in the case of the Base scenario there may be a slight increase in the possibility of not getting all fields plowed in years where winter comes early.

7.5 The pattern of variation

In chapter 3 some hypotheses about the expected effects of different measures on the pattern of variation were formulated. The proposition was that in the case of nitrogen leaching, measures like catch crops would reduce variation more than a tax or a price cut inducing lower fertilizing intensity. The results from the modelling supports this picture, but only partly.

Table 7.14 gives the results for some of the most relevant scenarios both for N and soil losses in Auli A. As for N, there are two scenarios especially deviating from the main picture concerning standard deviations and max/min. Those are Tax100M and Catch100. In the case of soil losses, the main difference is between catch crop scenarios/Soil-Sub and the rest. There is one important difference between the N and soil loss variation measures, though. In the case of nitrogen, they are based on estimated variation both over years and model farm fields. The measures in the case of soil losses cover only variation in the predicted mean values for each year.

The hypotheses developed in chapter 3 were based on a study of mechanisms in plant production only. The pattern for N in table 7.14 is also affected by the use of animal manure. The high leaching values comes from the farms with more manure N per ha than can be utilized by the crops – those represented by model farm 1.6. Introducing a manure market into the model as in Tax100M, reduces variation substantially – actually down to the level of Catch100.

Table 7.14: The effect of different policy measures on variation. Estimates for Auli A. 1973-1992.

Scenario	N-leaching				Soil loss			
	Mean	St.dev.[1]	Max.[1]	Min.[1]	Mean	St.dev.[2]	Max.[2]	Min.[2]
Base	40.4	26.1	249	2	1180	929	3282	52
Tax100	34.5	25.2	249	2	1171	914	3218	53
Tax100M	33.1	18.6	151	2	1171	914	3218	53
Price33	37.7	25.6	250	2	1148	885	3083	53
Soil-Sub	40.0	26.0	249	2	505	392	1576	27
Catch50	29.6	22.6	249	1	660	565	2112	52
Catch100	20.0	18.6	175	1	659	571	2091	52

1) Calculated on the basis of weighed observations for all model farm fields and years (see text).
2) Calculated on the basis of variation between years.

If we look at the grain farms without or with low amounts of manure, the picture becomes simpler. Table 7.15 gives the relevant figures for model farm 1.5 and model farm 1.8.

Table 7.15: The effect of different policy measures on the variation in N leaching. Estimates for two model farms in Auli. Estimates for 1973-1992.

Scenario	Model farm 1.5				Model farm 1.8			
	Mean	St.dev.	Max.	Min.	Mean	St.dev.	Max.	Min.
Base	48.7	17.0	98	10	36.5	13.3	90	6
Tax100	44.1	15.6	95	9	31.0	11.6	76	4
Catch50	34.3	15.8	88	6	24.0	13.4	80	2
Catch100	11.2	6.7	34	1	12.3	7.3	34	1

While there are some differences between Base, Tax100 and Catch50, the largest change in the variation measures comes in the move from Catch50 to Catch100. The reason for this is that in Catch50, a large proportion of the fields are still without catch crops each year. This gives room for high variation – even potentially increased variation since the minimum values will be lowered.

8 Variation in results across model farms

The results presented so far, cover substantial variation in costs and adaption patterns across model farms. We shall now proceed by concentrating on the level of farms and productions. Since data on erosion are only given at the landscape level, we will mainly focus on nitrogen related issues. We will start by focusing on fertilizer intensity. In the subsequent sections we will focus on manure utilization practices and catch crops respectively. The chapter will close with some evaluations of the measures directed towards changing soil preparation.

8.1 Taxes, fertilizer intensity and leaching – the differences between grain and meadow

The modelling shows a large difference between grain and grass production in the potential for reducing N losses using N taxes (or tradeable quotas). Figure 8.1 display the results for different tax rates. Since the patterns are very similar in all of the three landscapes, we have simplified the presentation by only focusing on results from Auli B.

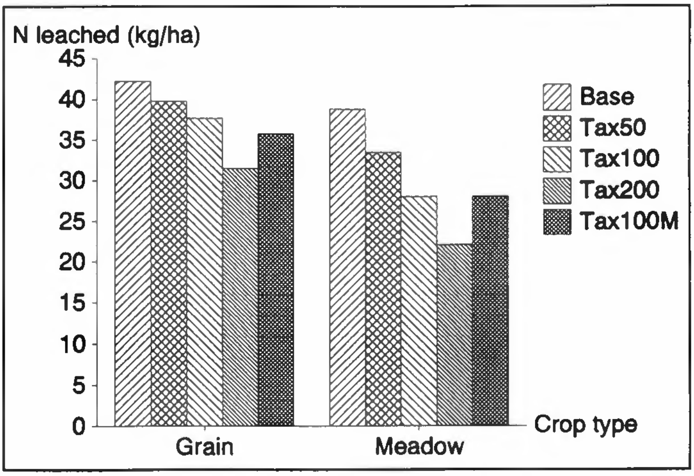

Figure 8.1: Estimated N-leaching from grain and meadow for different N tax level scenarios. Auli B. Leaching in kg/ha. The scenario names give taxes in percent.

Starting at a slightly lower level, the reductions in N-leaching are about twice as large in meadow as in grains. Not all of this is due to reductions in fertilizer intensity though. The relatively larger volume of animal manure on grass producing farms give these farms extra possibilities to reduce losses through changes in manure handling practices.

If we, as earlier discussed, accept a manure market to evolve somewhere in the interval between a 50 and a 100% tax, Tax100M is the best basis for comparison. Sale of manure influences the losses only in grain production. This is due to the specific distribution of highly intensive animal farms (model farm 1.6). As earlier mentioned, there are *in our case* only very small extra environmental gains from a market beyond what is obtained at Tax100M – i.e. a Tax200M will also show extra reductions compared with Tax200 of about 2 kg/ha in grain production.

Even though animal manure treatment is important for the pattern showing up in figure 8.1, most of the differences between grain and grass relates to intensity. Figure 8.2 shows the average fertilizer levels – i.e. the sum of both mineral fertilizers and effective manure N – for the different N tax levels. We still restrict the presentations to Auli B.

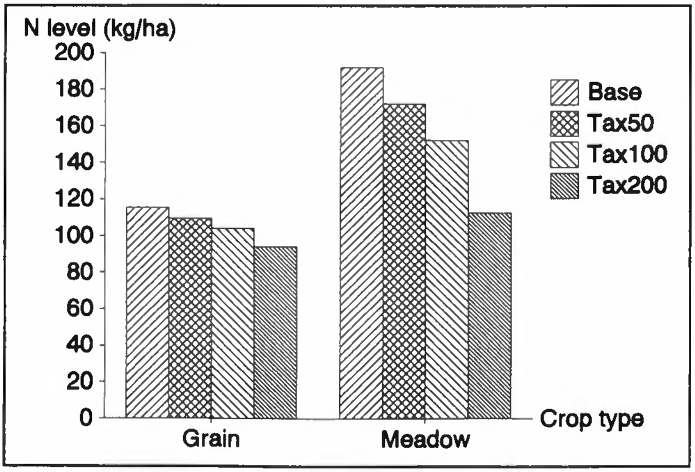

Figure 8.2: Estimated fertilizer levels in grain and meadow for different N tax level scenarios. Sum of N in mineral fertilizers and effective manure N in kg/ha. Tax levels in percent. Auli B.

While the fertilizer levels are much higher in grass production in the Base scenario, the reductions are substantially larger than in grain. To interpret the results, the concept of effective manure N needs some clarification. It is measured as the equivalent amount of mineral fertilizer N, meaning the amount of mineral N necessary to produce the same yields. The part of ammonia N spread in the plant growth season and incorporated into the soil, is evaluated equal to nitrate N. In the case of ammonia spread in the fall, a large part of what is incorporated into the soil will normally be lost before spring through leaching. What becomes effective for plant growth in later seasons as defined above is estimated using SOILN-NO (Vold, Bakken and Vatn 1995a). The same is done for the effect of the organic component in manure (ibid.). The results are comparable to those observed in experiments (Tveitnes 1994).

While expected yield functions for both grain and grass production are rather flat in the area around the optimum obtained in the Base scenario, the gradient of the yield functions increases much faster for grain than for meadow as the N level is reduced. This is a general observation concerning grass and grains. The effect is enhanced if we take the potential for substituting fertilizer N with N fixed by clover into account. Thus to be precise, what is observed in grass production is both an effect of reduced intensity and substitution.

Reduced fertilizer levels result in reduced yields. This effect is, in relative terms, much lower than the reduction in fertilizer levels though. The productivity of N is low at the optimal levels estimated in the Base scenario. Further, the amount of dry matter decreases at a lower rate than the plant uptake of N as the level of fertilizer N decreases. In the Tax200 scenario average grain yields are estimated to be about 5% lower per ha than those in the Base scenario. For grass production the reduction is about 10%.

Reducing grass production may lead to problems for the farmer. (S)he may substitute hay or silage for grain. But there are physiological constraints involved making it costly to do this to a large extent. These cost relations are handled in the model by an increase in the value of roughage as the volume decreases. This induces a varied pattern of response since the model farms are constrained differently. Model farm 1.1 decreases the fertilizer level most – from about 180 to 80 kg/ha going from Base to Tax200. In this case the model farm has a rather substantial grain area and thus no binding constraints on the area of meadow. Under the tax schemes, it becomes optimal to reduce the N level in grass production heavily and reduce the grain area to compensate for the reductions in grass yields. This way the overall reduction in total grass production is kept at a level of about 8-9%.

Model farm 1.3 is in the opposite position. Here the number of cattle per ha is so high that the farmer has to buy roughage already in the Base scenario. The fertilizer level is reduced from about 200 (Base) to 130 kg/ha (Tax200) keeping the reductions in dry matter at about the same relative level as for model farm 1.1. For model farm 1.3 it is no option to increase the acreage of meadow.

The different patterns of reactions follow from variations in the cost structures. Model farms 1.1 (50% meadow), 1.3 (80% meadow), 1.4 (hog/grain), 1.5 (hog/grain), 1.7 (grain only) and 1.8 (grain only) illustrate some of the tendencies.

Table 8.1: Changes in N-leaching (Δ N) and costs (NOK)[1] as compared with the Base scenario. Some model farm estimates, Auli.

	Tax100				Tax200			
	Δ N	Costs farmer		Soc. abatem. costs	Δ N	Costs farmer		Soc. abatem. costs
	kg/ha (%)	NOK/ha	NOK/kg ΔN	NOK/kg ΔN	kg/ha (%)	NOK/ha	NOK/kg ΔN	NOK/ΔN
Model farm 1.1	-10.5 (28)	610	58	18	-15.3 (41)	1040	68	34
Model farm 1.3	-8.7 (22)	370	42	8	-14.6 (38)	560	38	21
Model farm 1.4	-3.7 (9)	510	139	46	-7.3 (17)	820	112	37
Model farm 1.5	-4.6 (9)	340	73	12	-18.6 (38)	540	29	14
Model farm 1.7	-5.1 (13)	650	129	10	-9.3 (24)	1240	133	17
Model farm 1.8	-5.6 (15)	640	115	5	-9.6 (26)	1230	128	14

1) Norwegian kroner

There are three main observations to be made:

- The reductions in leaching are on average highest on animal farms, especially at the Tax200 level.
- The five chosen model farms show rather high variations in *social abatement costs*. Still these costs tend to be higher on farms with animal manure than on specialized grain farms.
- Farms with animal manure and/or meadow have substitution possibilities generally resulting in lower *costs for the farmer* than for specialized grain farms.

Most real costs in grain production are related to reduced yields. These changes are rather small according to our analyses. For farms with animal manure the tax makes it profitable to change manure handling practices. Some of these changes are rather costly, explaining the higher average social abatement cost level on these farms. The variation between the model farms with manure is to a large degree explained by variation in the pattern of changed manure practices.

Table 8.1. shows that the tax burden is highest on specialized grain farms, while the effect on leaching is on average the lowest there. The picture is not uniform though. Model farm 1.4 diverges substantially from the other animal farms. Here, no major substitutions between mineral- and manure-N becomes profitable even at the 200% tax level. Since reductions in losses turn out to be especially low on this specific farm type, it displays the highest costs per kg reduced N-leaching of all, both private and social costs.

8.2 Changes in manure utilization practices

To get better insights into the varying adaption patterns on animal farms, we will look more closely at the changes in the manure utilization practices. There are three types of alterations in the manure spreading system that are handled by ECECMOD:

- Increased storing capacity; from 8 to 10 or 12 months capacity
- Changes in spreading technology; from tank trailer to a pipe system. While for tank trailer both slurry and semi liquid manure is an option, the pipe system only spreads the semi liquid quality (100% water added).
- Reductions in time from spreading to incorporation of manure in the soil; alternatives are the end of every day or every second day.

In our opinion this covers the most interesting strategy options, at least if we limit ourselves to technologies generally available today. Increasing storing capacity has two effects. More of the manure will be applied in the plant growth season, reducing losses during fall and winter. Further, if tank trailer is used, soil compaction may be reduced since spreading in fall can be avoided. This is especially important in grass production where there is no soil tillage after spreading. Further, the compaction problems are highest in the fall, even though the problem probably is less severe in our landscapes than in more humid parts of the country. Less compaction results in reduced leaching through better conditions for plant growth and nutrient uptake.

Changes in spreading technology can also be divided into two dominating effects. Adding water means less losses to air. This effect is independent of the spreading equipment in itself and reduces the need for buying fertilizer N. The effect is largest in meadow. Increased infiltration also reduces the potential for surface runoff, while it actually may increase leaching. This happens if spreading is undertaken also in the fall. A larger percentage incorporated means larger volume potentially lost. One must remember, however, that adding water using tank trailer, will increase compaction, since it increases trafficking on the fields. But even compaction problems may be reduced by the choice of equipment. Changing to a pipe system has this effect, reducing losses through increased plant uptake.

Reduced time between spreading and tillage has the same effects as adding water to manure. Losses to air and through surface runoff are reduced, while again there exist a potential for larger leaching if conducted in the fall.

Modelling all these mechanisms correctly, demands estimation of parameters for each relationship specified for the various weather and soil conditions (see appendix A2, A4 and A5). The results obtained by such a differentiation contradicts somewhat the results from earlier analyses for Norwegian conditions (Christoffersen and Rysstad 1990; Simonsen, Rysstad and Christoffersen 1992). This is especially the case for a switch from ordinary slurry to semi liquid manure (100% water added). We observe in our analyses a much lower fertilizer effect of this change than was previously assumed (ibid.). This may be related to the fact that these authors do not differentiate between the ammonia effect and the compaction effect. They use results from trials where the effect is measured as total effect on yields. Handling ammonia evaporation and soil compaction separately yields distinctly different insights. Exploring this, we will start with the results for the model farms with milk/beef production in Auli. Technology changes – in this case compared to the S-1992 scenario – are highlighted in the table.

Table 8.2: Changes in manure technology following a change in N price. Model farms 1.1 - 1.3: Milk/beef.

	Base	Tax50	Tax100	Tax200
Model farm 1.1				
Storing capacity	8 mo.	8 mo.	**12 mo.**	12 mo.
Spreading equipment	Tank tr.	Tank tr.	Tank tr.	Tank tr.
Time to incorporation	18 h	**3 h**	3 h	3 h
Model farm 1.2				
Storing capacity	8 mo.	8 mo.	8 mo.	8 mo.
Spreading equipment	Tank tr.	Tank tr.	**Pipe syst.**	Pipe syst.
Time to incorporation	18 h	18 h	**3 h**	3 h
Model farm 1.3				
Storing capacity	8 mo.	8 mo.	8 mo.	8 mo
Spreading equipment	**Pipe syst.**	Pipe syst.	Pipe syst.	Pipe syst.
Time to incorporation	18 h	18 h	18 h	**3 h**

While all model farms chose 8 month storing capacity, tank trailer and incorporation after 2 days (18 h in average) in the short run (1992 scenario), model 1.3 changes to a pipe system already with economic and political conditions as in the Base scenario. As earlier emphasized the N price is lower in Base than in the S-1992 scenario. The adaption thus follows just from changing from a short to a long run perspective and is motivated first of all by the lesser compaction effect. This is environmentally desirable, and is a "win-win" situation since no special political measures are needed to obtain this effect. The private gain is sufficient. We further see that introducing taxes produces no changes on this type of farm before we approach the highest tax level.

Model farm 1.3 has most of its land in grass production. The other two model farms in table 8.2 have much more grain. The problem with soil compaction is less prominent, explaining the difference in adaption patterns. The main changes for model farms 1.1 and 1.2 take place somewhere between a 50 and 100% tax. While model farm 1.1 changes to 12 months storing capacity, model farm 1.2 converts to a pipe system for spreading. Again this is logical since the volume of meadow is highest on model farm 1.2.

Looking at the overall pattern, taxes have obvious effects, but there seems to be a rather low potential for using taxes to motivate farmers to change to the environmentally most favorable system – a combination of storing facility with 12 months capacity and a pipe system for spreading. This is due to the fact that choosing one of the options heavily reduces the private gain by also choosing the other. If 12 months storing capacity is the most favorable to choose as taxes increase, there are small private incentives left to also turn to the pipe system since the difficult compaction problems are already counteracted. For those choosing the other avenue, all compaction effects are removed, cutting the private gain with a full year storing to approximately the half.

Table 8.3: Estimated N losses, leached (nitrate) and to air (ammonia), for model farms 1.1 - 1.3 (milk/beef) for different scenarios (N tax levels), kg/ha.

	Base	S-1992	Tax50	Tax100	Tax200
Model farm 1.1					
Nitrate-N: Total	37.1	35.2	32.9	26.6	21.8
Δ Base		-1.9	-4.2	**-10.5**	-15.3
Ammonia-N: Total	9.3	9.3	6.4	2.9	2.9
Δ Base		0.0	-2.9	**-6.4**	-6.4
Model farm 1.2					
Nitrate-N: Total	37.8	35.9	34.0	29.6	24.4
Δ Base		-1.9	-3.8	**-8.2**	-13.3
Ammonia-N: Total	16.1	16.1	16.1	7.6	7.5
Δ Base		0.0	0.0	**-8.4**	-8.5
Model farm 1.3					
Nitrate-N: Total	38.7	39.8	33.9	30.0	24.1
Δ Base		**1.1**	-4.8	-8.7	-14.6
Ammonia-N: Total	21.1	43.1	20.7	20.6	19.8
Δ Base		**22.0**	-0.4	-0.5	-1.3

The effects of the changes in technology can be studied in table 8.3. We differentiate between leaching (nitrate-N losses) and losses through evaporation (ammonia). Effects clearly related to changes in the manure practices are highlighted. Scenario S-1992 is included to show the special effects for model farm 1.3. We observe a rather substantial reduction in losses to air going from the S-1992 scenario to Base in this case. The Base scenario also shows reduced leaching in this case even though overall fertilizer intensity is higher in the Base than in scenario S-1992 (the 20% N tax in 1992). Going from tank trailer to a pipe system decreases soil compaction which in this case turns out to have a larger effect on leaching than the change in intensity following a lower N-price. Comparing with the other model farms in table 8.3, the net effect of reduced compaction seems to be about 3 kg N/ha.

Generally, the effect of changes in manure practices on leaching are somewhat difficult to isolate since an increased N price also reduces fertilizer intensity and induces substitution to clover in grass production. Since there is no change in manure practice from Base to the different tax scenarios for model farm 1.3, this farm gives an indication of the intensity and clover effect. From this we can conclude that the separate effect of the induced changes in manure handling practices are largest for the ammonia losses (Tax100) both for model farm 1.1 and 1.2 . As assumed, this effect is greatest for a change to the pipe system (model farm 1.2). On the other hand we observe that a change to 12 month storing capacity (model farm 1.1) gives a larger reduction in leaching than a change to the pipe system (model farm 1.2). The negative compaction effect is removed in both cases while full year storage capacity also removes the losses of manure N in the fall.

The reasoning so far indicates that since soil compaction problems are less in grain production, taxes do not provide the same motive to make changes in the manure practice on animal farms dominated by grain production as those with much meadow. This is supported by the results for model farms 1.4 - 1.6.

Table 8.4: Changes in manure technology following a change in N price. Model farms 1.4 - 1.6: Pigs/poultry/grain.

	Base	Tax50	Tax100	Tax200	Tax100M
Model farm 1.4					
Storing capacity	8 mo.	8 mo.	8 mo.	8 mo.	8 mo.
Spreading equipment	Tank tr.	Tank tr.	Tank tr.	Tank tr.	Tank tr.
Time to incorporation	18 h	**3 h**	3 h	3 h	3 h
Model farm 1.5					
Storing capacity	8 mo.	8 mo.	8 mo.	**12. mo.**	8 mo.
Spreading equipment	Tank tr.	Tank tr.	Tank tr.	Tank tr.	Tank tr.
Time to incorporation	18 h	**3 h**	3 h	3 h	3 h
Model farm 1.6					
Storing capacity	8 mo.	8 mo.	8 mo.	8 mo	8 mo.
Spreading equipment	Tank tr.	Tank tr.	Tank tr.	Tank tr.	Tank tr.
Time to incorporation	18 h	18 h	18 h	18 h	**3 h**

Increased N price gives fairly small changes in manure practices. Reduced time till incorporation is observed at the 50% tax level for model farms 1.4 and 1.5. According to the model, it seems necessary to increase taxes fairly much to make it favorable for the farmer to turn to 12 months storing capacity. In scenario Tax200 this is achieved for model farm 1.5. Both model farms 1.4 and 1.5 have rather low amounts of manure per ha. Model farm 1.5 has the largest total volume of the two, explaining why the adaption takes place first here.

Model farm 1.6 is insensitive to a tax since it has more manure than is needed for optimal crop production. This farm has so much manure that it does not buy any fertilizer N even with an 8 month storage. Assuming a market for manure as in Tax100M gives a change though, since the value of manure N is increased making it favorable to reduce time till incorporation. Other model farms do not change their practices as a function of such a market except that some will substitute nitrate N with ammonia N in the spring. Tests done show that even a 200% tax level, will not motivate model farm 1.6 to enlarge the storing facility beyond 8 months even if there exists a market for animal manure. The potential for extra sales do not cover the costs.

Table 8.5 shows the effects on N losses. They are as expected. The effects of Tax100M on model farm 1.6 are substantial both concerning leaching and losses to air. As to the last loss, the figures for 1.6 cover all reductions, also those obtained while its manure is spread on other farms.

Table 8.5: Estimated N losses, leached (nitrate) and to air (ammonia) from model farms 1.4 - 1.6 (pigs/poultry/grain) at different N tax levels, kg/ha.

	Base	Tax50	Tax100	Tax200	Tax100M
Model farm 1.4					
Nitrate-N: Total	41.7	39.8	38.1	34.4	(38.1)
Δ Base		-1.9	-3.6	-7.3	(-3.6)
Ammonia-N: Total	9.2	3.7	3.7	3.7	(3.7)
Δ Base		**-5.5**	-5.5	-5.5	(-5.5)
Model 1.5					
Nitrate-N: Total	48.7	46.4	44.1	30.1	(44.1)
Δ Base		-2.3	-4.6	**-18.6**	(-4.6)
Ammonia-N: Total	11.6	4.7	4.7	5.7	(4.7)
Δ Base		**-6.9**	-6.9	-5.9	(-6.9)
Model 1.6					
Nitrate-N: Total	138.2	138.2	138.2	138.2	84.7
Δ Base		0.0	0.0	0.0	**-53.5**
Ammonia-N: Total	35.4	35.4	35.4	35.4	24.2
Δ Base		0.0	0.0	0.0	**-11.2**

The processes described so far can be summarized by looking at the effects on the estimated purchase of mineral fertilizer N as in table 8.6. Model farms with meadow (here 1.1 - 1.3) reduces its total N use more than other farms in absolute terms as taxes increase, illustrating the effects of rather flat yield functions for grass, and the various substitution possibilities on such farms. We further observe that all model farms with manure (here 1.1 - 1.5) reduce the level of purchased N more than specialized grain farms. The difference in absolute terms between model farms 1.4 and 1.7 is small though, since there are only minor changes in manure practice on model farm 1.4. While model farm 1.4 reduces purchase with about 30 kg/ha from Base to Tax200, a reduction of about 23 kg/ha is estimated for model farm 1.7.

Highlighted numbers relate to stages where changes in manure utilization contribute to extra large decreases in N purchases. Compared with the intensity reduction and substitution to clover N fixation (i.e. model farms 1.1 - 1.3), the manure effect is rather modest though. For model farm 1.1, about 10 out of a total reduction of 66 kg relates to the manure effect. For model 1.2 the figures are 7 to 63. The largest effect is on model farm 1.5 where half the effect relates to better utilization of N in manure.

Table 8.6: Total N levels and purchase of fertilizer N at different N tax levels, kg/ha. Selected model farms.

	Base		Tax100		Tax200	
	Total N	Purchased N	Total N	Purchased N	Total N	Purchased N
Model farm 1.1	139.1	110.5	110.4	**71.3**	83.6	44.6
Model farm 1.2	154.4	108.6	126.7	**74.4**	99.3	45.6
Model farm 1.3	176.0	80.2	147.4	51.0	118.8	21.6
Model farm 1.4	115.1	76.9	102.3	**58.7**	90.8	47.0
Model farm 1.5	117.1	67.0	104.3	**48.3**	95.1	**23.5**
Model farm 1.7	115.2	115.2	103.1	103.1	91.6	91.6

This indicates that on livestock farms with little or no meadow, a system with mandatory 12 month manure storing capacity should give higher reductions in N leaching than a 100% N tax. This seems to be confirmed by the analyses done. For model farms 1.4 and 1.5 there is even a tendency towards lower societal costs per kg N reduced leaching. While the societal costs for reduced N leaching are 46 and 12 NOK per kg in the Tax100 scenario (table 8.1), the costs in scenario Storage12 are 27 and 12 NOK for model farms 1.4 and 1.5 respectively.

For farms like model farm 1.6, a mandatory 12 months storing capacity has in itself little effect on leaching even if we assume that a market for manure exists, and societal abatement costs become higher in this case. It turns out that not much more manure will be sold than in a situation with an 8 month capacity. Given the existence of a 100% N tax, the situation seems different. Sales with mandatory 12 month storing capacity and 100% N tax is about 60% as high for model 1.6 as in the case with the same tax level, but no requirement on storing capacity. This has entirely to do with changes in the value of N.

To complete the picture, let us turn to the scenario with feeding practices reducing the level of N in manure – FeedingB. As pointed out earlier, this is a cheap strategy, but with rather small effects on leaching. Actually it is only on model farm 1.6 – farms with heavy manure N loads – that any substantial effect can be observed. Here average N leaching is reduced with 30 kg per ha from 138 to 108 kg in total. This is as expected, since with our assumptions about the use of manure, a reduction in N content will only have substantial effects on farms with no purchase of mineral N.

Reducing the content of N in manure diminishes its value, though. From this one should expect less response to a fertilizer tax given this otherwise positive change. This is excellently demonstrated by the response of model farms 1.1 and 1.2 to a combination of Tax100 and FeedingB. Both model farms have larger leaching in the combined scenario than in Tax100. The changes to 12 month storing capacity (model farm 1.1) and to a system of pipes (model 1.2) occurring in Tax100 (normal feeding) is not profitable any more with manure N levels given by FeedingB.

While we observe that counter effects may occur in our search for better solutions, the above example also shows how sensitive the results for manure handling are. This is already illustrated by the very diversified pattern of adjustments over model farms which we believe cover real life variations causing substantial differences in social costs. The observation further indicates that not only variation in farm structures, but also varying assumptions about the level of costs for different factors of production, will influence the results. First of all, the differences in farmers costs between the practices studied are often rather small. Second, studying manure utilization practices is a study mainly of discrete choice problems. Such choices are more difficult to model and the results more uncertain than those for continuous choice problems like fertilizer intensity. The results obtained still seem to be consistent and follow an expected pattern.

The choice rules adapted by the farmers are also very important for the results obtained. We would like to close this section with an observation relevant for milk/beef producing farmers. While studying the effects of different tax levels we soon learned that on such farms the adaption of pipe lines for manure spreading had a profound effect on yields because of less soil compaction. Since we modelled a profit maximizing farmer, this brought about two counteracting reactions. First, we observed that the marginal value of grass/hay was reduced due to its increased volume, making it profitable to reduce the level of N. Second, the marginal productivity of N increased, making it profitable to use more N. For some model farms this resulted in a net increase in N levels. On others the level was lowered giving only minor aggregated effects.

If we had assumed that the farmer does not maximize profits, but has a rather fixed need for roughage, we would have observed a very different adaption. In this case one would experience a rather substantial reduction in the level of fertilizer N with large reductions in leaching as the final result as a combination of increased ha yields and a rather flat production function with respect to N fertilizing. Milk production is regulated by individual farm quotas in Norway. This fact makes the alternative pattern of reaction more probable at least in areas with small alternatives for other crops than grass.

8.3 Catch crops

The effect of introducing catch crops turned out to be rather substantial in all landscapes. In the rules formulated for the mandatory catch crop scenarios, English rye-grass in grains and meadow are accepted as such a crop. Thus farms with meadow in the Base scenario will more easily meet the requirement than farms with only grain production. Winter wheat is not accepted as a catch crop, forcing the farmers to abandon it in scenarios with a 100% catch crop requirement.

The effect of catch crops in grains is due both to the extra N uptake after the main crop is harvested and the immobilization effect as organic matter is incorporated into the soil when plowing. The amount of N in the catch crop is estimated on the basis of trials (see appendix A5.5). The empirical research in this field has been going on for a rather short period, implying that there are larger uncertainties related to this part of the modelling as compared with that undertaken for ordinary crops. The N uptake is differentiated between year and areas on the basis of the temperature sum from the grain is harvested till the end of october.

The costs of using catch crops in grain can be divided in three:

- Catch crops compete with the main crop for nutrients, water etc. The expected reductions in yields are estimated on the basis of trial data (see appendix A5.4).
- The farmer experiences extra costs for seeds, sowing and fertilizers (appendix A4.1)
- Catch crops may force the farmer to use soil preparation methods that otherwise are not optimal.

The extra fertilizer costs relate to the immobilization effect of the catch crop. It results in reduced mineral N levels in the soil in the plant growth season, changing the conditions for crop growth. It thus becomes necessary/profitable for the farmer to add extra fertilizer N in the spring.[12] The immobilization effect is estimated by SOILN-NO and is on average at a level of 5-6 kg N per ha and year at least for the first 20 year period of such a regime.

We have previously stated that all scenarios, except S-1992, is conducted under long run assumptions. There is one exception from this, relating to the above mentioned effect of catch crops on the mineralization of N in the soil. In a short and intermediate time frame, catch crops will reduce net mineral N in spring and summer. In the long run – after some decades – the net effect is likely to become positive. In the modelling conducted here, we have chosen to model the catch crop as if it were introduced in year one of our study. This results in some extra costs for this measure as compared with the long run situation because of the extra need for fertilizer N. At the same time it most probably overestimates the potential for reducing

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[12] Adding fertilizer N is also necessary to secure consistency in the natural science modelling too, as explained in chapter 6.

leaching in the long run due to the gradual increase in the organic N pool. This effect is most probably small – partly because the farmer may adjust his N-level accordingly.

To cover the main tendencies in the material, four model farms are chosen for the presentation. Model farm 1.2 represents the grass producers, model farm 1.5 the combined hog/grain farms and 1.7 and 2.3 the specialized grain farms. Table 8.7 shows the estimated levels for N-leaching for 0, 50 and 100% catch crops.

Table 8.7: Estimated N-leaching (nitrate) for different levels of mandatory catch crops. Selected model farms, kg/ha.

	Base	Catch50	Catch100
Model farm 1.2			
Total	37.8	37.8	31.2
Δ Base		0.0	-6.6
Model farm 1.5			
Total	48.7	34.3	11.2
Δ Base		-14.4	-37.5
Model farm 1.7			
Total	38.0	22.1	14.0
Δ Base		-15.9	-24.0
Model farm 2.3			
Total	25.3	14.6	8.6
Δ Base		-10.8	-16.7

Before interpreting the results, it should be mentioned that due to variations in field sizes, model farms 1.5 and 2.3 fulfill the 50% requirement in Catch50 with an average of 53 and 58% catch crops, while model farm 1.7 hits the 50% level exactly. To simplify the comparison, the levels for 1.5 and 2.3 are adjusted in table 8.7 as if they also had reached the targeted level precisely.

Model farm 1.2 has about 60% of its land in ley. Thus the effect of mandatory catch crops is very modest here – no effects on leaching in Catch50 and reductions of about 17% in the 100% case. For the grain farms the effect is naturally much greater. Starting out from very different levels of leaching, these farms reach approximately the same state in Catch100.

Catch crops thus seem to have a large capacity for reducing leaching in grain. The result obtained by model farm 2.3 seems to represent a kind of floor. Since silt is the dominant soil on this model farm (80%), one would suppose that an extra gain could be obtained by changing the practice from fall back to spring tillage. As earlier pointed out, fields with catch crops are always plowed in fall in our analyses. This practice, however, reduces yields on silty soils with about 4%, reducing plant uptake of N with approximately 6 kg per ha. Analyses show, however, that this loss in yields increases leaching only marginally. A test on model farm 2.3 with catch crops and soil preparation set as in Catch100, but with plant uptake as if spring plowing were undertaken, showed a decrease in leaching of about 0.8 kg per ha. Thus only about 10 - 15% of the reduced crop uptake is estimated to leach under the given circumstances.

The estimates for model farm 1.6 suggest that even for farms with large manure surpluses, a substantial effect may be obtained. In the Base scenario the average leaching from this model farm is 138 kg per ha. For Catch50 and Catch100 the estimates are 109 kg and 69 kg per ha respectively.

Since mandatory catch crops have a rather low effect on N leaching from farms with grass as the dominant crop, it may be interesting to combine a fertilizer tax with a catch crop requirement to also reduce leaching more substantially on this type of farms. One would presume that the effect of adding a tax to the system with catch crops would not change leaching much on specialized grain farms, making the effect low and maybe very costly too. Table 8.8 sheds some light on this issue, showing the effect on N-leaching of adding a 100% N tax to scenarios with various catch crop levels. The columns show the extra reduction in leaching in cases with no catch crops (Base − Tax100), with 50 % catch crops (Catch50 − Catch50Tax100), and finally with 100 % catch crops (Catch100 − Catch100Tax100).

As we see, the effect of a 100 % tax is diminishing with increasing levels of catch crops on all grain farms. A 100% N tax represents a reduction in the N fertilizer level of about 10-12 kg per ha on the actual farms. This reduction in the fertilizer level reduces leaching with about 4-5 kg per ha in the case without catch crops (column 1). The effect is nearly halved in the situation with 100% catch crops (column 3). Still, it is far from negligible.

Table 8.8: The effect on N-leaching of a 100 % tax as a single measure and in combination with mandatory catch crops at different levels. Selected model farms. Differences in kg/ha.

	Base − Tax100	Catch50 − Catch50Tax100	Catch100 − Catch100Tax100
Model farm 1.2	8.2	8.2	8.1
Model farm 1.5	4.6	3.6	2.6
Model farm 1.7	5.1	4.2	2.5
Model farm 2.3	3.4	2.7	2.0

The results for model farm 1.2 deviates from the overall picture. The effect of the tax is both higher and remains constant whether combined with catch crops or not. Certainly, this has to be the case going from Tax100 to Catch50Tax100 since no catch crops are sown with a 50 requirement. The case with Catch100Tax100 is different though, with nearly 40% of the area covered with such crops. Still the separate effect is constant. The reason for this seems to relate to the manure handling system chosen at this model farm. At a 100% tax, the tank trailer is replaced by a pipe system (table 8.2). This causes more ammonia-N to be infiltrated. The isolated effect of this is, as earlier emphasized, an increase in the leaching as long as manure is spread in the fall. The use of catch crops seems to counteract this. The material shows a similar tendency for model farm 1.3 as it undertakes the same technological change. Thus the results are consistent. Model farm 1.1, which chooses to enlarge storing capacity for manure, shows a pattern more like the model farms for grain.

The social abatement costs will vary between farms since catch crops affect leaching and yields differently. Table 8.9 shows some of the tendencies.

Table 8.9: Social abatement costs for catch crops – as a single measure and in combination with a 100% N tax. Selected model farms, NOK per kg N reduced leaching.

	Catch50	Catch50Tax100	Catch100	Catch100Tax100
Model farm 1.2	0	22	19	20
Model farm 1.5	15	14	13	13
Model farm 1.7	19	17	32	31
Model farm 2.3	46	41	56	53

If we look at Catch50 and Catch100 first, we observe large differences in costs per kg N reduced leaching. The marked difference between the model farms of Auli and the one from Mørdre is due both to the lower absolute effect on leaching in Mørdre and the extra costs occurring on silty soils.

In most instances the estimates show that social costs decrease if a tax is added to the catch crop regime. This shows that even if the catch crop reduces the separate effect of a tax, the social costs are still lower than those caused by the catch crop itself. In grains the social costs per kg reduced N-leaching are on average about 10-15 NOK if a 100% tax is used. If such a tax is introduced together with 100% catch crop, the social costs for its separate effect increase to about 20-30 NOK compared with the catch crop – which according to table 8.9 has average costs varying from 13-56 NOK. Here we are at a stage where the chosen price level for the crops may influence the conclusions, though. Lower product prices (i.e. world market prices) would reduce the social costs of catch crops more then that of an N tax.

A solution with mandatory 100% catch crops is beyond what may seem a practical proposal. The analyses show, however, that even at that level, a combined solution with catch crops and an N tax does turn out to have rather positive efficiency properties. The problems occur as we turn to the distributional effects. While the tax is most costly for specialized grain farmers, this group also has to bear the largest costs in the case with catch crops. In combination the burden is doubled – which is also the message from table 8.10.

The tendencies are somewhat exaggerated though, since the costs for model farms 1.7 and 2.3 lie above the average for grain farms. It goes without saying that hog/grain farms where no major substitutions towards better manure utilization takes place, end up in the same situation as the specialized grain farms. This is the case with model farm 1.4.

Table 8.10: Farmers' costs for using catch crops – as a single measure and in combination with a 100 % N tax. Selected model farms, NOK/ha.

	Catch50	Catch50Tax100	Catch100	Catch100Tax100
Model farm 1.2	0	600	130	730
Model farm 1.5	210	540	470	830
Model farm 1.7	300	960	780	1450
Model farm 2.3	500	1170	940	1630

The tendency is very clear if we compare with farms with milk production – here model farm 1.2. For this farm most costs are inflicted by the tax. This is generally the tendency for the model farms of this type in our areas, since the volume of catch crops is rather low even in the Catch100, as earlier emphasized.

Even model farm 1.6 faces rather low costs. The levels are estimated to be 290 and 590 NOK in the 50 and 100% catch crop regimes respectively. This is due to the fact that this farmer bears no tax burden at all in the analyzed systems. It may certainly be a problem that the type of farms polluting the most has to bear the lowest private costs.

9 Policy measures – precision vs transaction costs

So far we have explored the dynamics, emission reduction capacities and cost aspects related to various policy measures. We have observed large variations in effects and efficiency properties across productions and natural conditions. If we had expanded our analyses to also cover variations in the damage functions between different recipients, variations in efficiency properties would have become even more evident.

In this chapter our aim is to discuss more principally the trade-off problem between high precision and increased transaction costs that was introduced in chapter 3. We will look at some of the policy measures already analyzed and discuss their potential for differentiation. We will also discuss briefly the type and level of transaction costs related to these instruments and examine some of their distributional aspects.

9.1 Policy measures and differentiability

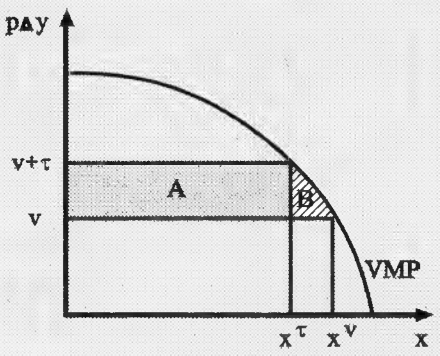
Emission regulations like effluent charges/tradeable permits or standards are of little or no practical relevance in our case. Thus the scenarios have basically covered two types of policy measures: Input taxes or prescriptions/subsidies for environmentally more favorable agronomic practices. We have also looked at some effects of subsidizing such practices. Certainly subsidies, prescriptions and taxes have different distributional effects and influence exit/entry considerations. This last issue is not further discussed here.

In situations where emissions are practically unobservable, it may still be possible to estimate relationships between emissions and the various elements of the chosen management practices like input levels and production processes under varying natural conditions. Our analyses in chapters 6, 7 and 8 are in some respects examples of the kinds of information necessary to establish such connections on a modelling basis. Given the relationships between emissions and management practices, economic incentives like taxes or subsidies could be attached to these practices, constructing a device imitating effluent charges. This option is discussed by Griffin and Bromley (1982).

High precision would demand establishing relationships between practice and leaching, and tax schemes specific for each firm, covering the variations between management practices/input use and emissions over the firm's activities and resource base. In our case differentiations between practices over both soils and crops would be highly relevant, thus making the level of the management taxes (or subsidies) very specific.

Infobox 9.1: Input taxes

Mechanism: Increases the cost for the farmer of using the input. If returns to scale are decreasing, this will motivate the farmer to reduce use, inducing lowered emissions as long as they are positively related to the input level. With the value of the marginal product (VMP) and the input factor price (v), as described in the figure, optimal factor use would be x^v. Increasing the price to the farmer by a tax τ would reduce optimal fertilizer use to x^τ.



The tax will also induce substitutions with other inputs. If these are taxed relative to their environmental effects, this constitutes no problem.

Potential for differentiation: Low or non existing. Differentiating taxes between regions implies that farmers in areas with low taxes may earn money from selling the input to regions where taxes are higher. This will in principle drive the tax level down towards the size in the area least taxed plus transportation costs. Some differentiation will normally prevail due to transport and transaction costs.

Transaction costs: Given standard assumptions, these will be low. Taxes may be collected at the level of production (inland) and on imports if the tax is differentiated between countries. There are two problems to observe though. The potential for "black markets" between countries increases transaction costs. Second, taxes may induce rather substantial fiscal effects for those using the taxed input. This may create difficult political processes around establishing, enforcing and maintaining such systems.

Distributional effects: The volume of the tax is related to several factors where the productivity/the functional relationship between the inputs and the outputs are important. In the case of mineral fertilizer taxes the relationships are such that distributional effects are substantial – especially in grains.

Large monitoring and administrative costs would most probably make policies with such high resolution very costly and thus inefficient. An alternative could be to make incentives equal for all firms (or groups of firms) in an area – i.e. using less partitioned relationships between managements practices, natural conditions and emissions. This way the cost of establishing the system would be reduced, but it would still be necessary to monitor the behavior of each firm to decide upon the taxes (or subsidies) to be paid as a function of chosen practices. The more variables to control, the higher the costs of developing and running the monitoring system.

In agriculture, even such a system would normally be too costly. More crude measures – like prescribing or taxing/subsidizing a (few) practice(s) in a region – may compete well if the costs do not vary too much over the various firms and natural resource base in the region. Such strategies would reduce monitoring costs. The potentially negative dynamic/long run effects of such systems are, however, unclear.

Input taxes seem to display the lowest transaction costs of the alternatives analyzed in this study – still these costs are not zero, as will be discussed later. The problems with such a policy are two fold. First of all there must exist a relationship between input use and emissions. In the case of phosphorus emissions those are found to be very weak and an input tax would not serve the goal of reducing losses. Second, it is a problem that an input tax cannot be (much) differentiated over a continuous market due to the potential for a "black" market between agents in low and high taxed areas, which would eliminate the effect of differentiation. In areas with substantial transport distances between the various tax level regions, some differentiation is possible to maintain due to the transportation costs.

Thus the strength of management taxes/subsidies or prescribed practices versus input taxes is their potential for being differentiated – not only regionally, but also between firms of various classes. The trade-off between precision and transaction costs is made by determining the size of the regions and/or the classes of firms.

Infobox 9.2: Management taxes/subsidies

Mechanism: Utilizes in principle the same type of incentives as an input tax. The farmer is faced with a set of charges differentiated over the various elements of the agronomic practice according to their potential for environmental damage and/or subsidies related to their conceivable positive effect. This way the total cost of each practice is reflected in the prices farmers face.

Potential for differentiation: In principle no restrictions on differentiations since the attributes that the incentive corrects are firm specific.

Transaction costs: These costs are largely related to the specification and resolution levels of the incentive system. Not all practices need to be taxed/subsidized relative to their effects. Certainly, it may be beneficial to concentrate only on those practices with the largest consequences. There may be substantial control problems related to this strategy because important variables may be difficult to observe/may demand farmers' cooperation – i.e. moral hazard problems may occur. Further, high degree of specificity may reduce motivations for cooperation.

Distributional effects: Difficult to determine in general. Depends heavily on the existing cost relationships and substitution possibilities, and how the rights structure is defined (taxes or subsidies).

Tradeable input factor quotas or permits is an incentive based system that has a somewhat larger potential for regional differentiation than a tax. In principle there exists motives for black markets to evolve here too, but the system establishes some extra transaction costs compared to the tax case reducing this potential. By restricting the right to sell to the region where the permit is issued and distributing permits over all accepted permit holders according to their acreage, each holder will get a right to buy volumes that will not be very different from what is optimal for her/him to use. In such a regime, a "black market agent" needs to undertake several small transactions before (s)he is able to collect a large enough permit volume to gain any income from transporting and selling the input factor in another region. A limit on how much each permit holder could buy from others would impose further restrictions on inter regional sales without destroying the functioning of each regional market.

9.2 Transaction costs and precision – the case of fertilizer taxes and mandatory catch crops

The most focused policy measures in this study have been a tax on mineral nitrogen fertilizers and a system with mandatory catch crops. To complete the picture already presented, we will look more specifically at some aspects of precision and transaction costs related to these types of measures.

As we have seen, it is difficult to obtain much differentiation across a country in the case of an input tax on a tradeable good like fertilizers, in contrast to mandatory catch crops allowing such differentiations. A medium sized nitrogen tax (50 - 100 %) seems to compete well with catch crops in the areas we have studied, assuming that the environmental effects are similar in all three landscapes. It may still be that if there exist large areas in Norway where restrictions on N use is economically not defendable, maybe due to low levels of environmental damages caused by nutrient losses, the costs induced in these areas by using a tax may well outweigh the gains obtained elsewhere.

In general, if the efficiency of a policy measure that cannot be differentiated varies over its area of jurisdiction, one has to make a trade-off between the losses incurred in regions where reductions in emissions *ceteris paribus* becomes too high and areas where the opposite occurs. In such a situation, a differentiable policy measure that is less efficient than an undifferentiable policy measure in all regions viewed separately, may turn out to be better when all regions are viewed as a whole.

Let us clarify by looking at two areas. Let the social gain related to an input tax T in a region A be denoted $f_A(T)$ and similarly $f_B(T)$ in region B, and f_A and f_B both be concave. Let the optimal tax in A be denoted T_A^* and in B denoted T_B^* with $T_A^* \neq T_B^*$. The total gain for both areas of a tax T is $U = f_A(T) + f_B(T)$. If differentiating the tax level is impossible, the highest total gain is captured when:

$$\frac{\partial U}{\partial T} = \frac{\partial f_A}{\partial T} + \frac{\partial f_B}{\partial T} = 0 \qquad \text{and} \qquad [9.1a]$$

$$\frac{\partial^2 U}{\partial T^2} = \frac{\partial^2 f_A}{\partial T^2} + \frac{\partial^2 f_B}{\partial T^2} < 0 \qquad [9.1b]$$

From [9.1a] it follows that the optimal solution occurs where the sum of marginal gains/losses in the areas equals zero.

Let the gains obtained by using a certain mandatory practice like catch crops in the two areas be R_A and R_B respectively, and assume that this strategy does not compete well in any area given optimal tax levels, i.e.

$$f_A(T_A^*) > R_A \quad \text{and} \quad f_B(T_B^*) > R_B \qquad [9.2a]$$

Let the uniform optimal tax from [9.1] be T^*. It may then be that

$$f_A(T^*) + f_B(T^*) < R_A + R_B. \qquad [9.2b]$$

This only depends on the size of the relative losses, which must be empirically judged.

The generally higher transaction costs in the case of mandatory and differentiated practices, increase the chance that the inequality in [9.2b] changes sign. The problem is that these kinds of costs are very difficult to assess. This relates both to uncertainties about how well the farmers conform with the rules, which types of control technology are available and may work well, which technology developments are possible etc.

The motives for farmers not to conform to a requirement, relate both to the costs it induces, the chance to be detected if the law is violated and the level of punishment. It is very important how the requirement is perceived by the farmers, whether or not it is found to be a fair requirement and conforms with their ideas of what is sensible to do (Vedeld 1996). In situations where the rules become well accepted also among farmers, the internal control mechanisms amongst them may reduce the control problem from the perspective of the regulatory agency (Lowe and Ward 1996).

Still, public monitoring and control systems will be needed. In the case of a catch crop requirement, monitoring could in principle be undertaken with very different systems ranging from local, in person control with the help of random spot checks to GIS based satellite control systems. The costs would not, however, restrict themselves to running such systems. They would also have to cover resources used to punish persons violating the rules etc.

Infobox 9.3: Prescribed management practices

Mechanism: Force farmers to utilize certain practices. Motivation need not exclusively work through the threat of punishment. In the context of "good management practices," farmers may internalize the defined rules as norms for good behavior. Still, one would suppose that the potential influence of such a mechanism depends upon the economic losses.

Potential for differentiation: In principle as high as for management taxes – i.e. it can be differentiated down to the firm level/productions/soils etc.

Transaction costs: In general higher than for input taxes and lower/similar to that for management taxes. Control systems have to be set up that are not needed in the input tax regime. Prescribed practices and management taxes/subsidies may have approximately the same transaction costs properties as long as they are restricted to the same practices. Still the authorities do not need to put resources into the fiscal transfers in the case of prescribed management practices.

Distributional effects: The real costs for the farmer will tend to be higher than in the case of management taxes/subsidies since (s)he cannot chose the most optimal solution for the actual farm. This difference is certainly reduced if the tax/subsidy is related to the same restricted set of practices as the system with prescriptions. There will be no taxes to pay or subsidies to receive.

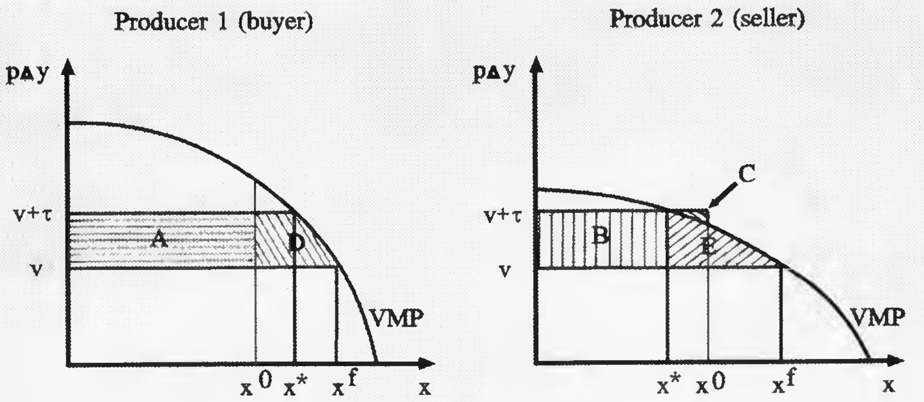
Thus to assess potential costs is extremely difficult. To see this, consider the current land use situation in Norway. The average size of the farms in South-Eastern Norway, where a catch crop requirement is most relevant is of about 15 ha. If transaction costs amounts 150 NOK per farm, it implies an increase of total abatement costs at about 1 NOK (5 %) in the case of a 50 % requirement and 0.5 NOK (2 %) if the requirement is 100 % (confer table 7.9). Since much of the information needed to execute control is already available, we have good reasons to believe that it should be possible to get below this level. By setting an acreage limit on farms involved in the program, costs could be further reduced.

An important argument against catch crops, relates to farmers' motivation for getting the crop to grow well. The catch crop competes with the cash crop and reduces yields. Thus the farmer will be motivated to reduce the amount of catch crop seed used, and since the growth of the crop also depends on weather factors, it may be difficult to say what has caused an occurrence of a bad catch crop. It could thus be difficult to formulate a clear and fair rule for when a field is considered catch cropped or not.

In the literature, it is often argued that market incentives are very competitive also because transaction costs are low. To some extent this only restates the fact that transaction costs are often not analyzed or are implicitly set to zero in the case of market transactions. A tax necessarily implies a lot of information gathering and processing both for administrators and farmers related to setting the right level and finding the best strategy for the farm. Further, a tax system may make it profitable to import fertilizers from a neighboring country, increasing control costs.

Infobox 9.4: Transferable input factor quotas

Mechanism: A per hectare quota of x^o is issued, yielding an aggregate quota of x^o times the acreage. This increases the marginal costs for the farmer of using the inputs believed to cause negative environmental externalities. In principle a transferable input factor quota works the same way as an input factor tax. This can be seen in the figure below, where VMP denotes the value of the marginal product curve, v denotes the input factor price, τ denotes the transferable quota price (or the input factor tax), x^f denotes the profit maximizing fertilization level without a tax or a transferable quota, and x^* denotes the profit maximizing fertilization level with a tax or a transferable quota price equalling τ.



The profit maximizing input factor use in the case of a input tax or transferable quota will in both cases be where the marginal input factor costs ($v + \tau$) equal the value of the marginal product ($p\ \Delta y$).

Potential for differentiation: Transferable quotas can be differentiated, but there is a limit to this differentiation. Consider a regionally differentiated quota. If the difference in the quota price in two regions is greater than the per unit transportation costs, it may be profitable for farmers in the region with the higher price to buy quotas from the low price region until the difference in the quota prices between the regions equals the transportation costs.

Transaction costs: These are of two kinds: (i) the costs agents incur searching for trading partners, and (ii) the costs of organizing the market. Provided that there is a publicly posted price for quotas, the search costs can be negligible. This requires that there is an organized commodity exchange. For ordinary goods such exchanges already exist, and work very much like a stock exchange. The transaction costs would then be limited to the service fees on trades, which generally would be low. Generally such fees would include a fixed portion (fee per trade) and variable portion (a percentage of the value of the amount traded).

Distributional effects: Compared to a tax on the polluting input, buyers of permits would obtain savings indicated by area A in the above figure, while sellers would obtain savings indicated by areas B + C. Compared to no regulation the extra costs incurred by buyers would equal the area D, while sellers would incur the extra cost indicated by area E less the area C (profits gained by the seller not offset by a loss in product volume due to reduced input factor use).

9.3 Distributional characteristics

Distributional characteristics of the various policy measures are important both directly and indirectly via their implications for resource use, exit/entry considerations etc. We will here restrict ourselves to highlighting some differences between taxes on emissions and input factors on the one hand, and taxes or tradeable quotas on input factors on the other.

9.3.1 Input taxes vs emission fees

Input or emission taxes will normally not have the same distributional effects, even in the special case where they are equally precise. Stevens (1988) shows that if the emission is characterized by increasing returns to scale with respect to the input, more fees will be collected in the case of an input tax as compared with a charge on emissions. With decreasing returns to scale the conclusion is opposite, while the two have equal effects in the case where returns to scale are constant.

To reach this conclusion, Stevens (ibid.) implicitly assumes environmental damages to be proportional to emissions. The dominant picture seems to be that the marginal damage cost function is increasing in emissions – i.e. the environmental cost of an extra unit of emissions is lower at low than high emission levels. In such a case, the above conclusion may hold even if emissions are characterized by decreasing returns to scale.

In the case with nitrogen emissions, we observe increased returns to scale. Thus the total tax volume of an input tax will be larger than what would follow if an emission tax was a feasible option. Since the emissions as a function of the N fertilizer level seem to be constant or even falling in a substantial proportion of the fertilizing interval (figures 6.1 and 6.2), the difference may be substantial. Looking at figures 6.1 and 6.2, we observe that emissions are not only dependent upon the N level but also the type of crop. Thus the *net effect* of the fertilizer level on emissions is, according to the model estimates, approximately zero for barley at a fertilizer level of 60 kg/ha and for wheat at about 90 kg/ha. Up until that level one may argue that relative to not fertilizing at all, fertilizing is positive for the environment, given that crops are grown.

This has some important policy implications. The character of the relationships between input and emissions will induce rather heavy taxes on farmers even in the case where the use is environmentally indifferent or positive. This is certainly an argument against the fairness of fertilizer taxes in spite their efficiency properties. A system with a *two tiered N price* related to purchase per ha would reduce this problem. It would produce some extra control problems, but make the input tax "mimic" an emission charge more closely. Another alternative would be to reimburse (some of) the taxes as lump sum transfers or increased product prices, which would actually be the market response.

In our analyses product prices are not changed as a function of the measures used. As long as these prices are politically set in Norway, keeping product prices constant in our analyses is justified. In cases where product prices would change as a function of the introduction of environmental policies, the distributional effects could be rather different from the ones discussed here. Since food products have normally very low price elasticities – much of the tax would be shifted to the consumers.

9.3.2 Fertilizer taxes vs transferable fertilizer quotas

Another alternative is transferable fertilizer quotas. To make this system equal to a tax, the total volume would have to be set at a level equivalent to the one following from a tax. If initial quotas were issued to farmers for free, there would be considerable cost savings to producers of such a system, while auctioning off initial quotas would make the government capture some of the rents from such quotas.

A system with transferable quotas could thus be used to reduce the distributional effects. Making the permits transferable, would further remove (some of) the efficiency losses that would arise if they could not be traded, since it will be impossible/costly to set the efficient quota for each farmer.

Assuming a smoothly working market for permits – actually zero transaction costs – efficiency is not influenced by the way permits are initially distributed. Through trade the fertilizers would be distributed to their most efficient uses. As described in infobox 9.4, there will be some income transfers between farmers though as an effect of this trade.

Both buyers and sellers will still be better off in this case than in the case of a tax. One would suppose, however, negative reactions even among farmers since those with abundant quotas will make money for free from selling something they are just given. In the policy process of forming such a system one would most probably observe pressure towards issuing permits that are as near as possible what is optimal for each farmer. This would incur extra transaction costs. Still one should not forget that even the quota market will not be free from such costs.

10 Discussion

10.1 Regulating inputs or the agronomic practice?

Nonpoint-source pollution like nitrogen leaching and soil erosion from agricultural land can hardly be regulated by emission oriented policy instruments due to the high costs of monitoring and control. In this study various policy measures related to input use or the agronomical practice in a broader sense have been analyzed. The basic goal of our study has been to increase the understanding of the potential of various measures to reduce losses of nitrogen, phosphorus and soil. The costs associated with each measure have also been studied.

10.1.1 Comparing various strategies

The analysis has covered reduced fertilizer intensity, the use of catch crops, changed tillage practices, split fertilization, changes in manure handling and in feeding practices. A complex picture has evolved, but there are also some dominant trends in the material to be observed.

Recall that desirable features of any policy instrument to reduce pollution from agriculture include:

- the least-cost way of reaching any targeted reduction in pollution levels, and
- incentive compatibility, i.e. the ability to induce farmers to behave in such a way that least-cost abatement is achieved.

This research started out asking whether a single measure like a tax (or tradeable quota) on nitrogen fertilizers could induce the required emission reductions both concerning N, P and soil losses. It should have the potential to reduce N-leaching directly through inducing reduced fertilizer intensity and changes in manure practices. Such a tax could result in increased use of split fertilization, and it might make catch crops economically interesting for the farmer. Through this last measure, even losses of soil and P could be substantially reduced through less erosion.

The analyses show that taxing the input does not have the wide range of capacities hoped for. An N tax will, according to our analysis, result in reduced fertilizer levels while it also induces environmentally favorable changes in the manure practices. It does not, however, affect split fertilization or the use of catch crops. At low to medium levels (up to about 100%) an N tax seems to be a fairly inexpensive strategy, though. Few other policy measures seem to be able to induce such reductions at lower social costs. Its effect is predicted to be largest on farms with milk/grass production, while the impact on leaching from grain producing farms is rather modest. In general it seems to be a problem that the effect of the tax on leaching is fairly low, i.e. a high tax level is necessary to influence leaching substantially. If so, the costs are increasing, and other measures become interesting options.

The main problem with the tax solution is the rather substantial distributional effects, as it also will charge uses of inputs that are not environmentally harmful. The distributional effects can be removed though, either by a scheme of reimbursement, through a system of tradeable permits or a two tiered price system. These strategies will all have their specific cost patterns as to administration and flexibility.

In specialized grain production reducing grain prices by 1/3 should in principle give the same decrease in leaching as a 50 % tax. In animal production the effect should be less due to different effects on manure handling. The modelling analyses confirm this pattern, showing moreover that such a change results in less environmentally friendly manure handling practices. Substantial effects of a price cut on environmental variables can mainly be obtained by cuts that reduce the size of the agricultural sector. The net environmental and distributional effect of this is a complex issue not discussed in this report.

Catch crops are, according to our analysis, a more expensive measure per ha or kg N reduced leaching than a low to medium high tax, measured in social cost terms. On clayey and sandy soils – the dominating soils in South-Eastern Norway – average social abatement costs per kg reduced N leaching is estimated to be about 50 % higher than for a 100 % N-tax. All costs are then born solely by the reduction in N leached. Our analyses predict, however, rather substantial reductions from a catch crop regime on soil erosion which a fertilizer tax does not generate. Further, it must be emphasized that the marginal cost of an N-tax increases rather strongly with increased taxes. The situation is different for mandatory catch crops. Here average and marginal costs are equal for large intervals. A catch crop regime will have lower distributional effects than an N tax.

A transition from fall to spring tillage – mandatory or induced by a subsidy – has the capacity to reduce erosion, while our analyses indicate no or low positive effects on N-leaching. The capacity to reduce erosion is substantial, still dependent upon topographical and soil characteristics. While reduced fall tillage turns out to be a cheaper and more effective measure towards reducing soil erosion than catch crops, the latter strategy may be preferable since it also affects N-leaching strongly. In total a larger positive environmental effect may be obtained by catch crops at the same level of social costs. The conclusion depends on the relative importance of the various types of emissions.

Strategies like changed feeding practices and split fertilization are also of some interest. Changes in the feeding practices, producing less excretion of N and P in manure, is an inexpensive strategy. Its effect on the environmental variables studied here is low, however, except in areas with high animal stocking rates. Split fertilization is not fully analyzed in this study, but its capacity to reduce N-leaching seems to be lower than expected, partly due to its negative effect on yields caused by additional trafficking. There is an important exception from this. On sandy soils, split fertilization turns out to have rather substantial effects on N-leaching. Given the types of sandy soils analyzed here, it further turns out to be profitable for the farmer to utilize this strategy at existing (1992) prices.

10.1.2 Choosing instruments

The picture that has evolved throughout this study, makes the choice of policy a difficult task. The cheapest strategy in the case of N losses – a medium sized N tax – has no effect on erosion. It cannot be geographically differentiated and thus adapted to variations in production patterns or environmental conditions. It has large distributional consequences. On the other hand, among the policy measures analyzed here, the fertilizer tax is the only instrument with any substantial potential for reducing nutrient losses in milk/grass dominated areas.

Catch crops and spring tillage – either mandatorily imposed or encouraged by a subsidy – are measures that can actually be differentiated down to the farm level if relevant. With respect to the precision of the environmental regulation this is a highly desirable feature. Neither of these measures, however, have any effect in areas dominated by milk/grass production. Whether a catch crop regime may also be interpreted as societally more costly than a medium (50-100 %) tax depends ultimately upon the character of the recipients and the relative importance of N-leaching, P and soil losses.

A combination of a medium sized tax and a catch crop requirement may seem to be the best compromise between conflicting goals. Since the catch crop requirement can be differentiated between regions, the important trade-off problem here relates to the tax level: The need to keep it fairly high in environmentally vulnerable areas dominated by milk production versus the extra costs invoked in grain producing areas or in areas with low environmental problems. In some situations, a combination of a tax and a regulation towards more spring tillage might serve best. Again, the capacity to differentiate when regulating the agronomical practice makes a switch from a tax/catch crop to a tax/spring tillage regulation feasible.

The extra social costs induced in some areas by a tax is a less important argument in the case of a medium sized as compared with a higher tax level since social costs are rather low. The distributional effects – especially the effect on income in grain production – will be substantial, however, even at the moderate level. Various compensation schemes have the capacity to counteract this effect. Using a system of tradeable N quotas will also reduce the distributional consequences substantially.

Generally we observe that the largest capacity to reduce losses lies in changed agronomic practices. This is illustrated both by the catch crop and spring tillage scenarios. Another illuminating example is the finding that in grain dominated areas one month delayed fall tillage is estimated to have the same effect on N-leaching as a 100 % nitrogen tax.

10.2 Uncertainties

10.2.1 Uncertainties in the technical relationships

When evaluating the above conclusions, one must have in mind the various uncertainties involved in a study like this. N-uptake by plants is one crucial factor. The modelling undertaken demands production functions for the various crops to be differentiated both by year and soil type in order to be reliable. The natural science modelling crucially depends upon these year specific yield functions. It is however only the yield *level* that is important. In the economic modelling, both *level* and *functional form* counts. Here, however, the average functions for the whole period – actually the expected yield function – is the most interesting.

Even if the existing experimental data do not cover all crops for all soil types and years, the data availability is judged sufficient to estimate reliable average functions. As to the yearly production functions, it has been possible to utilize data about actual yields from Statistics Norway to secure modelled levels that are close to actual levels. The way plant uptake of N is modelled – as a function of both dry matter yield and available N – the effect of possible errors in the yearly production functions is further counteracted.

The largest effect of the uncertainties related to yield functions seems to appear in the split fertilizing scenario. Here the most difficult point, the form of the yearly production functions, plays an important role. The functional form is of great importance when the model chooses the levels of the first and second round applications. Thus it is of special importance to improve this part in future studies.

Yield levels are also of importance in the case of catch crops. There are uncertainties both related to N-uptake and the effect of catch crops on erosion. The N-uptake by such crops may have been overestimated, hence its effect on leaching may be equally overestimated. However, sensitivity tests indicated that the uptake could be reduced substantially (at least 25%) without losing much of its N-conserving effect. Here one also needs to have in mind the problems related to transforming this practice from the format of trials to full scale agriculture.

The costs of catch crops may be over-estimated since in a long run perspective the N fertilizer level may be reduced due to remineralization of catch crop N. On the other hand, this same effect may result in increased leaching levels. This effect would occur especially in cases where the catch crop fails for various reasons. We are not able to suggest which of the two counteracting effects will be the strongest.

In the modelling, wheat turned out to give less N-leaching than barley and oats at the same N-level. This was expected, but the magnitude of the difference must be looked upon more as a hypothesis. Given the relationships as estimated by ECECMOD, an increase in wheat production may result in a rather substantial decrease in leaching. This is also due to the fact that yields are on average higher for wheat. Thus the same total volume of grain could be produces with less acreage tilled. The potential is restricted by the need for crop rotation as a substantial transition to much more wheat may actually decrease yields over time and affect leaching negatively. On the other hand, if the difference between the grain species is as in our analysis, a rather considerable reduction in leaching may have occurred over the last 10 years due to the increase in wheat production. A counteracting mechanism here though, is the increased use of a second round fertilizing in wheat to increase protein content. The effect of this practice is not analyzed in our study.

10.2.2 The uncertainties concerning farmers' behavior

The effect of an N tax on farmers' fertilizing practices depends both upon the realism of the production functions, as discussed above, and the logic of farmers' fertilizing strategies. The rather large variations in actual fertilizing even in grain production, may reflect real variability in local conditions. Still, the size of the variation is such that one may suspect farmers of not always fertilizing strictly by the profit maximization rule. They may also find it difficult to determine the optimal level.

One effect of this may be that farmers are less sensitive to changes in price levels than we have implicitly assumed in our modelling – indicating that the effect of a tax will be lower than estimated here. The interpretation may also be the opposite. Since N fertilizers have become less costly over time, it does not influence farmers' profits much to add some kilos extra. Increased use of straw shortener has reduced the problem of lodging. An increase in the N price could then produce extra incentives for farmers to reduce the fertilizer level. The effect on leaching could be rather substantial since "excessive use" produces the highest losses due to the non-linearities involved. Certainly, information is sufficient to bring about such changes. Since farmers will neither gain nor lose much by deviating somewhat from the optimal fertilizer levels, the development of "environmental consciousness" among farmers may help to reduce this kind of problem.

In the standard tax scenarios, we have assumed a manure market does not evolve. In the extreme case – where most farmers have excess N in manure – there will be no potential for a market to occur. In the intermediate ranges, sales may be induced by an N tax and the effect on leaching may be substantial. The problems with modelling this kind of market is that the quality of the results depends heavily on how farmers themselves evaluate the value of manure, the cost of arranging trades and the social acceptability of such transport and trade.

10.3 Gains obtained by integrated analyses

Integrating natural sciences and economics as in the study undertaken here, offers several advantages. It increases *relevance* since the various disciplines involved are forced to take into account parts of real life complexities outside their own domain. Environmental problems are complex, while the dynamics and interrelationships between the various elements of a large system are important. They are characterized by an interaction between societal institutions, choices made by economic agents given these institutions and the natural processes involved. Conducting *policy analyses* in such a field demands a cross disciplinary approach.

This strategy further increases *consistency*. The participation of various disciplines makes it both possible and necessary for each specialist to acknowledge the character of the various processes of other sciences. It forces researchers from the cooperating disciplines to incorporate insights from the other academic branches, both when analyzing problems within their own domain and when engaging in more cross disciplinary activities. This may influence both the understanding of the problem and the way various interacting models are formulated.

In the longer run, an important effect of this kind of research is its potential also for coordinating and directing empirical research. It is our experience that each sub-discipline tends to develop a set of "standard" research agendas that are not necessarily well adapted to either what happens in other disciplines of relevance, or the real life problems. Inter disciplinary research is an instrument by which empirical research may find the support necessary both to frame more relevant research agendas and conduct pre-tests of hypotheses to sort out what are really the more important issues to study in order to explain the functioning of a system.

ECECMOD has helped us as a research team to frame a research agenda. The modelling system needs to be further developed through increasing its consistency, improving the quality of important parameters and extensions to include areas more dominated by animal production. While the results presented here are not final – such a thing does not exist – it is our hope that they will help foster a more informative debate on the policy issues at stake. We are certain that the debate on the results presented here will be of importance in our continuing efforts to better understand the dynamics of the agro-ecosystems and the social systems within which they work.

APPENDIX A
The structure and dynamics of ECECMOD

This appendix gives an overview of ECECMOD. It presents the basic idea behind the modelling system and maps out its general structure. It continues with a more detailed presentation of the different elements of the modelling system - both the economic and natural science parts. The next step gives information about input data. The appendix closes with an overview of the estimated functions for yield response and nitrogen uptake in crops.

As to data and parameters, the appendix covers both the general needs of the model and the actual data used in the simulations previously documented in this report. Even though the presentation is rather comprehensive, it covers only a part of all technical information. In the text the reader will find references to technical reports with more extensive descriptions.

ECECMOD is not *a* model, but a system of models. Some are developed outside our project. Actually it is only the economic model - ECMOD - that is entirely built for fitting the purpose of ECECMOD. As to the natural science models, SOILN-NO is a new, reprogrammed version of the already existing SOILN. The hydrology model SOIL will be given a more brief documentation since we have used the original version. Our calibration and use of the model is more fully documented though. The erosion modelling is conducted with the help of EUROSEM and GRIDSEM. Here it is especially the application of and interaction between the models that is new. It has further been necessary to make fairly comprehensive adjustments, especially of GRIDSEM, to accommodate the system to work properly in our case.

The appendix is organized in the following way:

- In chapter A1 an overview of the modelling system ECECMOD – its structure and methodological basis – is given.
- Chapter A2 presents the economic part of the modelling system – ECMOD – the general principles, the structure and content of the various modules it consists of.
- In chapter A3 the various natural science models utilized are presented, the interrelations between them and the most important parameters estimated or set.
- Chapter A4 gives an overview of the most important input data like prices, costs, landscape and farm data, weather and hydrology data.
- Finally, the principles for estimating yield functions and nitrogen uptake in crops are given in chapter A5. This chapter also documents the most important functions and their parameters.

A1 Overview of the modelling system

This paragraph gives the background for ECECMOD and presents the main methodological choices made while constructing it. It defines the type of system it is built to cover and gives an overview of the basic structure of the modelling system.

A1.1 Introduction

ECECMOD is a mathematical modelling system constructed to study the effects of changes in political and economic conditions for agricultural production on nutrient leaching and soil erosion from agricultural land. It is the result of a cooperative endeavor between a group of economists and agronomists/biologists. It is constructed to cover

- farmers choices of agricultural practices under different political and economic conditions
- the effects of these choices on plant growth and soil processes
- the effect of agricultural practice, plant growth and soil processes on the loss of nutrients and soil through leaching and erosion.

ECECMOD is a research model - i.e. it is developed foremost to study the interaction between a complex set of processes. It is aimed both at policy analyses and to be used to generate hypotheses for research within the disciplines involved.

Environmental problems are system problems. As such they are created through interactions within sets of ordered processes where the different interactions define balances and imbalances - recreation and change. Thus, in constructing the model, it has been very important to define the system and construct the model in a way compatible with the structure of that system.

A1.2 Modelling within watersheds

ECECMOD is constructed to model nutrient losses in watersheds. It simulates the choices of agronomic practices on the actual farms in a watershed given existing or hypothetical economic and political conditions. It simulates processes in the soil induced by these choices and predicts losses through the soil profile to ground water and ditches, and mass transport on the surface to the watercourses of the watershed.

The model is constructed to capture the variation in a watershed as to agronomy, soil characteristics and topography. It can be used to predict losses over different periods of time, and is thus able to describe variation as an effect of changes in natural conditions. Its predictions though are best at the level of seasons or years.

The model does not cover losses from other types of land than agriculture, nor does it cover the processes in the ground water basin or the water courses. The model can be enlarged along these dimensions though without altering the existing structure. The modelling system is made operative for three smaller watersheds in South-Eastern Norway (see appendix A4.2).

A1.3 Basic methodological issues

The economic part of the model assumes optimizing economic agents maximizing profits under a given set of constraints. The agents further make their choices based on expectations that may be updated depending on the type of action. These are standard assumptions in economic modelling. The natural science part is based on a set of deterministic process oriented models for the simulation of hydrology processes, nitrogen transformations in soils, nitrogen leaching and erosion processes.

Variation, both spatially and across time, is important for the type of problem ECECMOD is constructed to cover. As to both types of variation, we have utilized the method of partitioning (Rastetter et al. 1992). This way variation is handled by dividing the objects of the study into relatively homogenous subgroups and applying a distinct (set of) fine scale equation(s) for each partition. Further a hierarchy of levels is constructed to systematically handle the relations between subgroups both of the same kind of order and of different orders.

The choices of agronomic practices are modelled at the farm level. This is done by partitioning all farms in a watershed into groups of similar type and constructing a representative model farm for each group. Important variations covered this way, are type and size of production, animal density and soil characteristics. Each farm model is in turn divided into a set of fields, each with homogenous soil. Agronomic practice including a crop rotation pattern is modelled giving each field a defined set of characteristics developing over time.

Nitrogen turnover and leaching is simulated for a set of soil profiles representing the variation in the area. It is basically a point (small plot) estimate, representative for a given soil type and a defined succession of agronomic practices. The model is thus constructed to produce such an estimate for each model farm field given the assumption that the field is homogenous in soil properties and given the agronomic practice conducted on that field for the given period of time.

Erosion analyses are conducted in two steps. First estimates of potential losses are produced at per day level for a plot defined to be homogenous in soil and topography (slope) and with defined successions of agricultural practices. Attaching these plot estimates to relevant pieces of land in the watershed, establishes a basis for estimating the flow of nutrients and soil through the landscape and to the relevant watercourses. At this stage of the modelling, the spatial extension of these homogenous pieces of watershed surface is taken into account. Since actual losses are dependent also upon the pattern of such pieces, a standard routing system is applied with a cell of 30*30 m - the grid cell - as the basic unit.

Hierarchy of levels:

1. *Point/farm field.* Characteristics: Homogenous in soil and agronomic practice. Modelling: Hydrology, nutrient turn over and leaching.
2. *Plot/grid cell.* Characteristics: Homogenous in soil, agronomic practice and topography. Modelling: Erosion.
3. *Farm field.* Characteristics: Homogenous in soil and agronomic practice. Modelling: Crop growth and farmers choices of agronomic practice.
4. *Farm.* Characteristics: Homogenous in size, manure intensity and type of production. Modelling: Farmers choices of agronomic practices.
5. *Landscape/watersheds.* Characteristics: Topography, soils and types of production. Modelling: Aggregated leaching, erosion processes in landscapes.

There is a trade-off between complexity and surveyability. The version used in this study has quite high resolutions both as to agronomic practices and soil conditions. Still, in the analyses of nitrogen turnover only three soil profiles - for a clayey, silty and sandy soil - are utilized. To some this may sound a bit coarse. Combined with the total variation captured in ECECMOD though, the problem has rather been to simplify and to get an overview of all the variation in the results produced. We have learned that there are gains related to capturing variation. But there are also gains related to simplifications and idealization making it easier to systematically compare between different specified situations.

The model is constructed to cover a succession of years, capturing the effect of variation in weather conditions. Again the model can be used for different time spans, and results can be monitored at different levels of resolution, even though we have mainly chosen to concentrate the production of results at the level of years. Variation over time is weather driven. It is further important to note that the weather is not allowed to vary over a watershed. With the sizes used here, this does not constitute any problem.

A1.4 The structure of the model

ECECMOD has the following structure:

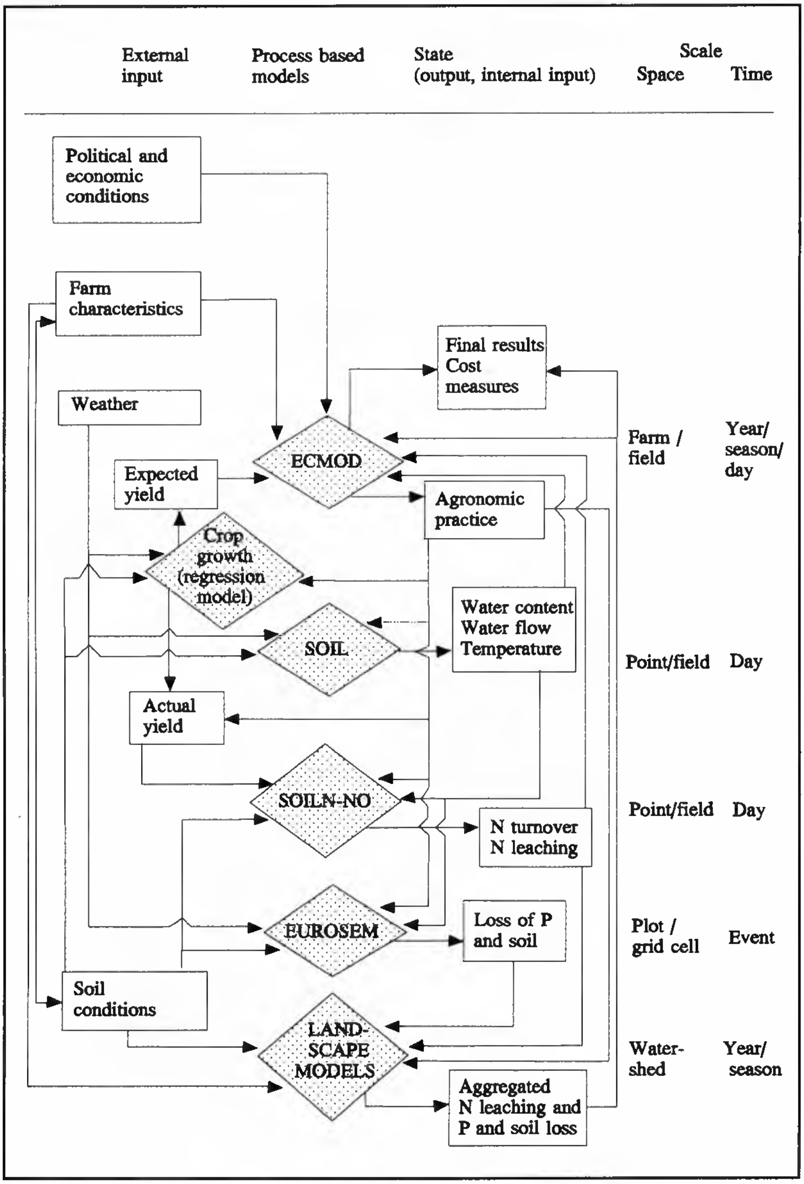


Figure A1.1: The structure of ECECMOD

There are four categories of inputs into the model:

- *Political and economic conditions.* This class of inputs consists of information about product prices, regulations and different types of support or taxing schemes. The model is built to handle a specific set of such conditions reflecting the existing situation in Norwegian agricultural policy and specific policy measures we have so far wanted to test the effect of. The structure of the model is such that it is fairly simple to enlarge the type of policy measures that can be analyzed. This group of inputs also covers cost relations (like input prices and time consumption for actual operations).

- *Farm and landscape characteristics.* The modelling is based on a set of data about the landscape/watershed analyzed: Topography, watercourses, soil conditions and land utilization pattern. Further it demands data at farm level about position in the landscape, type of production, size (acreage, number of different animals and excretion of nutrients per animal etc.). This data is used to categorize farms and attach each of them to a representatively constructed model farm.

- *Weather data.* This is data on daily basis about temperature, radiation and precipitation. It is normally data from only one point in or near the watershed.

- *Soil conditions.* The soil is partitioned into groups with a standard profile. For each soil group the profile dominating in the watershed is used. The agronomic history of the soil is also taken into account through the level of organic matter. The link to the farm fields, both at landscape level and model farm level, is established parallel to this categorizing.

The crop growth module in figure A1.1 is based on a set of production functions generated by regression. These functions are soil and crop specific yearly production functions $y_{ijt} = f_{ijt}(N)$ where N is nitrogen input, i is field/soil type, j is crop and t denotes year. The functions are produced on the basis of trial data and relates to what is defined as "standard" agronomic practices - i.e. use of mineral fertilizers and fall plowing only. As soon as there are deviations from this – determined by ECMOD – the functions are moderated in specific ways. Details about how this is done is given in chapter A5.

There are five types of submodels in ECECMOD:

- *ECMOD* is constructed to chose agronomic practice. It is based on a set of optimizing routines and consists of a set of modules related to the different choice problems. The optimizing procedures are mainly non linear. The model chooses agronomic practice for each farm field at the resolution necessary for the rest of the modelling (day, season, year). The optimizing is to a large degree made on *expectations*, with expected yields as the most important relation. The model also calculates measures to evaluate the costs of different strategies on the basis of data on changed emissions from the landscape models and cost data from previous runnings of ECMOD.
- *SOIL* is a deterministic hydrology model giving information about water content, water movements and temperature dependent upon weather and soil characteristics (Jansson 1991; Botterweg 1992). It is a one dimensional layered model. The information produced here is used both as driving data for nutrient turnover and erosion modelling and to determine sowing date (ECMOD).
- *SOILN-NO* is also a one dimensional, layered deterministic model describing nitrogen turn over (Johnsson et al. 1987; Vold and Søreng 1995). It produces information about loss of N as a function of chosen agronomic practice, plant growth, weather, and soil characteristics (soil type and agronomic history) expanded from point to field level assuming homogenous fields (ECMOD).
- *EUROSEM* is a process based model describing erosion as a function of agronomic practice, weather, soil characteristics and local topography. It is an episode oriented model diverging from the more dominating tradition of regression based analyses (Morgan et al. 1996; Botterweg 1996). It is used to produce estimates for losses of soil from a plot under the given circumstances. These estimates are used as input into the landscape model describing how much of the plot erosion – potential erosion – really leaves the land.
- *Landscape models*. Finally there are developed two systems or models for aggregating data from plot and/or field level to the level of watersheds. The aggregation of costs and N leaching estimates is a fairly simple weighing mechanism based on the relative distribution of productions, soils etc. in landscapes. As to erosion, *GRIDSEM* (Leek 1993) is used. It is a model estimating the movement of released matter in landscapes and capable of aggregating losses over larger areas.

Figure A1.2 and A1.3 show how data about the actual watershed is partitioned and processed and how results are finally obtained at the level of the watershed.

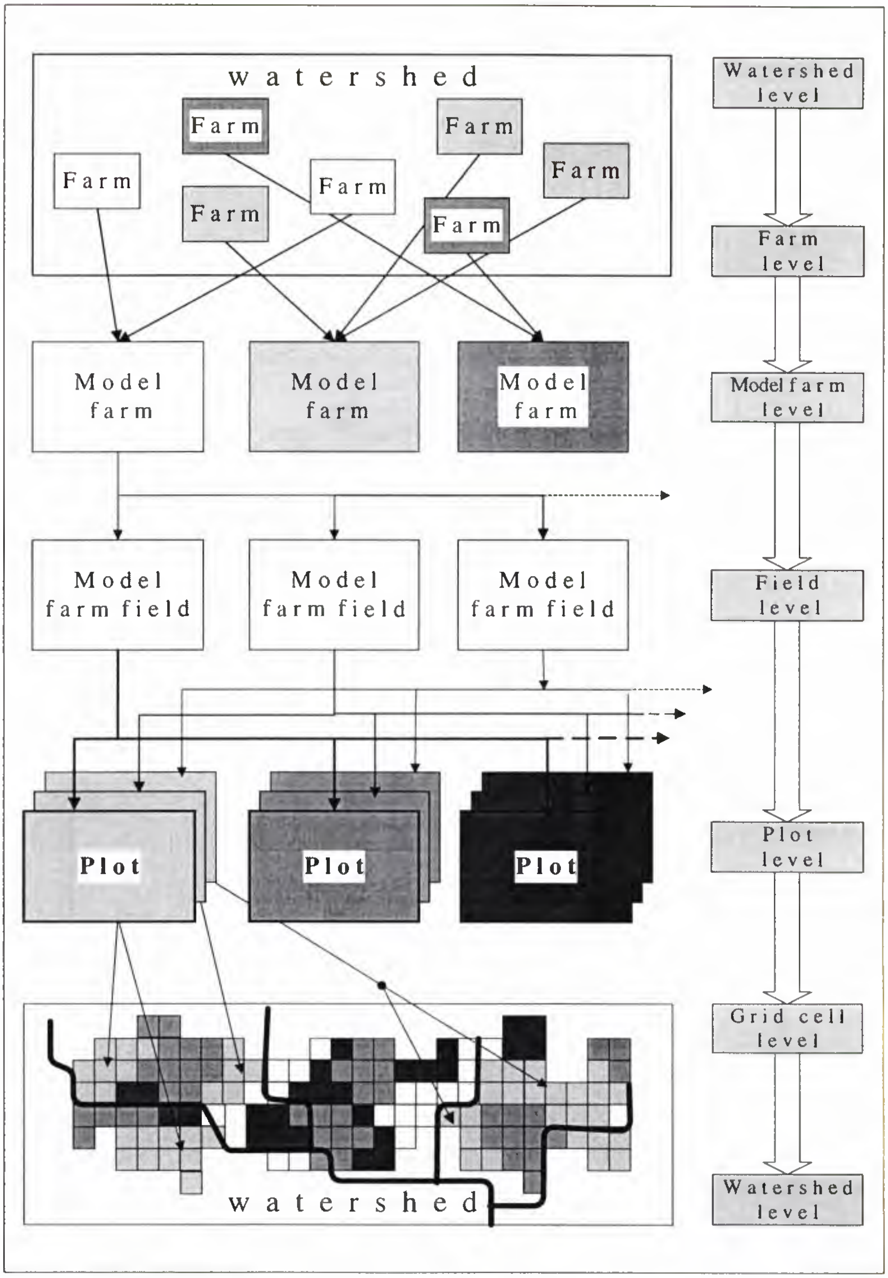


Figure A1.2: The relation between real farms, model farms and the landscape

According to figure A1.2 the farms of the watershed are grouped into categories represented by a model farm. Each model farm is partitioned into a set of fields covering the variation in soils typical for each group of farms. Adding topographic characteristics to such a model farm field establishes a set of plots. The link back to the landscape is reached through the following connections:

- The connection between the model farm and the set of real farms which it represents.
- Information about soil characteristics connecting defined pieces of land on these farms to the right model farm field.
- Information about topography/ slope linking the specific piece of land to the right plot and grid cell.

Through this structure a choice of agronomic practice for a defined model farm field simultaneously equips a set of spatial elements in the landscape with such a practice. Modelling hydrology, N leaching and erosion potential for each farm field or plot/grid cell, equips the same pieces of land with estimates for potential losses of nutrients and soil. Finally, total losses are estimated by aggregation (N) or by mass transport analyses in the landscape (P/soil) with the help of a routing system.

Figure A1.3 shows this connection at the analyses model level. A flow of information goes through the interlinked model structure from ECMOD to the landscape model. Actually ECECMOD is constructed so that each model can be run more or less separately. This is done to simplify an otherwise very complex and time

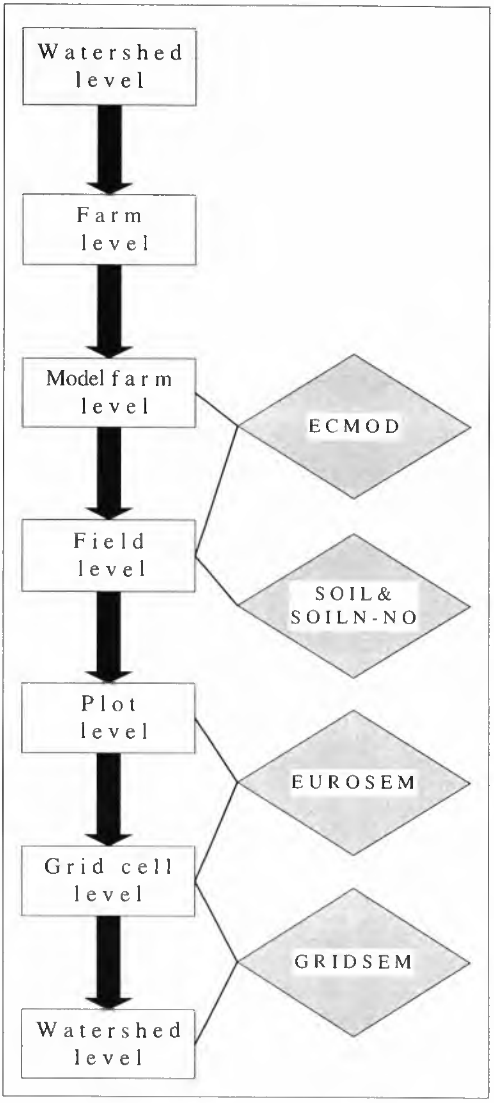


Figure A1.3: The relation between levels and models in ECECMOD.

consuming modelling. Important feedbacks in the system are taken care of with the help of initial analyses using models placed at later stages of the modelling. This way parameters containing necessary feedback information are obtained and used directly in models placed at earlier stages of ECECMOD.

The number of feedback loops is heavily reduced by the way crop growth is modelled (see chapter A5 for details). Actually, there are three important types of feedbacks or interactions to consider:

- the relation between crop growth, agronomic practice and soil mineralization
- the relation between choice of agronomic practice and hydrology
- the relation between weather conditions, hydrology and choice of dates for soil preparation and sowing

The relationship between crop growth, agronomic practice and soil mineralization is handled with the help of the system of year specific production functions to fit the needs of SOILN-NO, a set of production functions for expected yields to meet the needs of ECMOD, and a set of parameters in ECMOD where expected changes in N mineralization due to changes in agronomic practices are incorporated. These last parameters are obtained through separate and initial analyses with the help of SOILN-NO (see appendix A5.5).

As to the relation between choice of agronomic practice and hydrology some simplifications are made. Covering that relation fully, would have demanded us to run SOIL for each scenario and each model farm field. This is possible with the given structure, but we chose to simplify in the analyses presented here running SOIL only once for each landscape and soil type assuming grain to be the crop. In our case grain is very dominant covering more than 80 % of the area.

The relation between the weather and the choice of dates for soil preparation and sowing is handled through a separate and in advance analysis based on SOIL. Here a time series over days where soil preparation and sowing is possible was constructed. This enables ECMOD to chose sowing day on the basis of weather conditions, crops, field sizes etc.

ECECMOD is constructed so that information about state variables is obtained for each successive step of the modelling. This makes it possible to check the consistency of the results obtained as it also enables the user to produce data at the levels most suitable for hypotheses generation.

A2 ECMOD – the economic model

A2.1 General modelling principles

Agents in ECMOD are assumed to choose farming practices – i.e. decisions related to crop rotation, tillage practices, manure handling and fertilization – to maximize their expected profits. More specifically agents seek to maximize the expected net present value from farming, with technology (θ), crop selection (j), and inputs ($\mathbf{x}_{jit}$ and $\mathbf{b}_{jit}$) being the choice variables, i.e.

$$\pi(\theta^*, j^*_{it}, \mathbf{x}^*_{jit}, \mathbf{b}^*_{jit}) = \left\{ \underset{\theta_i\ j_{it}\ \mathbf{x}_{jit}\ \mathbf{b}_{jit}}{\mathrm{MAX}} \right\} \Sigma_{t \in T}\, ß^t\, \Sigma_{i \in I}\, a_{it}\, \Sigma_{j \in J}\, \varepsilon(j_{it})\, \{E_{\Omega\, t}\, [p_j\, f_{\theta jit}(\mathbf{x}^*_{jit}, \mathbf{b}_{jit}) - (\mathbf{v}_x + \tau)\mathbf{x}^*_{jit} - \mathbf{v}_b\, \mathbf{b}_{jit} - FC_{\theta i} + S_{ijt}] \qquad [A2.1]$$

$$\text{s.t.} \quad \Sigma_{i \in I}\, a_i\, d_{\theta ij}\, \mathbf{b}_{jit} \leq \mathbf{B}_t \qquad [A2.1.a]$$

where

θ_i	denotes the chosen production technology, $\theta_i \in \Theta$, where Θ denotes the set of available production technologies,
j_{it}	denotes the chosen crop, $j \in J$, where J denotes the set of possible crops,
$\mathbf{x}_{jit}$	denotes the use of ordinary inputs (like fertilizer) to be used on field i for crop j in time period t,
$\mathbf{b}_{jit}$	denotes the use of limited inputs (like the farmer's own time) to be used on field i for crop j in time period t,
T	denotes the index set for the farmer's time horizon, $T = \{1,2, ..., T\}$,
ß	is the discount factor, defined as $(1+r)^{-1}$, where r is the discount rate,
a_{it}	is the area of field i in time period t,
ε	denotes an ordering function, such that $\varepsilon(j_{it}) = 1$ if crop j is selected on field i in period t, and otherwise $\varepsilon(j_{it}) = 1$,
$E_{\Omega\, t}$	is an expectations operator given the farmer's information set prior to production period t, Ω_t,
p_j	denotes the product price for produce j,
$\mathbf{f}_{\theta jit}$	denotes a production function for technology θ,
$\mathbf{v}_x$	is the corresponding vector of prices – or in the case of inputs with no market prices the farmer's alternate value – for inputs **x**,
τ	denotes a vector of input factor taxes,
$\mathbf{v}_b$	is the corresponding vector of prices – or in the case of inputs with no market prices the farmer's alternate value – for inputs **b**,
$FC_{\theta it}$	denotes fixed costs associated with a choice of technology θ on field i for crop j in time period t,
S_{ijt}	denotes any subsidies on field i from certain agricultural practices,
$d_{\theta ij}$	denotes required use of restricted inputs per hectare using technology θ when crop j is grown on field i, and
$\mathbf{B}_t$	is a vector of restrictions for inputs $\mathbf{b}_t$.

In this decision problem some of the information is made available to the farmer as each growing season proceeds. More specifically, all the information needed to obtain an *ex post* optimal solution is not available to the decision maker at the times various decisions need to be made. Consequently the farmer must make his decision on the basis of expectations. In principle the decisions made should be *ex ante* optimal, but will generally not be *ex post* optimal. Examples of this kind of information include growing conditions through the growing season and the time for sowing crops on the various fields – the later the time of seeding, the lower the expected yields. This may influence the expected profit maximizing fertilization level on each field. Consequently [A2.1] should be solved sequentially.

To capture the yearly variability in growing conditions, ECMOD is run for a 20 year period (see chapter A1 for an overview, and Romstad and Vatn 1995 for a theoretical justification). The sequence in which [A2.1] is determined/solved in ECMOD is as follows:

(1) *Farm machinery*

Given farm size and type of production, each model farm is set up with standard machinery (based on 1992 figures for comparable farms, see section A4.2. for further documentation). This machinery may be changed if changes in the political or economic environment makes that profitable.

(2) *Crop selection*

Based on product and input factor prices, and possible environmental regulations – like catch crop requirements – crop rotation is determined. In ECMOD crop selection and preliminary fertilization decisions are made in separate modules specifically tailored to the cropping pattern of the various model farms. The details of the crop rotation module are discussed in section A2.3.

(3) *Tillage practices*

Tillage practices for each year are determined given crop rotation and manure handling practices. This module incorporates possible regulations – like subsidies for reduced fall tillage. The details of the tillage module are discussed in section A2.4.

(4) *Manure handling*

Based on the chosen crop rotation for the 20 year period, manure storage and handling practices are determined for model farms with manure. The details of the manure handling module are discussed in section A2.5.

(5) *Spring time management*

The possible times for sowing/planting of spring crops depend highly upon the weather. Based on the time required to prepare the fields for spring sowing and the actual weather in each year, dates for sowing on the various fields are determined. The details of the spring time management module are discussed in section A2.6.

(6) *Final optimization and adjustments*

Based on the decisions made in (2) to (5), and specific circumstances brought about by the set of regulations – final adjustments in the agronomic practices are undertaken. Changes in the fertilization level in the year(s) after a catch crop has been grown on a field is one example of such adjustments. The details of the final optimization and adjustments module are discussed in section A2.7.

Decisions made in (2) to (6) are all made from the perspective of maximizing expected profits utilizing various linear and non-linear programming techniques.

One may argue that the manure handling and/or tillage practices may affect the choice of cropping pattern, and should therefore affect crop rotation. At the outset this is true. The chosen decision sequence is chosen in ECMOD due to the following reasons:

- Manure handling and tillage practice decisions are not made on the basis of single years, but on the expected profits from a twenty year crop rotation, taking care of the investment aspects of these practices.

- The effects of manure handling and tillage practices do not change the relative profitability of crops, although on farms with large amounts of manure one may argue for choosing crops – like spring or winter wheat – with higher expected profit maximizing fertilization levels. As these two crops are more profitable than barley and oats, the main reasons for having barley and oats in the rotation are (i) that they reduce the occurrence of diseases that result from growing the same crop on the same field for several years, (ii) that they spread the peak work load periods, in particular during harvesting, and (iii) that they reduce the risk of an overall crop failure. We therefore find the chosen sequence reasonable.

A2.2 The model structure

ECMOD consists of five main registers (figure A2.1). One concerns input data. The second register covers the different analysis modules. A third register stores the output from these modules, while a fourth one covers the output from the natural science models of ECECMOD as they are used in the calculation of the final results of the study. These results – both different cost measures and data about changes in leaching and runoff parameters – are stored in a separate register.

Figure A2.1 shows a the system of flows – especially between the analysis modules register and the input and output data registers is very simplified. Each analysis module draws on a specific set of input data from these registers. Further the results from each analysis module actually go to the operation costs and agronomic practice registers directly and are used in subsequent modules by calling upon the relevant parts of these registers.

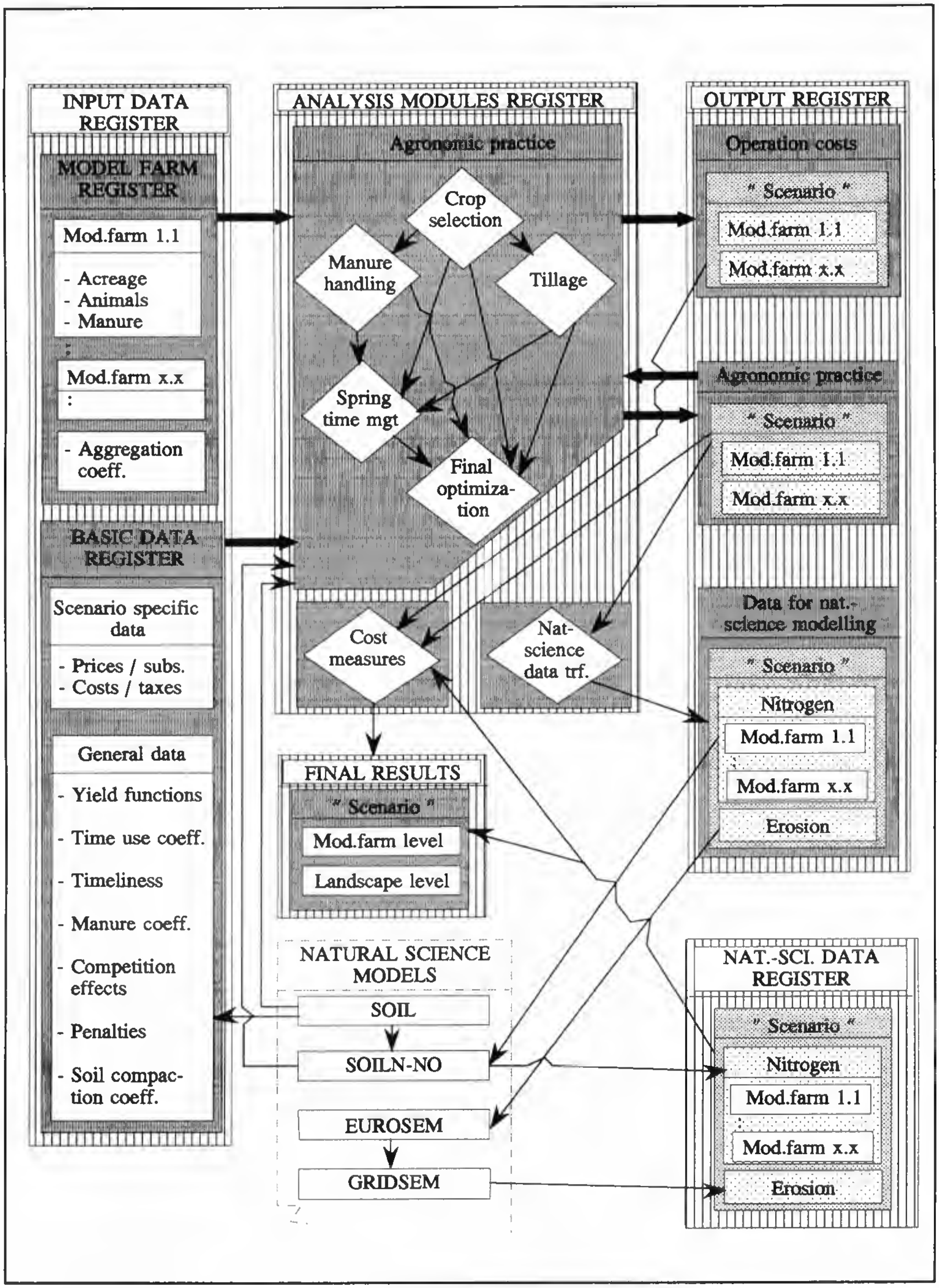


Figure A2.1: The structure of ECMOD.

The different parts of the model are described in further detail later – the modules in subsequent paragraphs of chapter A2 and the data used in chapters A4 and A5. Here we will just highlight some of the main characteristics of each register:

- *Input data register*, consisting of two parts:
  - A *model farm register* with information about size, field structure, soil characteristics and the number of animals on each model farm. There are no restrictions on the number of model farms. Each represents a set of farms in existing landscapes. The register also gives information about the connections between model farms and the landscapes, aggregation coefficients etc.
  - *Basic data registers*, consisting of (i) scenario specific input data and (ii) general technical data. The scenario specific data concern various changes in policy, implying changes in input or output prices or in specific types of support schemes. More direct regulations like prescribed practices etc. are handled by constraints established in the relevant analysis module. The register for general technical information covers parameters in production functions, time requirements for different operations and soils, manure coeff. etc.).

- *Analysis modules register*. This register consists of seven different analysis modules. Five of them concern the choice of agronomic practices – where a sequence of optimization problems are solved for each model farm separately. One module transforms the data about agronomic practices into the form necessary for the natural science modelling. The last module takes care of the calculations of different cost measures both at the model farm and landscape levels.

- *Output register*. This register covers the results from each analysis module for every scenario and model farm. The data are of three different categories. We have data about operation costs to be used in the cost analysis. We have data about agronomic practices to be used in subsequent analysis modules in ECMOD. Finally, we have an output register covering data about chosen agronomic practice adjusted to the needs of the natural science models used.

- *Natural science data register*. Here data from the natural science analyses are stored. Again data are organized by scenario. As for the nitrogen analyses, data are given for each model farm at the level of model farm fields. Erosion data/data about phosphorus loss are given at landscape level – either for the whole watershed or defined sub-levels.

- *Final results*. This register covers the results from both the economic and natural science modelling. Data are organized by scenario, model farm and/or landscape level. The register covers various cost measures, measures over nutrient losses etc. Cost measures cover both private costs and social costs, formulated per ha or per kg reduced nutrient losses.

The analysis modules concerning the choices of agronomic practice are certainly the most important part of the structure. They are integrated through a defined sequence of choices. Some of these choices may be conducted simultaneously by the farmer, even though capacity restrictions may force him/her to act sequentially. Using computer facilities, the capacity for making simultaneous choices is certainly large. Still, to construct an analysis system covering all important options possible for any farm and making all choices simultaneously, amounted to a nearly unsolvable problem. Added to the problem of capacity, we also faced problems with monitoring capacities and the issue of how to avoid non-convex sets in the modelling.

To construct a model system that is solvable, we have chosen to break the decisions down to a set of subsequent choices. In most cases this has caused no inconsistency. The problems we have faced concern mostly interrelationships between choices of crops, soil preparation and manure application systems. First, the sequencing used, makes it impossible for the model to change crops as a function of subsidies or regulations related to choices sequenced later in the structure. In our case this is relevant for measures directed towards changes in the soil preparation system. This turns out to be a minor problem though since the effect of changes in such practices is considered to be uniform over all crops. Existing data does at least not support a differentiation here.

Second, we have manure application and soil preparation which is modelled parallelly. If fall tillage is restricted or spring tillage is subsidized, a farmer that needs to spread manure in autumn, may chose to restrict spreading to a minimum number of fields. This trade-off problem is not handled well by ECMOD in its present form, implying that full effect of changes in soil tillage is not obtained without measures also securing all manure to be spread in the plant growing period.

Finally, at each step of the analyses, information about expected yields is used to determine the choice. This is the case both for the choice of crop, soil preparation system, sowing sequence and sowing date. As the modelling system is constructed, these expectations change slightly as the modelling proceeds. In the module choosing crops, only the expectation about yields given standard agronomic treatment as earlier defined, is used. When choosing soil preparation system, the expectation is updated with information about the effect of this specific choice. As far as knowledge is available to the farmer, (s)he may be supposed to take this information simultaneously into consideration while choosing both crops and tillage system. We see no problem with our approach as long as the expectations do not vary between relevant crops across variables added at later stages of the study. This is generally the case. In cases where later choices have effect – like the choice of sowing date with its subsequent influence on expected yield – the effects of sequencing are tested and found to be minor.

A2.3 Module 1: Crop rotation

Based on product and input factor prices, and possible environmental regulations – like catch crop requirements – crop rotation is determined. The model farms can be divided into three cropping categories: (1) grain producing farms, (2) farms producing contract crops – peas or grass seeds – and grain in rotation, and (3) farms producing own feed – roughage – and grain in rotation.

A2.3.1 Grain production

Where the climate is sufficiently warm, Norwegian grain farms grow four types of grain: (i) barley, (ii) oats, (iii) spring wheat and (iv) winter wheat. These grain types respond somewhat differently to fertilization. Consequently changes in the relative prices – for example through a tax on nitrogen fertilizers – may result in changes in the optimal crop rotation. Thus crop rotation must be modelled explicitly. The steps in the crop rotation module are:

(a) Choosing expected profit maximizing fertilization levels for the four grain types, and calculating the expected gross margins from these fertilization practices. For crop j on field i this profit maximizing fertilization level depends on the parameters of the expected production function, the product price (p_j) and the price of nitrogen fertilizers (v). These per hectare profit maximizing fertilization levels are found by solving:

$$\pi_{jit}(x^{*}_{jit}) = \left\{ \begin{matrix} \text{MAX} \\ x_{jit} \end{matrix} \right\} p_j\, f_{ji}(x_{jit}) - (v + \tau)\, x_{jit} - FC_{jit} \qquad [A2.2]$$

where:
- π_{jit} denotes expected gross margins from growing crop j on field i in year t,
- x_{jit} denotes nitrogen fertilization level for crop j on field i in year t,
- p_j denotes the product price for produce j,
- f_{ji} denotes the expected production function for crop j on field i,
- v denotes the price on nitrogen,
- τ denotes an (eventual) tax on nitrogen, and
- FC_{jit} denotes per-hectare fixed cost for technology θ for crop j on field i in year t.

[A2.2] is solved using non-linear optimization (PROC NLP in SAS).

(b) These per-hectare gross margins are then used as coefficients in a mixed integer programming module where the optimal crop selection for year t is chosen. Solving the mixed integer program for all twenty years at once was not possible due to technical limitations in the chosen software (PROC LP in SAS). Consequently for each year the following mixed integer programming model was solved:

Objective function:

$$\pi(j^{*}_{jit}, e^{*}_{it}) = \left\{ \begin{matrix} \text{MAX} \\ j_{jit} \quad e_{it} \end{matrix} \right\} \Sigma_{i\in I}\, a_i\, \Sigma_{j\in J}\, j_{jit}\, [\pi_{jit} - p_j\,(s_{jit}\,(j_{ji,-t}) + r_{ji} + c_{ji}\, e_{it} + S_{jit}] \qquad [A2.3]$$

where:
- π denotes expected gross margins at the farm level,
- j_{jit} is a dummy variable that is zero if crop j is not chosen, and one if crop j is chosen on field i in year t,
- e_{it} is a dummy variable that is zero if there is no catch crop, and one if a catch crop is chosen on field i in year t,
- a_i denotes the area of field i,
- π_{jit} denotes the profits from growing crop j on field i in year t (estimated in [A2.2]),
- p_j denotes the product price for produce j,
- s_{jit} is a penalty (kg/ha) for growing certain crops in succession,
- r_{ij} is the calculated risk premium for each crop that is calculated on the basis of historical variability in yields,
- c_{ji} is the costs (for herbicides and loss of yields due to the competition effect) of growing catch crops on field i in year t, and
- S_{jit} denotes any per hectare subsidies for certain agricultural practices.

s.t.

(a) Integer constraints:

$$\Sigma_{j \in J}\, j_{jit} = 1, \text{ one } j_{jit} = 1, \text{ other } j_{jit} = 0, \ \forall\ i \in I \qquad [A2.3a]$$

(b) Total area constraint:

$$\Sigma_{i \in I}\, \Sigma_{j \in J}\, a_i\, j_{jit} \le A \qquad [A2.3b]$$

where: A denotes the total area.

(c) Minimum and maximum constraints for each crop:

$$a_{j\min}\ A \le \Sigma_{i \in I}\, a_i\ j_{jit} \le a_{j\max}\ A \qquad [A2.3c]$$

where: $a_{j\min}$ denotes minimum required fraction of the area seeded with crop j, and
$a_{j\max}$ denotes maximum allowed fraction of the area seeded with crop j.

(d) Catch crop constraint (when applicable):

$$\Sigma_{i \in I}\, \Sigma_{j \in J}\, a_i\ \ \delta_e\,(e_{it}) > \alpha A \qquad [A2.3d]$$

where: δ_e is an ordering function that equals one if a catch crop is grown on field i, and zero otherwise, and
α denotes the fraction of the total area that should be planted with catch crops ($e_{it} = 1$).

As this model – [A2.3] subject to the constraints [A2.3a] through [A2.3d] – is solved for one year at a time, a constraint on minimum and maximum shares of the total area to each crop is needed to avoid that the most profitable crops are grown until the penalty – s_{jit} – is sufficiently large. This introduces some rigidity in the model and may for some scenarios lead to sub-optimal crop selection. If it had been technically possible to solve the crop selection problem for all twenty years at once, the constraint [A2.3c] would not have been needed.

As indicated by [A2.3] the penalty, $s_{jit}\,(j_{ji,-t})$, is additive. This implies that it does not influence the profit maximizing fertilization level, only the yield level. One could argue for a multiplicative influence, but in this module the purpose of the penalty is to avoid repeated growing of the more profitable crops (spring and winter wheat). An additive specification is easier to implement in a mixed integer framework, and is sufficient to avoid that the more profitable crops are grown repeatedly. The structure of the penalty is as follows:

Table A2.1: Penalty (kg/ha) for growing the same crop in consecutive years (0: same crop not grown, 1: same crop grown).

	Penalty (kg/ha)			
Type of crop	001	101	011	111
Barley	0	150	250	500
Oats	0	50	100	200
Spring wheat	0	200	400	800
Winter wheat	0	250	500	1000

Notes:	001	same crop not grown the two previous years
	101	same crop grown with one year with another crop in between
	011	same crop grown last year, but not the previous year
	111	same crop grown last two years

In addition to these penalties for growing the same crop in consecutive years, straw resident diseases may transfer from one type of grain to another, in particular between spring and winter wheat, but also

- from spring and winter wheat to barley, and
- in some instances from barley to spring and winter wheat.

The only grain that is not a host for diseases for other grains is oats. Despite its relative lower profitability oats therefore plays an important role in the grain rotation. These interactions are incorporated in the objective function of the linear program for crop selection to facilitate a crop rotation that reduces the needed costs for pesticide control.

Inputs into the module are:

- The production functions for each crop and soil type used in step 1 to make the preliminary calculations of profit maximizing fertilization levels and the corresponding profits (see Romstad 1995 for further details).
- An initial crop rotation for each farm model. This initialization is needed to set the appropriate penalty, $s_{jit}(j_{ji,-t})$ for year one, to be used in step 2 of the module.
- Product and input factor (nitrogen) prices and eventual environmental regulations in the form of restrictions (like minimum fraction of the area with catch crops).

A2.3.2 Grain and contract crops in rotation

Generally the profits from growing contract crops (peas or grass seeds) are higher than the profits from growing other crops. In parts of the study area (the Auli watershed) peas and grass seed are common contract crops. As is the case with most contract crops, there are specific terms in the contracts on how these crops are to be grown. In connection with crop selection, embedding these crops in an overall crop rotation is important. In ECMOD this is done by placing these crops out in the rotation consistent with the contract terms, and letting other crops be grown on an expected maximum profits basis.

In linear programming this is done by fixing these crops – in SAS this is done by specifying the "fixed" option for these crops. Otherwise, the general principles of the previous section apply to modeling crop selection with contract crops.

An additional input for modelling contract crops is on which fields these crops are to be grown – consistent with the contract terms.

A2.3.3 Grain and grass in rotation

The grain and grass rotation differs from the two previously described types of rotations because the markets for grass (except for hay) are limited. Grass – in the form of silage (the major roughage under Norwegian conditions) – is not a commodity that is easily transported with its low value/high volume and weight. In recent years transporting silage has become somewhat easier with the emergence of plastic wrapped silage balls, but care needs to be taken during the transportation not to rip the plastic. Transporting silage over long distances is therefore not an economically good option.

This implies that modelling grass production is somewhat different from grain production. More specifically farmers will grow grass for feed on the farm, but growing more grass than what is needed on the farm makes little sense as transportation costs will reduce the net price to these farmers. In a similar fashion, growing less grass than what is needed for feed on the farm (cattle and sheep require a minimum amount of roughage for dietary reasons) is also unlikely to pay off. Again, grass transportation results in reduced profits.

We therefore argue that farmers face a non-linear price for own produced grass. For low feed volumes (below the minimum dietary feed requirements for the animals) the farmers envision a high price, that gradually decreases until it hits a "floor" where it pays to buy fodder even with high transportation costs. Figure A2.2 shows these relationships in more detail.

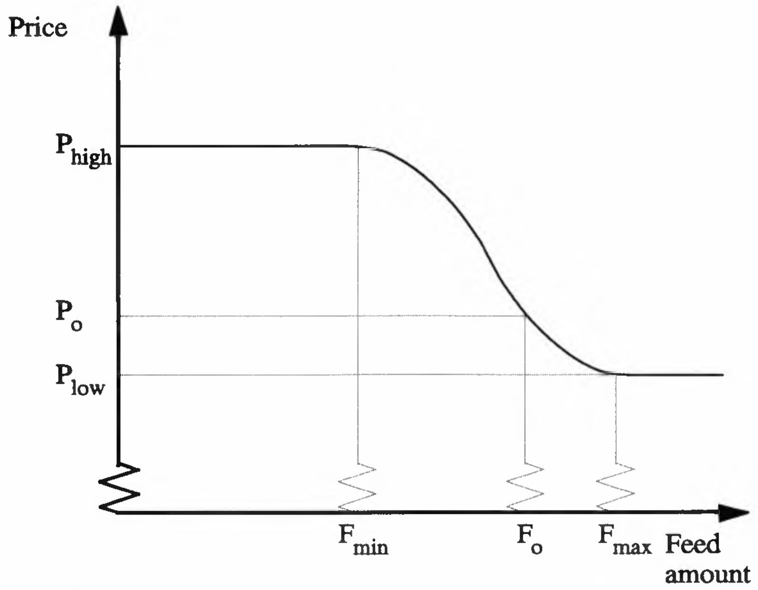


Figure A2.2: The price function for grass as a function of total grass production and coarse feed requirements (F_o), the price ceiling for feed (P_{high}), the price floor for feed (P_{low}), the minimum feed requirement (F_{min}) and the feed amount beyond which produced feed needs to be sold (F_{max}).

More specifically the *price-feed amount* curve in figure A2.2 is constructed the following way:

- F_{min} is 0.6 F_o
- F_{max} is 1.2 F_o (= 2 F_{min})
- P_{high} is 1.2 P_o
- P_{low} is calculated on the basis of F_{min}, F_{max}, P_o and P_{high} and the parameters that determine the functional form (a 3rd degree polynomial).

With this non-linear price that basically is a function of the recommended roughage usage for a given number of animals, and the estimated yield functions for grass, the problem is to maximize fertilization usage and allocation of fields to either grass production (mainly for in-farm use) and grains (barley or oats for sale). The maximization problem is given in [A2.4]:

$$\pi(\phi^*_{it},x^*_{it}) = \left\{ \underset{\{\phi_{it}\ \ x_{it}\}}{\mathrm{MAX}} \right\} \begin{aligned} &\Sigma_{i\in G}\, a_i\ \{p_g\, [\Sigma_{i\in G}\, a_i\, g_{it}(x_{it})]\, g_{it}(x_{it}) \\ &-(v+\tau)\, x_{it} - FC_{git} + S_{jit}\,\} \\ &+\Sigma_{i\in G'}\, a_i\ \{p_b\, (f_{bit}(x_i) - (s_{it}(j_{i,-t})) \\ &-(v+\tau)\, x_{it} - FC_{bit} + S_{jit}\,\} \end{aligned} \qquad [A2.4]$$

where:
ϕ_{it} is the amount of grass grown on field i in year t,
x_{it} is the amount of nitrogen applied per hectare on field i in year t,
G denotes the index set of fields with grass,
a_i denotes the area of field i,
p_g is the price function for grass,
g_{it} is the yield function for grass on field i,
v is the price of nitrogen fertilizer,
τ denotes any tax on nitrogen fertilizers,
FC_{git} are the per hectare fixed costs of having grass on field i,
S_{jit} denotes any per hectare subsidies for certain agricultural practices,
G' denotes the index set of fields with non-grass crops, so that $\{G \cup G' = I\}$ and $\{G \cap G' = \emptyset\}$, I is the index set of all fields,
p_b denotes the price of the non-grass crop (barley),
f_{bit} is the yield curve for barley on field i,
s_{it} is the penalty for consecutively growing barley on field i, and
FC_{bit} are the per hectare fixed costs of having barley on field i.

s.t.

(a) Total area constraint:

$$\Sigma_{i\in G}\, \delta_G(\phi_{it})\, a_i + \Sigma_{i\in G'}\, \delta_{G'}(f_{bit})\, a_i \leq A \qquad [A2.4a]$$

where:
δ_G is an ordering function that equals one if grass is grown on field i,
$\delta_{G'}$ is an ordering function that equals one if barley is grown on field i, and
A denotes the total area.

(b) Catch crop constraint (when applicable):

$$\Sigma_{i\in G}\, \delta_G(\phi_{it})\, a_i + \Sigma_{i\in G'}\, \delta_e(f_{bit})\, a_i \geq \alpha A \qquad [A2.4b]$$

where:
δ_e is an ordering function that equals one if a catch crop is grown on field i, and zero otherwise, and
α denotes the fraction of the total area that should be planted with catch crops ($e_{it} = 1$). Meadow/grass is also accepted as a catch crop.

The crop rotation for grass is such that once a field is seeded with grass, it remains under grass cover for four years. It is then tilled, and the next spring seeded with barley or oats. On fields where grains precede grass, barley is always the chosen crop, as barley is the best suited grain in which to also seed grass. Otherwise a rotation of barley and oats is chosen according to the following rule: if a field has more three or more years with consecutive growing of grains, every other year is seeded with oats, but in such a way that the last year before grass is seeded, barley is chosen.

Making both discrete and continuous choices of the type indicated in [A2.4] is a computer time consuming process. To reduce the computer optimization time, various crop selection alternatives, based on past years is undertaken. More specifically, only fields that have been seeded with grains or have completed a four year grass cycle enter as fields where decisions about the type of crop need to be made. To exemplify – consider a farm with five fields, one seeded with grains and the remaining four with grass. Of the four grass fields, one has completed its fourth year. Consequently there are four crop selection alternatives:

- seed grain on both fields
- seed grain on one field, grass on the other (the fields are ordered, which makes this two choice alternatives), and
- seed grass on both fields.

Each of these alternatives is run separately, and the alternative with the highest expected profits is chosen. Note that the larger the area seeded with grass, the lower the fertilization levels on these fields becomes as an increase in grass yields reduces the "grass price". Conversely, the smaller the area with grass, the higher the grass fertilization levels.

A2.4 Module 2: Tillage

A2.4.1 Modelling principles

Decisions on tillage practices involve two steps: (i) investment in the necessary equipment for the various tillage regimes, and (ii) choice of tillage practice given the available tillage equipment. These steps are replicated in this module.

When deciding on what tillage equipment to acquire, the decision maker must consider how suited the soils and crops grown are for the various practices, and the costs and possible subsidies associated with these practices. Table A2.2 shows the connection between tillage practices, required tillage equipment, and whether the practice meets the reduced/spring tillage requirements (implying eligibility for eventual tillage subsidies).

Table A2.2: Tillage practices, required technology and reduced/spring tillage requirements.

Tillage practice	Needed equipment Plow[1]	 Harrow[2]	 DSM[3]	Tillage requirement met
Fall plowing	yes	no	no	no
Fall harrowing	no	yes	no	no
Spring plowing	yes	no	no	yes
Spring harrowing	no	yes	no	yes
Direct sowing	no	no	yes	yes

1) Includes standard harrow.
2) Special harrow needed when harrowing is the only tillage practice chosen.
3) Direct sowing machine.

The investment decision is modelled in an integer programming framework (PROC LP in SAS). For the various types of tillage equipment acquired, there is an inherent possibility of choosing certain tillage practices while others are ruled out. For each investment decision the following is considered:

- the field suitability for possible tillage practices under the acquired equipment,
- fixed costs associated with the investment decision,
- variable costs associated with the investment decision, and
- possible regulations (rules prohibiting fall tillage or subsidies for spring tillage).

For now, exempting fixed costs, the per hectare gross margins for each tillage practice, k, on soil type i for grains can be expressed as follows:

$$\pi_{ki} = (1 - \phi) \, [p \, h_{ki} \, u_{ki} \, f_i^{\bullet} (x_i^{\bullet}) - v \, x_i^{\bullet} - c_{ki} + S_{ki} \,] \qquad [A2.5]$$

where ϕ denotes the fraction of the total area that is seeded with grass,
p denotes product price (barley is used as the grain crop),
h_{ki} is a an average coefficient for the expected effect of sowing time on soil type i caused by tillage practice k,
u_{ki} is an average coefficient for the expected effect of a certain tillage practice on soil type i caused by tillage practice, k,
$f_i^{\bullet}$ is the average expected yields for the optimal crop rotation at the expected average profit maximizing fertilization level for barley on soil type i, $x_i^{\bullet}$,
v denotes the input factor price,
c_{ki} denotes other variable costs associated with tillage practice k on soil type i, in particular time costs for tillage and changes in fuel consumption, and
S_{ki} denotes any subsidies associated with tillage practice k.

These tillage specific expected gross margin coefficients are then used in the objective function of an integer programming model where the optimal technology choice is made. This model has the following structure:

$$\pi(\theta^*) = \left\{ \begin{matrix} \mathrm{MAX} \\ \theta \end{matrix} \right\} \Sigma_{i\in I} [(1-\phi)\, a_i\, \pi_{k_i} + \phi\, a_i\, \pi_{g'i}] + \Sigma_{\theta\in\Theta} FC_\theta (k_i) \qquad [A2.6]$$

where	ϕ	denotes the fraction of the total area seeded with grass,
	a_i	denotes the area on soil type i,
	π_{k_i}	denotes the per hectare profits for grains as defined in [A2.5],
	$\pi_{g'i}$	denotes the per hectare profits for non-grain crops,
	FC_θ	denotes the yearly fixed costs for tillage practice θ.

s.t.

(a) K integer constraints (one for each tillage practice):

$$\Sigma_{i\in I}\, \eta_{k_i}(\theta) = 1, \text{ one } \eta_{k_i}(\theta) = 1, \text{ other } \eta_{k_i}(\theta) = 0 \qquad [A2.6a]$$

where	η_k	is an ordering function equalling one if tillage practice k is chosen on soil type i otherwise it equals zero (the effect of this constraint is that it incorporates the fixed costs associated with the necessary technology for this tillage practice).

(b) Total area constraint:

$$\Sigma_{i\in I}\, \Sigma_{k\in K}\, a_i\, \eta_{k_i}(\theta) \leq A \qquad [A2.6b]$$

where	A	denotes the total area.

(c) (Eventual) tillage requirements

$$\Sigma_{i\in I}\, a_i\, \delta(k_i) \geq \alpha A \qquad [A2.6c]$$

where	δ	denotes a mapping function that equals one if the tillage practice on soil type i, k, meets the tillage requirement, and zero otherwise,and
	α	denotes the area fraction required to meet any spring/reduced tillage restriction.

In brief, the model chooses the set of tillage practices, to maximize overall profits on the farm. If tillage practices that require different technologies are chosen, the additional fixed costs of all these technologies are added. This model formulation implies that tillage practices that require more than one technology, are chosen only if the additional profits of these practices more than offset the fixed costs of the necessary additional technologies. Also note that if the farm has any grass production, it is required to have the "plow" technology. Consequently for such farms, it is less likely that other techniques than "plow" are chosen. This likelihood decreases the larger the non-grain fraction is. Another implication of this model formulation is that the smaller the total area on the farm, the less likely it becomes that more than one technology is chosen.

The second step of the tillage module is to determine the tillage practices for each year on each field to be tilled, given the technologies available from the solution of step one. This optimization step is also done in an integer programming framework (PROC LP in SAS). For each field the following objective function for tillage practice k is specified:

$$\pi_{kit} = p_j \, h_{kit} \, b_{kit} \, f^*_{ijt} (x^*_{it}) - c_{kij} + S_{ki} \,] \qquad [A2.7]$$

where	p_j	denotes product price for crop j,
	h_{kit}	is a coefficient for the timeliness effect of chosen sowing time on field i in year t caused by tillage practice k,
	b_{kit}	is a coefficient for the expected yield effect of a certain tillage practice on soil type i in year t caused by tillage practice, k,
	f^*_{ijt}	is the expected yields for the optimal crop rotation at the expected profit maximizing fertilization level, x^*_i, in year t (chosen in the crop selection module),
	c_{kij}	denotes other variable costs associated with tillage practice k on soil type i, in particular time costs for tillage and changes in fuel consumption, and
	S_{ki}	denotes any subsidies associated with tillage practice k.

These field, crop and year specific coefficients are then inserted in the objective function of an integer programming model with the following structure:

$$\pi(k^*_{it}) = \left\{ \underset{\{k_{it}\}}{\mathrm{MAX}} \right\} \Sigma_{i \in I} \, \Sigma_{k \in K} \, a_i \, \pi_{kit} \qquad [A2.8]$$

where	K	denotes the set of possible tillage practices, given the solution of [A2.6]
	a_i	denotes the area on field i,
	π_{kit}	denotes the per hectare profits for grains as defined in [A2.7],

s.t.

(a) I integer constraints (one for each field):

$$\Sigma_{k \in K} \eta_{ki}(k_{it}) = 1,\ \text{one}\ \eta_{ki}(k_{it}) = 1,\ \text{other}\ \eta_{ki}(k_{it}) = 0,\ \forall\ i \in I \qquad \text{[A2.8a]}$$

where η_{ki} is an ordering function equalling one if tillage practice k is chosen on soil type i, otherwise it equals zero.

(b) Total area constraint:

$$\Sigma_{i \in I} \Sigma_{k \in K} a_i\ \eta_{ki}(k_{it}) \leq A \qquad \text{[A2.8b]}$$

where A denotes the total area.

(c) (Eventual) tillage requirements

$$\Sigma_{i \in I} a_i\ \delta(k_{it}) \geq \alpha A \qquad \text{[A2.8c]}$$

where α denotes the area fraction required to meet any "green winter area" restriction, and

δ denotes a mapping function that equals one if the tillage practice on field i in year t, k_{it}, meets the tillage requirement, and zero otherwise.

A2.4.2 Input and output data

Inputs into the models (see also figure A2.1) are:

- product and input prices,
- any scenario specific regulations (area restrictions, taxes or subsidies),
- the crop choices and expected yields calculated in module 1 (crop selection), which are averaged for step 1 (choice of technologies) and year specific for step 2 (choice of tillage practice on each field).

Outputs are chosen technology, tillage practice and various economic information for the final economic evaluation of each scenario

A2.5 Module 3: Manure Handling

In this module manure storage capacity, manure spreading technology, and time from spreading to incorporation are chosen.

A2.5.1 Modelling principles

In the real world the farmer can choose among a large number of technologies and combinations of such. In this sense the choice set can be said to be (almost) continuous. However, the choices are still discrete, so in order to keep input data demand and output generation at a reasonable level there is a need to limit the choice set.

The choice of technology combination is modelled in two steps. For each technology combination the expected profit is estimated. The chosen technology combination is then the technology yielding the highest expected profit.

Formally the model can be expressed by:

$$\text{MAX}\{E[\pi^{*1}], \ldots, E[\pi^{*z}], \ldots, E[\pi^{*Z}]\} \qquad \text{[A2.9]}$$

where Z is the total number of technologies (18), and $E[\pi^{*z}]$ is the expected profit when using technology z. For a given year and technology this is defined by

$$E[\pi^{*z}] \equiv \underset{\mathbf{N}}{\text{MAX}} \left\{ E[\pi^z] = E\left[\sum_{i=1}^{I} \left(a_i \left[p_i f_i(N_i) \Omega_i^z(N_{i1}, N_{i2}, N_{i3}) - \sum_{q=1}^{3} v_{iq}^z N_{iq} - v_m N_{im} \right] \right) - FC^z \right] \right\} \text{[A2.10]}$$

where		
	z	is the technology index
	i	is the field index
	q	is the manure spreading season index
	$\mathbf{N}$	is a vector of choice variables (N_{iq} and N_{im} $\forall i,q$)
	N_i	is the total amount of nitrogen available to the plants during the growth season ($N_i = N_{i1} + N_{i2} + N_{im} + N_{ic}$)
	N_{i1}	nitrogen from manure applied in spring, kg N/ha
	N_{i2}	nitrogen from manure applied in summer (set = 0 for small grains), kg N/ha
	N_{i3}	nitrogen from manure applied in fall (assumed to have no effect on the current growth), kg N/ha
	N_{im}	nitrogen applied as mineral fertilizer, kg N/ha
	N_{ic}	carry over effect from manure applied previous years, kg N/ha
	a_i	area of field i, ha
	p_i	price of crop on field i, NOK/kg
	$f_i()$	product function for crop on field i, kg/ha
	$\Omega_i^z()$	correction factor due to soil compaction/trafficking (a function of manure applied in different seasons) and date of sowing
	v_m	price of mineral fertilizer, NOK/kg N
	v_i^z	variable costs for technology z, NOK/kg N
	FC^z	fixed cost associated with technology z, NOK

Equation [A2.10] may look complicated, but it is an ordinary profit function. $p_i f_i()\Omega_i^z$ is the gross income per ha for field i. $\Sigma v_{iq}^z N_{iq}$ is the variable costs per ha in connection with spreading of manure, while $v_m N_{im}$ is the variable costs related to spreading mineral fertilizer.

The gross income less the variable costs yield the gross margin per ha. The gross margin multiplied by the area of the field and summed over all fields give the total gross margin. This less the fixed costs, FC^z, yield the net income, or profit.

In addition to non-negative constraints on all choice variables, equation [A2.10] is maximized subject to the following constraints

$$\sum_{i=1}^{I} a_i \sum_{q=1}^{3} \frac{N_{iq}}{1-\gamma_{iq}^{z}} = \bar{N} \qquad [A2.11]$$

$$\sum_{i=1}^{I} a_i \frac{N_{iq}}{1-\gamma_{iq}^{z}} \leq \iota^{z}\bar{N} \qquad \forall q \qquad [A2.12]$$

where γ_{iq}^{z} loss of nitrogen (as ammonia) to the air after spreading for field i in season q when using spreading technology z
$\bar{N}$ total production of manure-N (ammonia) per year, corrected for losses during storage
ι^{z} storage capacity expressed as fraction of year for technology z.

These two constraints are both connected to storage capacity. Equation [A2.11] simply says that all manure produced during a year must be spread (two spreading seasons on hog/grain farms, three on farms with meadow), while [A2.12] puts a limit on how much it is possible to spread in each season, it is not possible to spread more than the storage capacity.

Since we are not modelling the amount of stored manure explicitly, we need to make some assumptions in order to pin down some other relevant constraints. Applied in spring, manure is a substitute for mineral fertilizer. If the manure is spread in fall, the only fertilizing effect will be the carry over effect next year, which is relatively small. Since the costs of spreading manure are almost the same in spring and fall, this leads to an assumption that the storage is full when applying manure in spring.

In the case of hog farms, which are spreading manure only in spring and/or fall, the manure application in spring must be greater than the manure production in the time between the spreadings. The stored amount in spring plus production during summer less what is applied in spring should be less than the storage capacity. Formally:

$$\iota^{z}\bar{N} - \sum_{i=1}^{I} a_i \frac{N_{i1}}{1-\gamma_{i1}^{z}} + \alpha\bar{N} \leq \iota^{z}\bar{N} \qquad [A2.13]$$

Rearranging and canceling terms yield:

$$\sum_{i=1}^{I} a_i \frac{N_{i1}}{1-\gamma_{i1}^{z}} \geq \alpha\bar{N} \qquad [A2.14]$$

where α is the time, expressed as fraction of a year, from spring application to fall.

Regarding cattle/milk farms we have modelled three spreading seasons, with its consequences for the constraint set. In this case, what is applied in spring plus summer must be larger than the production of manure during this period.

$$\sum_{i=1}^{I} a_i \sum_{q=1}^{2} \frac{N_{iq}}{1-\gamma_{iq}^{z}} \geq (\alpha_1+\alpha_2)\bar{N} \qquad [A2.15]$$

where α_1 is the period of time between spring and summer application and α_2 is time between summer and fall, i.e. $\alpha_1+\alpha_2 = \alpha$. The sum of application in spring and summer cannot exceed storage capacity plus production between spring and summer.

$$\sum_{i=1}^{I} a_i \sum_{q=1}^{2} \frac{N_{iq}}{1-\gamma_{iq}^{z}} \leq (\iota^{z}+\alpha_1)\bar{N} \qquad [A2.16]$$

Finally, we must ensure that storage capacity is not exceeded between spring and summer, resulting in the following constraint:

$$\sum_{i=1}^{I} a_i \frac{N_{i1}}{1-\gamma_{i1}^{z}} \geq \alpha_1\bar{N} \qquad [A2.17]$$

A2.5.2 Level of resolution

In principle, the module can calculate optimal manure application for each model farm field. However, it turned out to be to time consuming to do this, and the resolution level had to be reduced. We are thus only modelling optimal fertilizer level for groups of crops. On cattle/milk farms, which have no winter wheat, the modelled crops are grain and meadow, while on hog farms we have differentiated between winter wheat and other grains. In both cases the differentiation is due to different manuring possibilities, i.e. on meadow there are three spreading seasons, on winter wheat there is only one and for other grains there are two. The parameters (prices, production function, etc) are found by weighing by area the parameters for each field in the underlying input data.

A2.5.3 Carry over effects

Carry over effects from manure are of two types. Some of the ammonia spread in fall will still be available the next spring. The other type is organic N entering the N pool in the soil. From this pool, a certain amount is made available to the plants each year, dependent on its size. By adding to the pool, i.e. by spreading manure, the amount made available to the growing crop will increase. The effect of mineralized organic N is assumed to be a constant fraction of the total amount of organic nitrogen produced/spread annually. The major assumptions behind this is that differences in application from year to year are evened out over time (the percentage added to the pool in the soil is rather small), and that this effect is not soil type dependent. Since the optimization is static, i.e. each year is treated independently, the ammonia carry over effect is set prior to optimization. Since the value of manure applied in spring is larger than in fall, optimal application of manure in fall is driven by the size of storage, or more precisely how much must be applied in fall in order not to exceed storage capacity during winter. By requiring application of ammonia in fall to be equal for both groups of crops, we insure consistency across years. The carry over effects are estimated using SOILN-NO.

A2.5.4 Technology choice set

The manure handling chain consist of different links, from storage facility via spreading technology to what is done after application. Since storage capacity determine how much can/must be applied in the different season, especially in fall, we are modelling three sizes of storage: 8, 10 and 12 months. As to spreading technology, the standard solution in Norway has been to spray semi liquid manure using tank trailer. In addition to this we have modelled two other options: tank trailer spreading semi liquid manure added 100% water and application of the same manure type using a system of pipes/hoses. The different application technologies yield different losses of ammonia to air and different soil compaction losses. On grains, the manure is incorporated into the soil after application. The loss of ammonia depends on the period of time between application and incorporation. We have modelled incorporation on the average after one respective two days.

Since none of the technologies at different stages are mutually exclusive, we end up with a set of 18 technologies.

A2.5.5 Input and output data

The flow in the module is shown in figure A2.3 (next page). For each technology, data is read into the module (upper left corner). Input data can broadly be divided in two groups: farm specific data and general data. The first group consists of data about number of fields, soil type and area (from the Model farm register), and crop data, generated using Module 1 (Crop

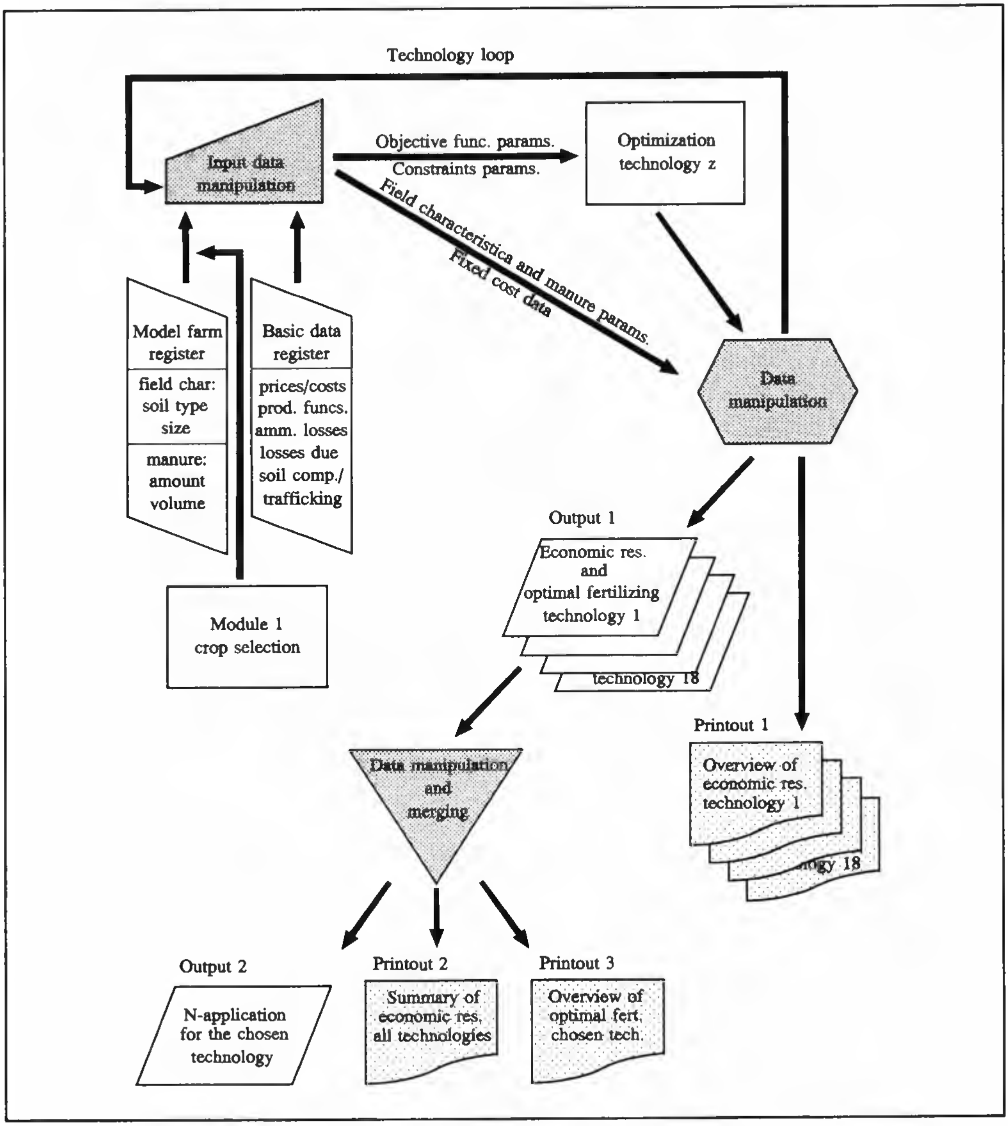


Figure A2.3: Overview of the data flow in the manure handling module.

selection, see section A2.3). As shown above, constraints in the model are mostly connected to manure production (amount and volume, see section A4.2), hence data on this is also read. Farm specific data are merged with a set of data from the Basic data register, e.g. prices (crop dependent), production function parameters (dependent on crop and soil type), data on losses of ammonia during spreading (dependent on crop, soil type and technology) and parameters for yield losses due to soil compaction/trafficking (dependent on crop, soil type and technology). In addition data on variable costs are needed in order to form the gross margin function for all fields. Given this parameter data set, an objective function, as described in section A2.5.1, and a set of constrains (equations [A2.11] - [A2.17]) are formulated. The objective function is optimized, the results are manipulated, yielding output 1 and printout 1 in the figure, whereafter the process starts over with a new technology.

The raw output from the optimization routine contains data on application of manure and mineral fertilizer, in the different spreading seasons. This is, however, done for the crop groups, as described above, so there is a need to distribute this out to the specific fields. By this procedure we get the fertilizing practice on every field for the given technology. On each field, the amount of different manure fractions (e.g. ammonia and organic N, soluble and adsorbed P) are calculated along with ammonia losses to the air. Since fixed cost do not affect the optimal level of fertilizer, fixed costs have been omitted so far. By subtracting fixed cost from the gross margin, calculated by the optimization routine, the profit is found. All this information is written to a permanent data set (output 1). In addition to this data set, an overview of the economic result, broken down into different income and cost types, is printed.

After completing the optimization for all technologies, the profits are compared, and the technology yielding the highest profit is then chosen. The results for the chosen technology is written to a data set, output 2, containing the same information as described in the previous paragraph (output 1). A summary of the economic result for all technologies, is printed, in order to get more insight into the choice of technology when comparing different scenarios (printout 2). An overview of the fertilization practice (mean over all years of manure N in different season, mineral N and the carry over effect for the different crops), is also printed (printout 3). This makes it possible to check the results and to compare different scenarios.

A2.6 Module 4: Spring time management module – choice of sowing date

This module determines sowing date and chooses sowing sequence for fields. The module is only run for the spring period. Dates for fall crops like winter wheat are set since competition between farm resources and the effects of the date chosen on N-uptake are minor.

A2.6.1 Modelling principles

The module determines sowing date principally by minimizing the costs of yield loss due to delayed sowing. The module is run for each year and takes account of actual development in the soil conditions based on weather observations. These are transformed by SOIL to a year and soil specific list informing ECMOD about dates when soil preparation is possible in spring (see chapter A3.1).

The optimization problem relates to two sets of choices. First, the farmer has to choose the sequence of fields to prepare. This choice is based on comparing the value lost per ha of land if sowing date is delayed. Second, the farmer has to choose how long days it is profitable to work in the spring period.

The module starts by defining which fields are to be sown the actual spring. This is dependent upon the chosen crop. Next it searches for the field to start with. Not all fields will be fit for conducting soil preparation at the same time. Information about the conditions in the soil is utilized to determine when a field is ready for starting. If two or more fields are fit at the same day, the module solves the following problem:

$$\text{MAX} \; \{ \; [\psi_{idt} E(\pi_i)] \; = \; p_i \; E(y_i) \; \} \qquad [A2.18]$$

where	ψ_{idt}	is a dummy variable that is zero if field i at day d of year t is not fit for tilling and 1 if it is so.
	$E(\pi_i)$	denotes expected gross income for field i
	p_i	is price for the chosen crop at field i
	$E(y_i)$	denotes expected yield per ha for field i with its given crop when sown at the optimal date

Having chosen the field with the highest expected gross income (per ha), the module observes the time needed for the spring operations of that field and processes information about the development in soil conditions. As enough hours are found to finalize all operations for the specific field, the module starts searching for other fields that can be prepared, still choosing the one with the highest expected profits. The process goes on until all actual fields are sown. The module further recognizes at which time of the day a field is finished and may thus start with another field the same day if soil conditions so allows.

Actually the sequence is run for three different day lengths and subsequent wage levels. Final sowing dates are found from the sequence satisfying the following:

$$\underset{w}{\text{MAX}} \; \{ \; E(\pi_w) \; = \; \sum_i [\; (p_i \; E(y_i) \; \frac{h(d_{it} \; - \; d_{0it})}{100}) \; - \; c_{kiw} \;]\} \qquad [A2.19]$$

where	$E(\pi_w)$	denotes expected gross margin with wage w, which is related to the a specific day length
	$h(d_{it}\text{-}d_{0it})$	denotes relative yield dependent on sowing day d_{it} on field i and year t and first possible sowing day on the same field and year. $h = 100$ if $d_{it} = d_{0it}$
	c_{kiw}	is variable costs for tillage practice k at field i at wage w (which is related to a specific day length).

h() is a function both of actual sowing date and the first possible sowing date which in turn depends both on soil type and year. More information about this function (data and estimations) is given in section A5.4.1.

Separating problem [A2.18] from [A2.19] actually assumes that the farmer knows whether the spring is going to be a difficult one or not. To the extent that an early or late spring provides reliable information on how the reminder of the spring would be, these relationships should be modelled simultaneously. There are, however, many other factors influencing the optimal sequence of tillage and seeding times, indicating that the optimal work effort may vary throughout the planting season. Modelling sowing date choice by letting the farmer adjust day length successively throughout spring would on the other hand have complicated the modelling far beyond what can be considered relevant. Tests done indicate that the importance of the simplification of using a fixed work day length through a given planting season is minor, not warranting the extra work of modelling variable lengths of the work days.

A2.6.2 Input and output variables

The input data are as follows:

- Model farm register: size and soil type of the different model farm fields.
- Basic data register: prices, cost data, time use coefficients and days when spring tillage is possible per year, area and soil type
- Agronomic practice:
    - Crop selection: crop and expected yield per field and year
    - Manure handling: volume of manure spread for each field, season and year, technology used
    - Tillage: tillage practice per field and year

Output variables are specific for each field and year. They cover actual sowing day, first possible sowing day, actual wage and time used for the spring preparations.

A2.7 Module 5: Final optimization and adjustments

A2.7.1 Modelling principles

Based on the decisions made in the previous four modules, the final optimization and adjustments module adjusts the agronomic practices made in the other modules, and calculates actual yields on each field in every year in the twenty year time horizon.

There are several adjustments undertaken in this module. Most of these adjustments are related to the expected optimal fertilization level and final yields. Since the expected yield functions are based on standard fall tillage other tillage practices will change expected yield and optimal fertilizer levels. A similar example is the effect of chosen sowing date on yields and fertilizing. This is a type of information utilized in previous modules. The role of Module 5 is to bring all this information together and make a final estimation of fertilizer levels and yields simultaneously.

One special adjustment category is related to changes in soil mineralization. In the case with continuous catch crops, the amount of plant available N will be reduced, at least for some decades due to increased immobilization. SOILN-NO is used to produce estimates for this effect. It is necessary to incorporate the change into the analysis since it will influence optimal fertilizer levels. It is also important to make the adjustment to bring consistency between the estimated yields and the actual level of plant available N in the soil. A similar adjustment is made for crops following after a meadow due to increased plant available N levels in the soils.

Other calculations are of a more straight-forward nature like allocating mineral fertilizers (based on the results from the manure spreading module). The adjustments are:

(1) Adjustment of grain fertilization levels due to sowing time. The dates obtained in the spring time management module produce an adjustment coefficient, h(d) where $0 < h(d) \leq 1$, that is multiplied with the expected yield function.

(2) Adjustment of yields and grain fertilization levels due to damages on the soil structure from some manure spreading technologies. These damages produce an adjustment coefficient, $m_{it\theta}$ where $0.9 < m_{it\theta} \leq 1.1$ that is multiplied with the expected yield function.

(3) Adjustment of grain fertilization levels caused by the presence of catch crops, and the lagged effects of catch crops. The presence of catch crops produce a multiplicative adjustment coefficient, $\kappa = 0.96$ (see A5.4.4), while the lagged effect of catch crops in the previous year increase the optimal fertilization level by $e_{i,-t} = 5$ kg/ha, and in two or more previous years increase the optimal fertilization level by $e_{i,-t} = 6$ kg/ha.

(4) Adjustment of grain fertilization levels caused by certain tillage practices. Fall plowing ($k = 1$) implies that this multiplicative coefficient, $b_{ijk} = 1$, while other tillage practices result in $.7 < b_{ijk} < 1.1$.

(5) Adjustment of grain fertilization levels caused by grains being preceded by grass or grass being seeded in grains to get grass production on field i in period t+1. These coefficients are additive. The lagged effect on the expected optimal fertilization level by grains following grasses, $g_{i,-t}$, equals −25 kg/ha, while the optimal fertilization level of seeding grass in grains should not exceed 100 kg/ha.

Mathematically these adjustments are expressed the following way:

$$\hat{\pi}_{ijt} = p_j\,[h_{it}(d_{it\phi} - d_{0it\phi})\, m_{ijt\theta}\, \kappa(e_{it})\, b_{ijk}\, \hat{f}_{ij}\,(\mathrm{MIN}(x_{ijt}, g_{i,+t}) + e_{i,-t} + g_{i,-t})) - s_{ijt}\,(j_{ij,-t}))] \qquad [A2.20]$$

$$- (v + \tau)\, x_{it} - FC_{ijt} + S_{ijt}$$

where

$\hat{\pi}_{ijt}$	denotes the expected profits on field i when crop j is grown in year t,
p_j	denotes the product price on crop j,
h_{it}	denotes the adjustment coefficient on field i in year t due to the sowing date, $d_{it\phi}$, and first possible sowing date, $d_{0it\phi}$,
$m_{ijt\theta}$	denotes damages caused by certain manure spreading techniques,
κ	denotes the adjustment coefficient caused by catch crops (e_{it}) being seeded on field i in period t,
b_{ijk}	denotes the adjustment coefficient on field for crop j for various tillage practices, k,
$\hat{f}_{ij}$	denotes the expected yield function for crop j on field i under standard agricultural practices,
x_{ijt}	denotes the expected optimal fertilization level on field i in year t,
$e_{i,-t}$	denotes an additive term for the lagged effects on the expected optimal fertilization level due to catch crops in the previous year,
$g_{i,-t}$	denotes an additive term for the lagged effects on the expected optimal fertilization level due to grass in the previous (four) years on the field in the previous (four) years,
$g_{i,+t}$	denotes an additive term for the reduction in expected optimal fertilization levels on field i in years where next year's crop is grass,
s_{ijt}	is the penalty for consecutively growing the same crop on field i,
$j_{ij,-t}$	is an index for the crops grown in previous years,
v	denotes the price on nitrogen fertilizers,
τ	denotes any nitrogen fertilizer tax,
FC_{ijt}	denotes the fixed costs of growing crop j and any catch crops on field i in year t, and
S_{ijt}	denotes any subsidies caused by certain agricultural practices in conjunction with growing crop j on field i in year t.

Solving [A2.20] for the optimal fertilization level on each field i in year t, x^*_{ijt}, the final adjustment module allocates mineral fertilizers (adds mineral fertilizers until the profit maximizing fertilization level is reached), based on the results from the manure handling module. In this connection it is important to note that if the nitrogen equivalent amounts of manure on a field exceed the adjusted optimal fertilization levels, no adjustments are made in the fertilization practices. This only occurs for modules with large amounts of manure compared to the cultivated area. Generally most fields are fertilized with both manure and mineral fertilizers, where the mineral fertilizer levels are adjusted.

The final step in the module is to calculate the actual yields and profits obtained for each crop on every field in every year. This process involves replacing the expected yield function,

$\hat{f}_{ij}$ in [A2.20] by the actual year specific yield function, f_{ijt}, resulting in expression [A2.21]:

$$\begin{aligned}\pi_{ijt} = p_j\, [&h_{it}(d_{it\phi} - d_{0it\phi})\, m_{ijtk}\, k(e_{it})\, b_{ij\phi} \\ &f_{ijt}\,(\mathrm{MIN}(x^{*}_{ijt}, g_{i,+t}) + e_{i,-t} + g_{i,-t})) - s_{ijt}\,(j_{ij,-t}))] \\ &- v\, x_{it} - FC_{ijt} + S_{ijt}\end{aligned} \qquad [A2.21]$$

where f_{ijt} denotes the year specific yield function on field i for crop j in year t,

x^{*}_{ijt} denotes the expected optimal fertilization level calculated in [A2.20], and

all other terms are the same as in [A2.20].

There is an important distinction between [A2.20] and [A2.21]. The former equation is the expression for the expected profits from which the expected optimal fertilization level, x^{*}_{ijt}, is calculated based on the choice of all the other agronomic practices. The latter is a deterministic calculation, where x^{*}_{ijt} is inserted.

A2.7.2 Input and output data

The inputs to the module are:

- From the crop selection module: Crop selection, including the use of catch crops. For grasses the profit maximizing optimal fertilization level is also obtained from this module (see section A2.3 for details).
- From the tillage module: The chosen tilling technology and tillage practices on every field in every year.
- From the manure handling module: The amount of nitrogen from manure applied to every field in every year.
- From the spring time management module: The date of sowing on every field in every year.
- From the basic data register: The parameters for the year specific production functions.
- From the scenario data: Input and product prices, fixed costs, and specific costs pertaining to the environmental regulations in the scenario to be analyzed.

Outputs are crop, final yield, N fertilizer level in total and split on different seasons. The extra N fertilizing because of the catch crop effect is also recorded. Various economic variables for the cost efficiency evaluation is produced.

A2.8 Module 6: Natural science data transformation module

This module restructures data from the different ECMOD-modules and make them usable for the natural science models. We chose to make this extra step both because the programming languages differ between the models and because it gave better control over the borderline between the two modelling spheres. Actually module 6 does not only transform data. It also adds information, mostly of the kind where the modelling is rather simple like N uptake in weeds or not modelled explicitly at all, but set, like tillage date in fall etc.

The module consists of two parts – one for the nitrogen modelling and one for phosphorus loss and erosion.

A2.8.1 Data for the nitrogen modelling

SOILN-NO needs data both about crop growth, the character of different elements of the agronomic practice, and when the various operations are conducted:

- *Nitrogen uptake* in plant material above the ground is calculated on the basis of the estimate on actual dry matter crop produced by the final optimization module (Module 5). This module also gives information about type of crop. Stubble is added to the harvested crop as a fixed proportion. N-uptake is calculated as a function of dry matter in above ground plant mass (grass/grass seeds) or of both dry matter and nitrogen fertilizer level (grain). The functional relationships used are documented in section A5.5. For peas uptake from soil is minor, and is set to the same level each year.

  For crops that have more than one growth season, the module produces crop uptake for each season. That is the case for meadow (three seasons) and winter wheat (fall and spring/summer). Further crop uptake is given for the period after harvest – like grass in fall, weeds after grain or catch crops if used. Plant residuals from peas to be incorporated into the soil when tilled is also estimated.

  Further, start and end for each crop growth season is estimated or set. Sowing date is based on the estimate from the spring time management module (Module 4). In the existing version of ECMOD, harvesting dates and the date when plant uptake stops in the fall is set.
- *Mineral fertilizing* levels are given by the final optimization module (Module 5). The first date for fertilizing in grains is set equal to sowing date. If fertilizers are given a second time in grains, the date is set relative to the sowing date – with a shorter

time interval if sowing date is late. Also in the case of grass production, date for spring fertilizing is related to how early the year is, while later in the year dates are related to the specified time for harvesting.

- *Manure* is treated in the same way as mineral fertilizers. Total volume distributed on different fractions (ammonia-N, N in faeces and N in litter), is provided by the manure handling module (Module 2). Dates for spreading are again related to sowing dates or harvesting dates if manure is spread later in the season in the case of meadow. The date for spreading in the fall relates to the plowing date.

- *Root development* is set by this module too. A standard root development scheme is constructed for each type of plant. Different root depths are determined dependent upon when the crop is sown, harvested, tilled etc.

- Finally the dates for *soil preparation* are set. Information about type of preparation is provided by the tillage module. Module 6 determines the dates based on information about sowing date from the time management module. Dates for soil preparation in the fall are set.

The data are converted to ascii-format, to be readable by SOILN-NO

A2.8.2 Data for phosphorus and erosion modelling

Basically the erosion modelling needs much of the same information as the nitrogen modelling. The system is somewhat simpler though, and we can thus be more brief here. Most important in this case is the production of an index for *crop system* based on type of crop and soil preparation system. The module utilizes information on the level of model farm fields from module 3 and 5 to make this categorizing.

As an example spring grain tilled in the fall, is one type of system. Another is spring grain tilled in the fall sowed with catch crops. A third may be meadow in its fourth year, tilled in the fall etc. There are all together 58 systems defined for the analyses done here.

The second important set of data is related to *fertilizing*. Data about amount of mineral fertilizer N and P and the different fractions of N and P in manure spread are given per model farm field. Information is further given about whether the fertilizers are incorporated into the soil or not and when both spreading and incorporation takes place.

A2.9 Module 7: Abatement cost calculations

The output from the various modules of ECECMOD needs to be compiled to obtain the private and social abatement costs from the scenarios. This is the primary purpose of the abatement cost module. Another objective of this module is to collect the vast amounts of information generated from the other modules in a format that facilitates easier interpretation of the results. All this information is compiled at two levels: (i) at the model farm level, and (ii) at the landscape level.

For each scenario the abatement cost module fetches price and cost information from the basic cost register, information on the agronomic practices with the corresponding profit estimates for each field, as well as the corresponding estimates for nitrogen leaching at the field level. The estimates for phosphorus run-offs and erosion are only available at the landscape level.

Each model farm field is weighted according to its share of the total area in the landscape or of the model farm acreage from the model farm register. Weighted estimates for profits and leaching are then compared with the Base scenario, and private and social abatement costs are calculated.

A3 The ecological models

A3.1 Choice of models

The main task for the ecological part of the modelling system to be applied in ECECMOD is simulation of the hydrology processes in the soil-plant-atmosphere system, nitrogen transformations and transportation in the soil-plant system and finally the simulation of soil loss and phosphorus losses with runoff and erosion. The ecological models to be applied should fulfil as much as possible the demands directly originating from the overall goal of the project and some additional demands as formulated here:

1. The model(s) should be able to deal with and discriminate clearly between the three main soil types clay, silt and sand, and between the actual study areas with different climatic characteristics.
2. Further, a high resolution in time is needed for variability analysis and as a consequence the model(s) must be able to handle weather data with a high resolution in time.
3. Because of the climatic conditions in Norway the models should be able to simulate snow dynamics and frozen soil.
4. The model(s) must run over a 20 year simulation period for a large variety of agricultural practices, what calls for computer and data technical solutions.
5. Botterweg (1995) has shown that user's experience is an important factor affecting results obtained in the application of complex ecological models. Thus for ECECMOD, models should be preferred the users already have experience with.
6. Exchange of information between the ecological models and with the economic models should be as simple as possible.

Only complex deterministic models cover the requirements listed, but complexity is not a goal in itself. With increasing complexity of the models, the number of parameters to be estimated increases, too. So, a balance have to be found between what is achieved in precision by more complexity in the process descriptions and what is lost in precision by introducing more parameters that will have estimation errors.

Taking into consideration what is mentioned above, it was decided to use the following ecological models:

1. SOIL for modelling hydrology processes in the soil-plant-atmosphere system,
2. SOILN for modelling nitrogen dynamics in the soil-plant system,
3. EUROSEM for modelling erosion on a plot scale, and

4. GRIDSEM for modelling erosion on the watershed scale.

No adequate deterministic model was found for phosphorus losses and it was decided to use "manual" calculation here.

The four models and phosphorus analyses are not operated independently but are linked together. SOIL output includes information to be used as input in SOILN and EUROSEM, while GRIDSEM uses EUROSEM output as input. The phosphorus analyses have to be based on output from both SOIL, EUROSEM and GRIDSEM (figure A3.1).

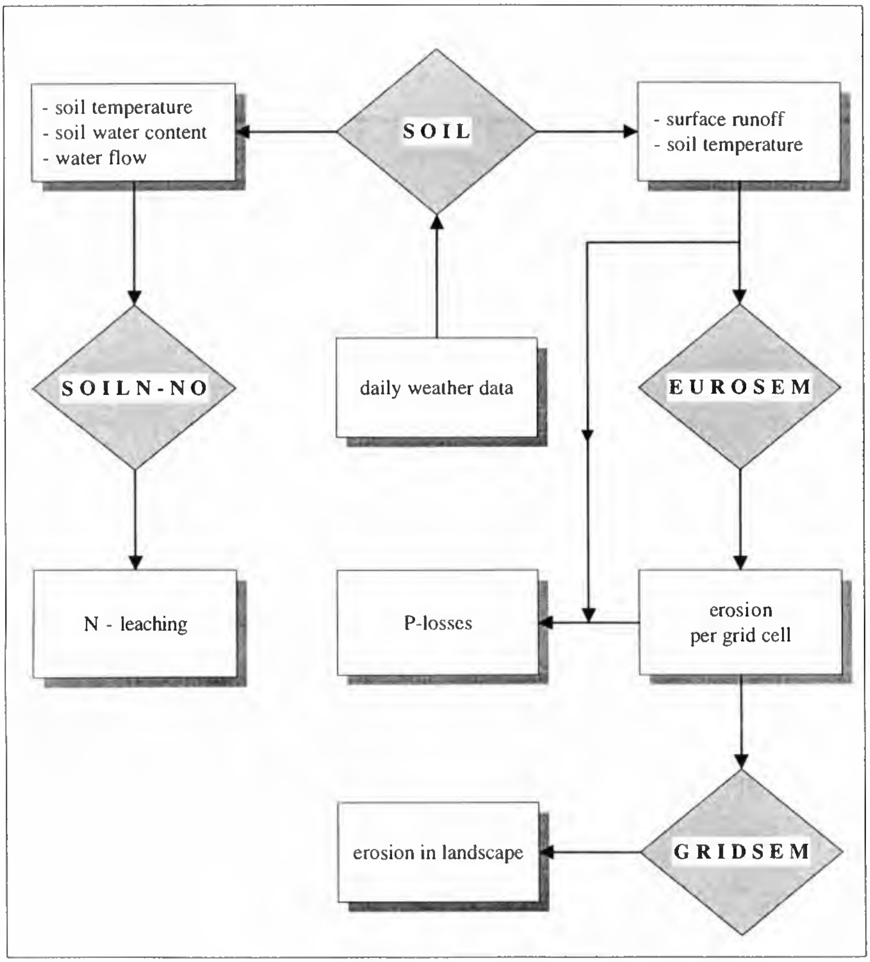


Figure A3.1: The information flow between the four natural science models applied in ECECMOD.

SOIL and SOILN have been developed at the Swedish University of Agricultural Sciences, Department of soil sciences. SOIL has been applied with minor changes in the program, but SOILN has been rebuilt and improved radically, such that a new name, SOILN-NO, was needed. EUROSEM or European soil erosion model is a deterministic erosion model developed by a group of European scientists and GRIDSEM originates from the University in Oslo, Department of Hydrology. In the following sections the different models and their methods of application are described in more detail.

A3.2 Hydrology model SOIL

Taking into account the different selection criteria listed in section A3.1, it was decided to use SOIL as hydrology model in ECECMOD. Since the publication of the first version (Haldin 1980; Jansson 1980), the model has continuously been expanded and improved. SOIL has been shown to simulate hydrology satisfactorily for a wide range of soil types and vegetation covers in different climate zones (Jansson 1994). In ECECMOD version 7.51 of the model is used.

A3.2.1 Model description

This section briefly describes the main principles applied in SOIL. It is followed by a section about the model calibration and application where input needs are discussed. For a complete description of the model, the reader is referred to Jansson (1991).

SOIL is a process based one dimensional hydrology model that simulates water and heat flow through a layered soil profile covered with vegetation (figure A3.2). Water flow is assumed to be laminar and solved with Richards equation for unsaturated flows. To solve this equation two soil physical relations, pF-curve and unsaturated conductivity as function of saturated conductivity, have to be known. Evapotranspiration is divided into evaporation of intercepted water on plant surfaces, evaporation from the soil surface and transpiration by the plants. Potential evaporation is calculated from input weather data. Reduction factors depending on plant available water in the soil profile and water content in the surface layer are calculated to get actual evapotranspiration. Typical agricultural practices like irrigation and artificial drainage are included. Heat flow in the model is the sum of conduction and convection. Compartments for snow, intercepted water and surface ponding are included to account for processes at the upper soil boundary. Snow conditions are considered both as a water storage and boundary condition for soil water flows and as an insulator regarding energy exchange. Precipitation is divided into rain and snow depending on air temperature.

During snow melt the soil surface temperature is zero when infiltration occurs. Different types of lower boundary conditions can be specified, including saturated conditions and groundwater flow. The number of weather input variables may vary depending on objectives for model application and/or availability of data.

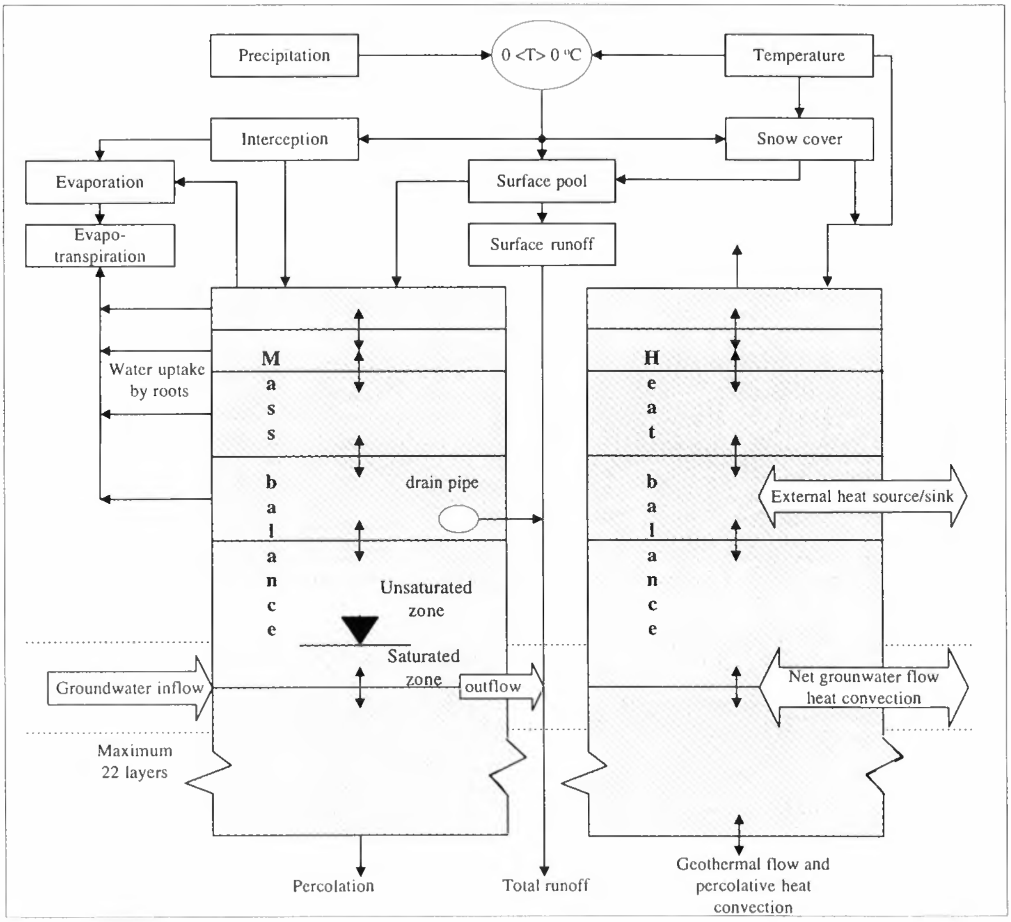


Figure A3.2: A schematic representation of the SOIL model with mass balance (left) and heat balance (right). The upper part represents the upper boundary conditions . The depth of lateral in- and outflows are user defined. Lower boundary conditions are defined by vertical flows at the bottom of the profile (after Jansson 1994).

As proposed by Botterweg (1993), the calculation of surface runoff has been improved in cooperation with Jansson, the constructor of the model. There are made two changes: a) surface runoff is not any longer taken into the profile for later to be released as runoff; b) the surface pool has to reach a minimum volume before runoff starts and it has a surface area that catches rain fall directly.

A3.2.2 Model calibration and ECECMOD's application of SOIL

An overview of the relations between SOIL and the other parts in ECECMOD is given in figure A3.3, showing a series of inputs needed and the outputs used by the other modules and models. In this section the decisions made when building the input files and their final content are discussed together with the structure of the output files. The weather input data series are described in section A4.3 while the hydrological output data series are presented separately in section A4.4.

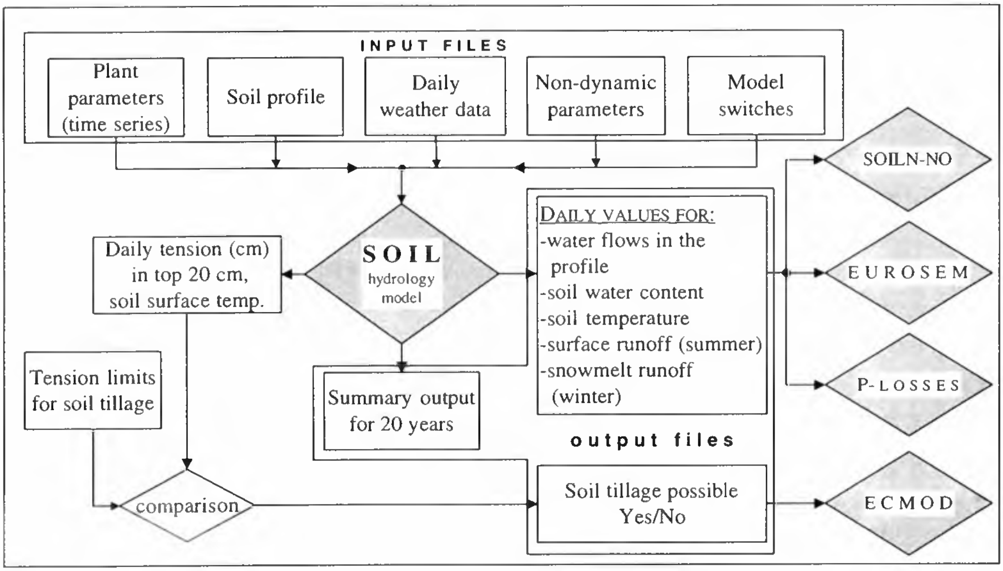


Figure A3.3: A flow chart showing the different inputs needed to run SOIL for ECECMOD and the outputs from the model runs to be used by other models and calculations in ECECMOD.

A3.2.2.1 Model calibration

The primary objective of model calibration has been to build a parameter set for each of the three main soil types producing an output that fits measured data as good as possible.

Secondly, the application of SOIL output in ECECMOD requires that expected differences in hydrology between the study areas and soil types are captured in the model output. The model user has to decide when simulated results are close enough to measured values. Here the type of application of the calibrated model has to be considered and for ECECMOD more emphasis is given to get the temporal variation correct than to fit the absolute values. Model results from simulating a single soil column should ideally represent the mean of a large number of real fields, equal in main soil type, but which may differ in other important aspects. So the final parameter sets obtained must give realistic output, but not necessary exactly what has been measured incidently on a single field. It has to be realized that the parameter values after calibration cannot any longer be looked on separately. What is important is which combination of parameter values that gives the best result, and it cannot be excluded that other combinations of parameter values could give a similar output. The outcome of a model calibration will always depend on the aim of the model application (Botterweg 1995). SOIL is calibrated for one of the study sites (the Mørdre area) and applied in the other study site (the Auli area) without further calibration. (For information about the study-sites see A4.2)

Botterweg (1995) has shown that SOIL's temperature module give acceptable results when default parameter values given in the manual are used and no further calibration is done for this aspect. When calibrating water flows and soil water content, output time series have been compared with measured data series (table A3.1). Available field data for clayey soils were several series with continuous measurements of surface runoff and drain pipe runoff from fields at Romerike close to the study area Mørdre. In addition to the same type of data series for a silty soil located inside Mørdre, also water suction values measured at different depths during the growing season were available. No field data were available for sandy soils, but it is accepted that on average the amount of surface runoff from sandy soils should be less than for clay and silt. In cases where no data for calibration were available, the model output has been evaluated against empirical results and what should be expected in accordance with expertise on hydrological processes in soils.

The parameters varied in the calibration process are those describing the soil physical characteristics as given in the profile input file (table A3.2). Further groundwater flow parameters and soil water uptake by roots have been adjusted. (See section A3.2.2.3 for a detailed description of the parameters.) The procedure used has been to change parameter values to fit model output as good as possible to measured time series and total annual figures of runoff flows. Because of the sparse amount of measured data available with a high time resolution, no objective calibration method could be applied. For calibration of the silt profile, local precipitation and temperature data from the meteorological station at Hvam, located at the border to the Mørdre field, have been used in addition to the Gardermoen weather data series (see section A4.3). The simulation period for calibration covered one year.

Table A3.1: Overview of available field data for calibration of SOIL for clayey and silty soils.

Set[1]	Area	Soil type	Variables	Spatial resolution	Time resolution
1	Mørdre	silt	tension	plot; depth 5, 20, 40, 60, 80 cm	day, only growing season
2	Mørdre & Romerike	silt	surface runoff drain runoff	field (6 ha) -"-	month
3	Romerike	clay	surface runoff drain runoff	several fields 0.82- 3.2 ha	varying between 1-10 days (whole year)

[1] Reference: Geest (1993), Ludvigsen (1995) and Øygarden (1989). Data sets made available by JORDFORSK, Centre for soil and environmental research, Ås, Norway.

Table A3.2: Soil physical input parameters to be estimated for each layer in the soil profile.

Parameter name in SOIL	Dimension	Parameter description
Parameters counting for all the layers in the soil profile		
XPSI	cm water	the upper limit (tension) for the use of the Brooks and Corey expression (Brooks & Corey 1964)
A0T & A1T	-	Coefficients in the empirical function for the temperature dependency in the hydraulic conductivity
location of soil layers and the soil physical parameters, for each layer		
UDEP	cm	upper depth of the soil layer in the profile
LDEP	cm	lower depth of the soil layer in the profile
NVAR	-	tortuosity factor in the Mualem equation (Mualem 1976)
SATC	cm/hour	saturated conductivity, *excluding* the contribution from macro-pores
SATCT	cm/hour	saturated conductivity, *including* the contribution from macro-pores
PORO	volume %	soil porosity
WILT	volume %	soil water content at wilting point
coefficients used in the Brooks and Corey expression for calculation of unsaturated conductivity out of saturated conductivity, for each layer		
LAMBDA	-	pore size distribution index
RES	volume %	residual water content
PSIE	cm water	air entry pressure

For ECECMOD it was decided to restrict the simulations to three main soil types; clay, silt and sand due to limitations in the crop growth production functions (see chapter A5). For each of the main soil types, a soil profile was selected from the soil database available at Swedish Agricultural University, Department of Soil Sciences. Selection criteria has been *a*) the particle size distribution expected for a typical clayey, silty or sandy soil and *b*) the profiles are divided into 8-10 layers down to one meter. The high vertical resolution is needed to achieve model stability. Earlier experience with SOIL has shown that the Swedish profiles made a good starting point for creating a model soil profile for the southern part of Norway (Botterweg 1990). The parameters extracted from the data base matches the parameters required by SOIL for calculation of saturated and unsaturated hydraulic conductivity for the different layers in the profile (table A3.2).

Pf-curves and unsaturated conductivity as function of water content are given in figure A3.4 for the three soil profiles used. At the start of the calibration, the pF-curve for the profiles was inspected and modified slightly to represent typical profiles for a clayey, silty or sandy soil respectively.The soil parameter values after calibration of the profiles are given in table A3.3.

The clay profile has low saturated conductivity values through the whole profile, with a sudden decrease at 80 and 90 cm depth. It was necessary to raise the outflow from the drain pipes, which in reality may partly be caused by macro-pore flow which was not simulated separately in ECMOD's application. For silt the measured data came from a field with a 1 m thick silt layer covering heavy clay. Nearly all fields with silty soils in ECECMOD are from the same area and this profile was accepted to be representative for ECECMOD's application.

A3.2.2.2 Plant parameters

Plant growth is not simulated dynamically in ECECMOD's application of SOIL and the influence of plants on the hydrological cycle through evapotranspiration is realized by user defined time series of plant growth depending variables. This procedure means that root development and root distribution over the different soil layers is not a function of soil water content. From field and laboratory observation it is known that drought in early summer reduces root development while a wet start of the growing season often gives a high root density limited to the upper soil layers (Heen 1979). Systematic measurements of root and above ground plant development over several growth seasons under Norwegian conditions were however not available. So, calibration of a dynamic plant growth model would not be possible. The error introduced with the chosen strategy is unlikely to be more serious than that introduced by using a plant growth module which is insufficiently calibrated due to lack of data.

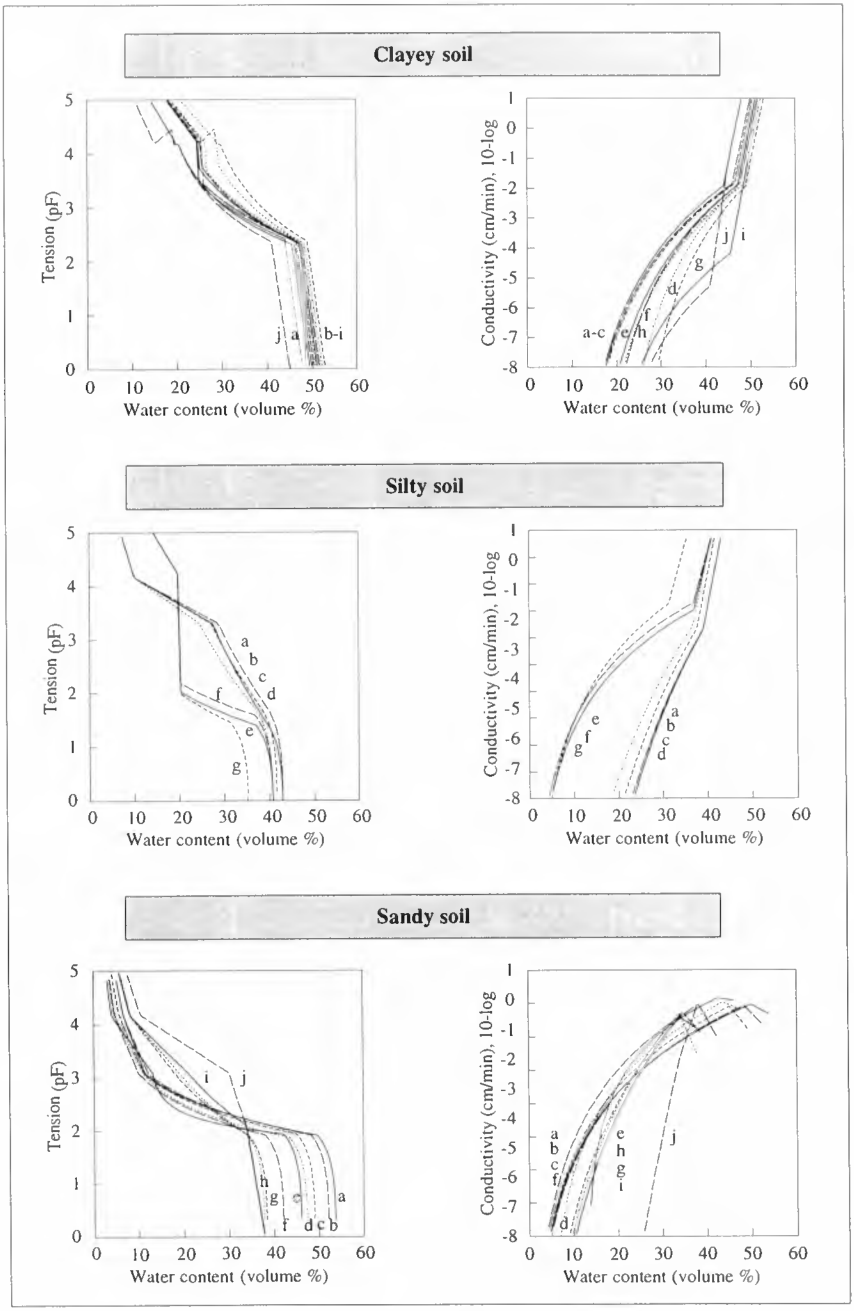


Figure A3.4: pF-curves (left) and unsaturated conductivity at different depths as function of soil water content (right) for clay, loam and sand profiles used in the hydrology model SOIL. (a-j refers to the different soil layers as given in table A3.3)

Table A3.3: Soil profile parameters after calibration of the clay, silt and sand profiles to be used for hydrology simulation in ECECMOD. If changed, the parameter values as found in the original soil database are given in italics in parentheses. (a-j refers to the different soil layers presented in figure A3.4)

			CLAYEY SOIL		XPSI=2000	A0T=5.40E-01	A1T=2.50E-2
U-LDEP	SATC	LAMBDA	RES	PORO	PSIE	WILT	SATCT
0-10 (a)	1.8 *(.001)*	0.35 *(.08)*	10.3 *(.30)*	48	188 *(38)*	25 *(30)*	530 *(30)*
10-20 (b)	2.0 *(.20)*	0.35 *(.08)*	10.3 *(.31)*	50	188 *(38)*	25 *(31)*	530 *(30)*
20-30 (c)	2.05 *(.25)*	0.34 *(.07)*	10.3 *(.32)*	51	170 *(20)*	26 *(32)*	530 *(30)*
30-40 (d)	2.06 *(.26)*	0.33 *(.15)*	20.0 *(24.)*	51	160 *(9.8)*	29 *(33)*	530 *(30)*
40-50 (e)	2.0 *(.30)*	0.33 *(.06)*	13.3 *(.31)*	51	152 *(1.6)*	25 *(31)*	530 *(30)*
50-60 (f)	2.3 *(.60)*	0.36 *(.09)*	16.0	52	152 *(1.5)*	25 *(31)*	530 *(30)*
60-70 (g)	2.4 *(.70)*	0.37 *(.10)*	24.6	53	156 *(5.6)*	25 *(32)*	530 *(30)*
70-80 (h)	2.0 *(.80)*	0.33 *(.06)*	14.3 *(.32)*	52	153 *(2.9)*	26 *(32)*	530 *(30)*
80-90 (i)	0.01 *(1.50)*	0.43 *(.16)*	15.7	50	154 *(4.0)*	20 *(26)*	4.9 *(142)*
90-100 (j)	0.001 *(1.0)*	0.40 *(.13)*	15.7 *(5.7)*	45	159 *(8.8)*	15 *(21)*	3.8 *(74)*
100-110	0.001 *(.18)*	0.13 *(.06)*	14.3 *(.31)*	47	156 *(9.7)*	25 *(31)*	2.8
110-120	0.001 *(.07)*	0.13 *(.06)*	13.3 *(.32)*	49	158 *(7.5)*	27 *(33)*	1.1 *(.10)*
120-130	0.001 *(.01)*	0.14 *(.07)*	12.3 *(.34)*	50	208 *(58)*	28 *(34)*	0.01
130-140	0.001	0.15 *(.08)*	10.3 *(.32)*	50	194 *(44)*	26 *(32)*	.001 *(.00)*

			SILTY SOIL		XPSI=2000	A0T=5.40E-01	A1T=2.50E-2
U-LDEP	SATC	LAMBDA	RES	PORO	PSIE	WILT	SATCT
0-10 (a)	15.6 (1.6)	0.10	5.20	43	10	10	2996 *(596)*
10-20 (b)	15.2 *(4.2)*	0.10	4.20	43	20	10	2996 *(596)*
20-30 (c)	14.8 *(9.8)*	0.10	2.20	42	20	10	2948 *(648)*
30-50 (d)	13.8 *(8.8)*	0.11	0.04	41	20	10	2941 *(341)*
50-70 (e)	13.8 *(8.8)*	0.42	0.04	41	20	20 *(10)*	2924 *(324)*
70-90 (f)	23.9 *(8.9)*	0.43	0.04	41	30	20 *(10)*	2935 *(135)*
90-110 (g)	29.8 *(9.8)*	0.35	0.06	35	20	20 *(10)*	2900 *(100)*
110-150	0.2 *(0.1)*	0.30	0.08	40 *(35)*	15 *(20)*	30 *(10)*	100
150-250	0.05	0.30	0.08	40 *(35)*	15 *(20)*	30 *(10)*	70

			SANDY SOIL		XPSI=2000	A0T=5.40E-01	A1T=2.50E-2
U-LDEP	SATC	LAMBDA	RES	PORO	PSIE	WILT	SATCT
0-10 (a)	8.8 *(2.8)*	0.55	0.12	53.8	71.0	6.7	2.8
10-20 (b)	8.4 *(1.4)*	0.52	0.13	52.3	71.5	6.7	1.4
20-30 (c)	8.0 *(1.0)*	0.53	0.12	49.2	73.1	5.7	1.0
30-40 (d)	10.8 *(3.8)*	0.62	4.01	47.5	64.5	4.8	3.8
40-50 (e)	14.0 *(7.0)*	1.48	12.60	46.2	79	4.0	7.0
50-60 (f)	10.6 *(.6)*	0.50	0.11	42.2	66.5	4.7	0.6
60-70 (g)	10.8 *(.8)*	0.24	0.19	38.5	49.9	8.1	0.8
70-80 (h)	11.2 *(.18)*	0.22	0.19	37.8	52.7	8.2	0.18
80-90 (i)	9.0 *(1.0)*	0.21	0.21	37.9	72.8	8.0	1.0
90-100 (j)	12.8 *(4.8)*	0.05	0.32	37.8	12.7	10.4	4.8
105-115	12.1 *(.01)*	0.03	0.33	39.3	1.3	9.8	0.008
125-135	20.0 *(14.)*	0.09	0.29	41.6	22.6	9.6	14.0
145-155	12.2 *(1.2)*	0.03	0.37	43.9	1.3	17.6	1.2
165-175	48.0 *(44.)*	0.04	0.46	52.2	9.6	27.3	44.0
185-195	12.0 *(.001)*	0.28	39.73	51.9	21.9	32.7	0.001

Two series of plant parameters are built, one for perennial plants like grass and one series annual crops, e.g. grain, followed by stubble and soil tillage. The grass is cut twice during a growing season. In table A3.4 the necessary plant parameters and their function in SOIL are given. Figure A3.5 shows the annual time series for three of the parameters. Figures of plant height for grass are based on information from Skjelvåg (pers. com.), and the other parameters are a function of plant height (Jansson 1994). The time series represent expected mean values and the same series are used for each year simulated. During the growing season the simulated water content in the soil layers between 50 and 100 cm is sensitive to the amount of active roots present. The water uptake by roots has been utilized in the calibration process by adjusting parameters related to this process (see table A3.7).

Table A3.4: Plant growth dependent input variables in SOIL given as annual time series with daily values (see also figure A3.4).

PARAMETER	DIMENSION	PARAMETER DESCRIPTION
Surface resistance	$s.m^{-1}$	Coefficient in Penman's combination equation for potential transpiration in the form given by Monteith (1965). The surface resistance is not linked to the leaf area index.
Leaf area index	-	Ratio total living leaf area / soil surface area.
Displacement height and roughness length	m	Coefficients in the equation to calculate the aerodynamic resistance, part of Penman's equation mentioned above.
Root depth (max.)	m	Maximum root depth, the distribution of roots between the surface and maximum root depth is given by a model switch. In ECECMOD an exponential decrease with depth has been chosen for clay and a linear decrease for silt and sand.

A3.2.2.3 Model switches and other parameters

Switches

SOIL asks the user to set a series of switches and parameters to define the system to be simulated and to make choices about what kind of routines to be used for different sub-processes in the model. With the exception of computer technical switches and parameters the final switch setting given in table A3.5. The final parameter values after calibration are listed in table A3.7. The reasoning behind the switch settings and parameter values is given, too.

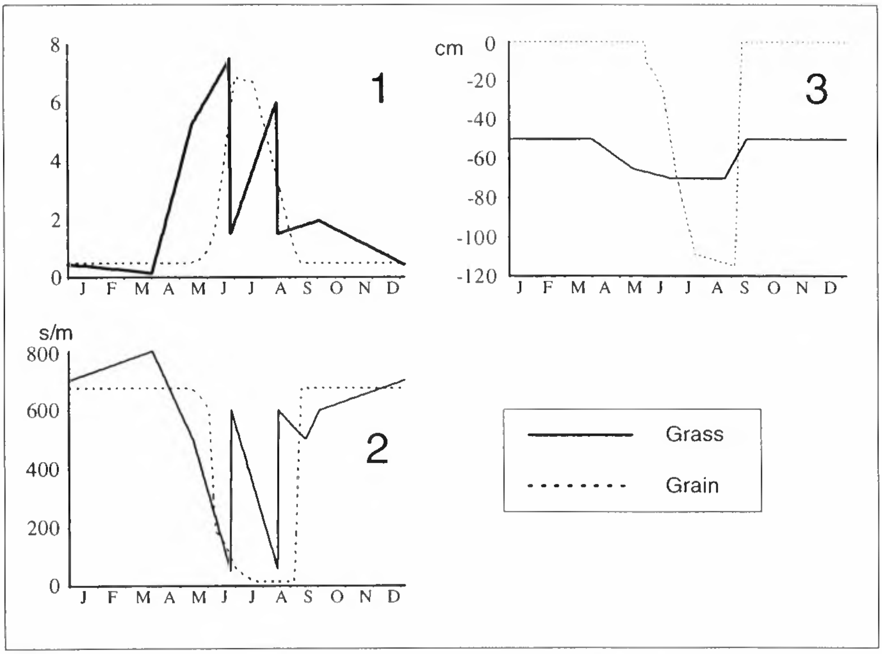


Figure A3.5: Daily values for leaf area index (1), surface resistance (2) and maximum root depth (3) for grass and grains for one year.

Table A3.5 Switch settings in SOIL for simulating hydrology processes for ECECMOD. The number in parentheses refers to a more detailed discussion at the end of the table. Switch settings are equal for all three soil types if they are not mentioned explicitly. Notes (1)-(4) at the end of the table.

SWITCH NAME	CHOICE	CONSEQUENCE FOR SIMULATION
CRACK	off	no explicit account will be taken to macro pores. (1)
EVAPOTR	3	Potential transpiration is calculated with Penman-Monteith formula and evaporation from soil surface is treated separately with the same formula. (2)
FRINTERA	on	Interaction between soil temperature and soil moisture will be considered at temperatures below 0°C. (3)
FRLIMINF	1	Infiltration capacity to the soil is reduced when ice occurs in the uppermost soil layer. Only the liquid water content in the low flow domain has a capacity to infiltrate water. (3)
FRLIMUF	on	Upward movement of water towards a frozen soil layer will be minimized by the use of the lowest water content of the frozen soil layer or of the boundary between the adjacent soil layers. (3)

"cont."

Table A3.5 cont.

SWITCH NAME	CHOICE	CONSEQUENCE FOR SIMULATION
FRLOADP	off	The total soil water potential during partially frozen conditions will not include the load governed by the mass of soil above the specific soil depth (3)
FRPREFL	on	Two different water flow domains are used when the soil is partially frozen. The high flow domain is the part of the flow system that has larger pores than ice occupies when freezing occurs. (3)
FRSWELL	on	Swelling of soil layers will be considered if the total volume of ice and liquid water exceeds the porosity of a soil layer. (3)
GWFLOW	clay=on silt=on sand=off	**On**: A net horizontal groundwater flow is calculated according to parameter values (table A3.6). A drain pipe flow is calculated. **Off**: No horizontal ground water flow is calculated. A unit gravitational gradient is assumed as driving force for a vertical flow from the lowest soil compartment
UNITG	sand=1	The water flow from the bottom layer will be calculated from the unsaturated conductivity of the bottom layer assuming a unit gradient gravitational flow. The switch has no function when GWFLOW=on.
HEATEQ	on	Heat flows between adjacent layers will be calculated (3)
HEATWE	on	Conduction and convection are accounted for when heat flows in the soil are calculated. (3)
SNOW	on	Snow dynamics are simulated.
SUREBAL	2	The soil surface temperature will be calculated from the energy balance at the soil surface taking account for both aerodynamic properties in the air and thermal properties in the soil.
INSTATE	on	Initial values for state variables are read from an external file. (4)
INTERCEPT	on	Interception of precipitation in the vegetation will be considered, and evaporation losses calculated from this storage.
ROUGHNESS	off	Aerodynamic resistance is calculated as a function of roughness length, displacement height, van Karmens constant and wind speed.
WUPTAKE	2	Water uptake by roots is calculated and a compensatory uptake takes place if a deficiency occurs at some layers simultaneously as an excess of water exists at other layers.

(1) Running SOIL with the switches and parameter values achieved in the calibration process, it was found that changes in the output relevant for ECECMOD are negligible when CRACK was put ON. For convenience reasons the switch is kept to off.

(2) Other values for this switch would give less or more complex treatments of evaporation and transpiration. Our simulations did not demand more complexity for these processes.

(3) A set of 5 switches has been used such that a reliable simulation of winter conditions is achieved.

(4) At the start of the simulation, the initial state of the system has to be defined by a series of state variables. The first period in a simulation is always sensitive for the initial state. This error source is minimized by starting the simulations at 01.01.70 while year 1 in ECECMOD analyses equals year 1973.

Values for parameters not updated during a model run.

SOIL requires a large number of parameter values to be determined. The parameters that influence the system modelled for ECECMOD are presented in the following.

The profiles for the three soil types were divided in 8, 7 and 7 layers for clayey, silty and sandy soils respectively (table A3.6). Soil parameter values read from the soil profile input files (table A3.3) are linearly interpolated to get values for the layers defined for the simulated profile.

Table A3.6: Number and upper and lower boundaries (cm from soil surface) of the soil layers defined in the soil profiles for clay, silt and sand used to simulate hydrology processes in ECECMOD.

Layer	Soil profile		
	Clay	Silt	Sand
1	0 - 10	0 - 10	0 - 10
2	10 - 20	10 - 20	10 - 20
3	20 - 40	20 - 40	20 - 40
4	40 - 60	40 - 70	40 - 60
5	60 - 80	70 - 100	60 - 100
6	80 - 110	100 - 150	100 - 150
7	110 - 160	150 - 250	150 - 250
8	160 - 260	-	-

The model is run for the period 1970.01.01 - 1994.01.01 with a time step of one day and 32 iterations per day. Output used in ECECMOD covers the period 1973.01.01-1992.12.31.

Table A3.7: Parameter values not updated during a single run of SOIL. Parameter values adjusted during calibration are <u>under lined</u>

PARAMETER / PARAMETER GROUP	VALUE	PARAMETER DESCRIPTION
Numerical parameters		Water flows between the top 7(clay) or 4(silt, sand) layers are decided to be recalculated once at each iteration; time step will be shortened by 50% in case of frost, heavy infiltration or shallow groundwater.
Evapotranspiration parameters		
ALBEDO	25%	A standard albedo of 25% is chosen for vegetation and soil.
INTLAI	0.2 mm	Interception storage capacity per LAI-unit.
INTRS	5	Surface resistance when intercepted water occurs.
LATID	60.1	Latitude of site, for calculation of day length and global radiation. Same value for both areas that only differ 30´´ in latitude.

"cont."

Table A3.7 cont.

PARAMETER/ PARAMETER GROUP	VALUE	PARAMETER DESCRIPTION
Water uptake by roots		Water uptake by the roots is governed by the calculated potential transpiration, the moisture condition and temperature in the soil.
UPMOV	0.5 (clay) 0.8 (silt & sand)	Degree of compensation of water uptake by roots (see switch WUPTAKE).
WUPCRI	clay: 1500 silt: 1200 sand: 1000	Critical tension (cm water) for reduction of potential water uptake.
Groundwater flow and drain		These parameters make sense only for clay and silt where groundwater flow and tile drains are included.
DDIST	10 m	Distance between the drain pipes.
DDRAIN	-0.9 / -1.0 m	Depth for drain pipes in respectively clay and silt profile
GFLEV	clay silt	Peak groundwater flow at 1 m depth, base flow at 1.2 m depth. Peak groundwater flow at 1 m depth, base flow at 2 m depth.
GFLOW	clay: 0.001 mm/day silt: 0.05 mm/day	Groundwater peak flow and base flow.
GWSOF	clay: 0.1 mm/day silt: 0.0	Groundwater inflow at layer 7 (110-160 cm).
Surface pool		
SPCOVTOT	15 mm	The whole surface is expected to be covered with water when the surface pool contains 15 mm water.
SPOOLMAX	clay & sand: 3 mm Silt: 10 mm	Maximum amount of water in the surface pool before surface runoff takes place.
SURDEL	0.3	The first order rate coefficient when calculating the surface runoff from surface pool.
Frost and snow		
FDF	clay=40, silt=30, sand=20	A soil type depended coefficient in the freezing point depression function.
SNOW		Below -2 ^{0}C all precipitation is snow and above 2^{0}C rain. In between a linear partitioning between snow and rain is assumed. For the other snow related parameters default values are used.

A3.2.2.4 Input weather data

SOIL is run with a time resolution of one day and driving input variables used are given in table A3.8. Global and net radiation are not given directly, but calculated by SOIL as a function of latitude, day of the year and the given cloudiness (Jansson 1991). Processes affected by radiation are evapotranspiration and snow melt, but compared to using measured radiation the differences are minor and will not influence ECECMOD's conclusions. A description of the weather data time series is presented in section A4.3.

Table A3.8: Weather variables given as daily values in the input driving file for SOIL in simulation of hydrology processes for ECECMOD.

Variable description	Dimension
Air temperature	^{0}C
Relative air humidity	% or Pa
Precipitation	mm
Wind speed	m/s
Cloudiness	1/8 fraction

A3.2.2.5 Calibration results

The goodness of fit for the calibrated model is shown in figure A3.6 and A3.7 for respectively silty and clayey soils. For the silty soil the differences between simulated and measured runoff and drain flow are larger, but the timing of the flows is correct. The higher simulated values can be explained by the higher precipitation values used in the simulation. For the clayey soil the simulated accumulated runoff and drain flow for the calibrated year are nearly equal at the end of the year to the measured values for field A. The next year differences occur, but simulated values are within the range found in measured data series as presented by field A and B. As ECECMOD preliminary is interested in relative changes, the achieved results are considered to be acceptable for this application.

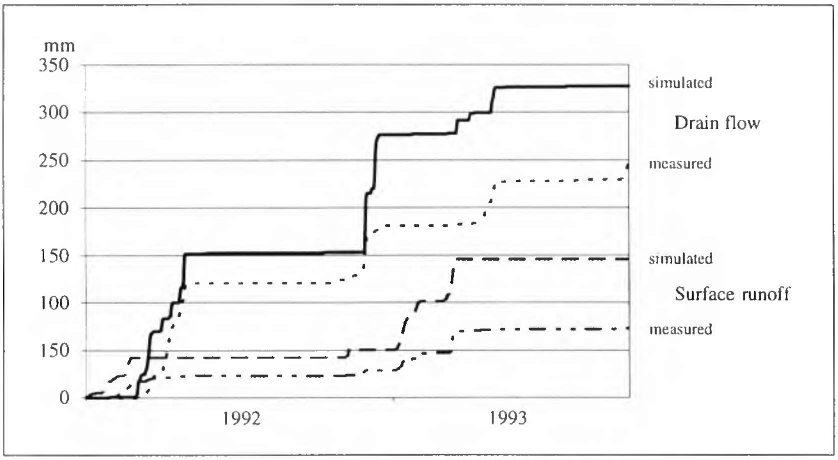


Figure A3.6: Simulated and measured accumulated surface and drain flow for a field (5.0 ha) with silty soil inside the study site Mørdre. 1992 is the year SOIL is calibrated for. (Measured data from Ludvigsen 1995 and Deelstra pers. com.).

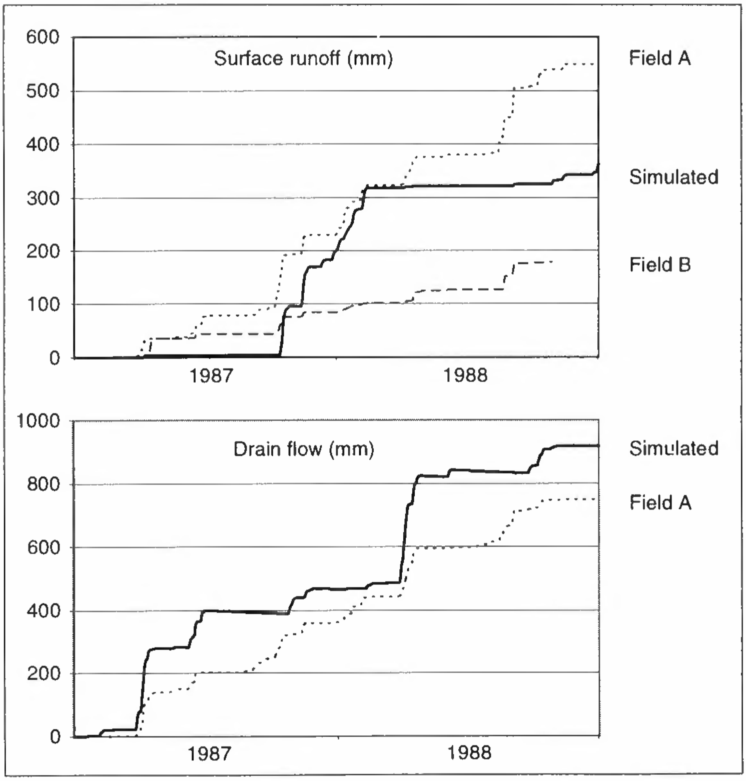


Figure A3.7: Simulated and measured accumulated surface runoff from two fields (A and B) and drain runoff for one field (A) with clayey soils at Romerike. Field A = 0.8 ha, field B = 3.2 ha. 1987 is the year SOIL is calibrated for. (Measured data from Øygarden 1989).

A3.2.3 SOIL output data to other parts of the ECECMOD system

Figure A3.2 gave an overview of the type of SOIL outputs used by other models in ECECMOD. In the following the main characteristics of these outputs are presented.

A3.2.3.1 Hydrology data for SOILN-NO

SOILN-NO uses a standard format for reading driving variables that are output variables from SOIL. Table A3.9 shows the list of variables transferred between the two models. Together 6 hydrology data sets are produced to be used as input by SOILN-NO, one for each soil type and study area. Only the outputs for the discontinuous grain crop are used.

Table A3.9: SOIL output variables exported to SOILN-NO.

Variable description	Dimension
Vertical water flow between layers	mm/day
Infiltration from surface into the soil	''
Infiltration from surface pool into the soil	''
Drainage flow from each layer into the drain pipes	''
Surface runoff	''
Soil temperature in each layer	^{0}C
Soil water content in each layer	volume %
Actual transpiration divided by potential transpiration	-
Groundwater percolation	mm/day
Air temperature	^{0}C
Global radiation	Jm^2/day

A3.2.3.2 Runoff, temperature and snow data for EUROSEM

Simulation of winter erosion with EUROSEM is possible when runoff is given as input instead of precipitation (see A3.4). Other important information is the temperature of the soil surface. To fulfil EUROSEM's demands, the series with output variables listed in table A3.10 have been prepared. Further transformations of these data series are described in section A3.4.

Table A3.10: SOIL output variables exported to EUROSEM. Output series from simulations with grain and grass as crop on clayey, silty and sandy soils have been exported for both Mørdre and Auli.

Variable description	Dimension
Depth of snow cover on the soil surface	m
Water equivalent of the snow cover	mm
Surface runoff	mm/day
Soil temperature in top layer	^{0}C
Soil surface temperature	^{0}C
Air temperature	^{0}C

A3.2.3.3 Soil tillage in ECMOD

The spring time management module in ECMOD includes determination of dates for soil tillage i.e. on which day a certain model farm field can be tilled. The possibility for soil tillage is determined by soil water content as simulated by SOIL. In addition to soil water content, air temperature must be taken into account. For Norwegian conditions (soil types, climate and machine type) spring soil preparation should not start before the soil water content has reached a tension of about 100 cm (pF=2) in the top-soil (Børresen, pers. com.). The soil temperature should have risen above +4 ^{0}C.

The following procedure is used to estimate a series of days in spring on which soil tillage is possible. From the SOIL output for grain, for the period April- June, days were selected with a tension equal 100 cm in the 20 cm thick top soil, and the results were compared with registrated data for start of soil preparation (Øygarden 1989; Ludvigsen 1995). This is repeated for tensions of respectively 90, 110 and 120 cm with or without an additional demand that soil surface temperature should be above +4^{0}C. The results were inspected and it was decided to set the final selection criteria as given in table A3.11. The final results give a reasonable series of days when tillage is possible with enough days for the farmer to finish soil preparation, but also that years are clearly discriminated. The farmer may become more under pressure later in spring and thus be willing to start soil preparation before the soil has dried enough. For this reason the critical tension is decreased after May 15.

Table A3.11: Criteria for the selection of days in spring soil tillage is possible.

Time period	Tension in top 20 cm of the soil (cm water)	Soil temperature (^{0}C)
01. April - 15. May	120	> 4
16. May - 14. June	110	> 4

Series are prepared for the 3 main soil types for both study areas for each of the 20 years in the simulation period.

A3.2.3.4 Calculation of P-losses

Phosphorus losses related to the application of manure (see section A3.5) depends both on infiltration and runoff during the days following application. File with daily runoff and infiltration values is created for this purpose for the two study areas, 3 soil types and two main crops.

A3.3 Nitrogen transformation and losses

The modelling of nitrogen dynamics and nitrogen losses in ECEC combines a dynamic modelling of nitrogen transformations/transports with estimates of nitrogen uptake in plants. The latter is based on a combination of statistical data for annual yields and production functions, and a nonlinear regression model for transformation of yields and nitrogen uptake in the whole plant (Chapter A5). The Swedish model SOILN was chosen for modelling the nitrogen transformations and transport in soil. This model was reprogrammed and changed in several aspects, so as to meet the requirement in ECEC. The new version of the model is named SOILN-NO. A brief description of the SOILN-NO model is given below, emphasizing the changes in relation to the original SOILN model, followed by a full documentation of the parameter values and initial values for state parameters.

A3.3.1 Choice of model

Several models have been developed for studying nitrogen transformations and losses in both agricultural and forest soils. The models vary in complexity from relatively simple regression models to comprehensive mechanistic models. The numbers of parameters are normally large for complex mechanistic models, in contrast to the regression models. The Danish Daisy model is an example of a very complex mechanistic model, while the Swedish SOILN model is considered to be of medium complexity. The choice of model type is governed by the purpose of the simulations. The validity of a regression model is normally limited to situations/scenarios similar to that of the empirical dataset for which the model is calibrated. In contrast, complex mechanistic models are normally considered to be more reliable tools for extrapolations to "new" situations (weather conditions and agricultural practices), "new" meaning situations other than those forming the basis for calibration of the model. Thus, a complex model was clearly needed for the ECEC purposes. The problem with complex models, however, is that the parameterization tends to becomes an overwhelming task due to the large number of parameters involved. Thus there is a tradeoff between the gains and the costs of increasing model complexity.

The objectives of the ECEC project demanded a relatively complex model to account for the variable agronomic practices involved, but the complexity should be minimized for the reasons given above. On this background, the relatively simple model SOILN was chosen as a point of departure for the N modelling efforts within the ECEC project. In spite of the strengths of the SOILN model, it soon became evident that the model was insufficient in several respects. As a consequence, it was decided to reprogram the model in a version that is easy to modify and extend. Modifications and new facilities were implemented in a reprogrammed version, which was named SOILN-NO.

A3.3.2 Important characteristics of SOILN-NO

The one-dimensional layered structure of the SOILN and SOILN-NO model take account of the spatial variability in the vertical direction while homogeneity is assumed in horizontal directions. Carbon and nitrogen dynamics in the layers are governed by a system of differential equations for each layer. Organic-N is distributed over litter, faeces and humus, and organic-C pools are included for both litter and faeces to control nitrogen mineralization and immobilization rates. There is only one litter pool in the SOILN model, in which all C and N in plant litter and biomass is included.

A3.3.2.1. Litter pools

The use of a single litter pool is not satisfactory in situations where there are several types of plant material with different rates of decomposition. In order to express the characteristics of different types of plant material, it was decided to extend the SOILN-NO model to include two litter pools. One litter pool was characterized by a fast rate of decomposition ("light litter") and the other by a slow rate of decomposition ("heavy litter"). The microbial biomass is not a separate pool of C and N, but is included in the light litter fraction. Nevertheless, microbial transformations are treated explicitly, and controlled by a separate set of parameters (growth yield, C/N ratio, humification coefficient), as in the original SOILN model. Figure A3.8 shows a schematic representation of the carbon and nitrogen flows in the SOILN-NO model. The different plant materials are characterized by their relative fractions of fast and slowly decomposable litter, and their C/N ratios.

Rapidly decomposing plant material, such as green manure, has a high proportion of light litter, whereas the heavy litter fraction is dominating in more recalcitrant plant material such as straw. The plant material is further characterized by its C/N ratio. In the figure, a shaded box with C is shown for each pool where carbon is treated explicitly. The lack of carbon in the humus fraction represents an adequate shortcut for the model to perform well regarding the N-dynamics, but the C-flow and C mass balance is incomplete. As a result, calibration against respiratory data is awkward, but still possible by assuming a constant C/N ratio of the humus pool (=10 in our case) and a synchronization of C and N-mineralization from the humus pool.

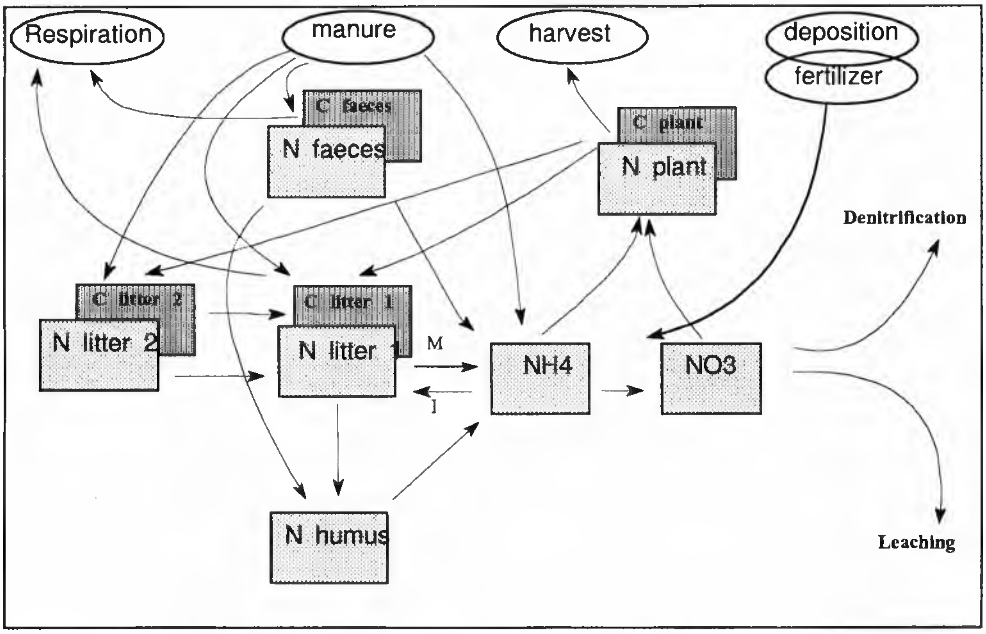


Figure A3.8 Nitrogen and carbon flows in the SoilN-NO model.

Table A3.12 show the relative fraction of fast litter for different types of plant residues, found by Vold, Breland and Bakken (1994) and Bakken and Vold (1995). These values were partly based on calibration against experimental data (parameters in table A3.19 to A3.20), and partly on information from literature.

A3.3.2.2 N uptake by plants

The daily potential nitrogen uptake by plants is distributed as potential uptake from the soil layers according to assumed root distribution. Compensatory uptake may occur. Lack of nitrogen in some layers is compensated by possible excess nitrogen in other layers. The daily uptake is less than the potential uptake at days were the compensatory uptake in layers with possible excess nitrogen is less than the lack of nitrogen in other layers.

The original SOILN model has an N-uptake sub-model where the potential daily uptake is calculated according to a logistic growth function. It is also possible to use a relatively simple crop growth model to calculate the potential N-uptake (Eckersteen and Jansson 1991). This Crop-Growth model take account of several environmental variables. However, none of these N-uptake approaches satisfied the application requirements of the project, where it was mandatory that the simulated N-uptake equal the preset nitrogen uptake (=model inputs) based on plant production functions, statistical yield data and a transformation of such estimates into whole plant N contents (appendix A5).

The insufficiency of the original SOILN model in this respect made it necessary to develop a new N-uptake approach. The new dynamic N uptake model (Vold and Søreng 1995) calculates the potential daily N-uptake according to a combination of a logistic growth function that coincide with a predefined nitrogen content in the crop at harvest, and a compensation for possible lack of soil nitrogen at days earlier in the growth season. Thus there is a compensatory N-uptake in both time and space.

Table A3.12: C-N ratio and fractions of light litter in different types of dead plant material.

Plant residue	*light litter (%)*	*C:N ratio*
catch crop	50	35.5
grass (above ground residues)	50	27
grass (roots and stubble)	50	27
straw (above ground residues)	15	70
grains (roots and stubble)	15	30
green manure	70	10
weed	50	27
Bedding (in manure)	5	70

Source: Vold, Bakken and Søreng (1994), Bakken, Vold and Vatn (1995).

A3.3.2.3 Driving files, inputs and initial values

A large data file is needed to describe the agronomic practices in the ECEC simulation. This is due to the many agronomic operations involved, and the fact that the simulation has to account for shifting agronomic practice over a 20-year period for a large number of different fields. The original SOILN model does not have the necessary input apparatus required to handle this task efficiently. The SOILN-NO model was made with more powerful/flexible routines, which enabled an efficient transfer of information from the economic modelling of farmers' behavior via driving variable files that can be used by SOILN-NO.

The model inputs include initial values of model variables, parameter values, and hydrological driving files (from the SOIL model). The driving variables comprise hydrological data generated by the SOIL-model and data for all agronomic operations (sowing, harvesting, tillage etc), and nitrogen uptake by plants.

A3.3.3 Parameters and initial values

The SOILN and the SOILN-NO model contains a large number of parameters. Estimates of parameters with a clear physical interpretation were either obtained by measurements or from the literature. Other parameter estimates were found by linear regression against measurements of model variables obtained in field or laboratory experiments (Bakken and Vold 1995).

Some parameters, such as rate constants and efficiency coefficients, cannot be found in the literature or by linear regression. These parameters are often found by trial and error. We have utilized a more objective way to estimate the parameters by non-linear regression. Most non-linear regression problems can only be solved by an iterative solution algorithm. At present, there is no such algorithm connected to the original SOILN-model. To meet the needs, the well-known Levenberger - Marquardt algorithm, as implemented by Press et al. (1988), was connected to the SOILN-NO model. The algorithm was used to estimate parameters that control the microbial C and N dynamics (Vold, Breland and Bakken 1994) and to calculate the effect of certain agronomic practices on the N availability to subsequent crops (manure, green manure, and catch crops). In addition, parameters were determined by partial considerations, exploiting data from laboratory experiments designed for such purposes. The strategy for these parameter estimations were to adopt a stepwise procedure, starting with abiotic "global" parameters, followed by biological parameters in a logical sequence according their interdependency (Bakken and Vold 1995). The parameter estimates obtained are presented below.

In addition to the parameter values, initial values for humus N is essentially a part of the parameterization exercise, even for such long simulation periods as 20 years due to the slow turnover rate. Initial values for all organic pools were determined in one iterative exercise, using the model as parameterized for ECEC project. This exorcise and the results are described below.

A3.3.3.1 Soil organic N pools, initial values

The amounts of nitrogen in humus and heavy litter are essential initial values, since they represent the cultivation history of the soils; soils under permanent pasture accumulate large reserves of soil organic N which is declining after tillage (resulting in large net mineralization). For each cultivation practice, a pseudoequilibirium will be reached after some decades. We decided to assume equivalent cultivation history for all our soils, thus the initial values of N in humus and heavy litter was determined for each site according to this criterium. The actual values were chosen as follows: For each combination of soil type and landscape type (i.e. weather conditions) we ran 20-year simulations of continuous barley cropping (autumn plowing) fertilized with 11 g N m^{-2} y^{-1}. The initial values for humus N and heavy litter C&N for each site were then determined so as to obtain a reasonably stable level of heavy litter C&N (although fluctuating according to variable plant productions), an average decline in the humus N of 0.5 g hums-N m^{-2} $year^{-1}$ (in the whole profile), and a stable vertical distribution of both pools (humus and heavy litter). The initial values for the other C and N pools (light litter and mineral N) are less important for simulation results for a 20-year period (unless extreme values were chosen). The values for these pools were chosen equal to the simulated values at spring time towards the end of the 20 years simulation periods. The obtained initial values achieved are shown in table A3.13 to A3.18.

It is important to note that the parameter values used during these exercises were those that were used during the whole ECEC modelling procedure (se below).

Table A3.13: Initial values for clay, Auli.

g N m^{-2} \ layers	1	2	3	4	5	6	7	8
Humus nitrogen, Nh	360	360	62	17	8	5	0.6	0.6
Light litter nitrogen, Nl1	0.5	0.25	0.1	0.1	0.05	0.05	0.05	0.05
Heavy litter nitrogen, Nl2	5	2.5	0.5	0.25	0.15	0.15	0.15	0.15
Light litter carbon, Cl1	4	2	0.5	0.25	0.1	0.1	0.1	0.1
Heavy litter carbon, Cl2	200	100	15	10.0	5.0	5.0	5.0	0.1
Nitrate, NO3	0.3	0.3	0.3	0.3	0.3	4.0	10	20
Ammonium, NH4	0.01	0.01	0.01	0.01	0.01	0.05	0.2	0.2

Table A3.14: Initial values for sand, Auli.

g N m^{-2} \ layers	1	2	3	4	5	6	7
Humus nitrogen, Nh	390	390	65	22	14	5.0	0.6
Light litter nitrogen, Nl1	0.5	0.25	0.1	0.1	0.05	0.05	0.05
Heavy litter nitrogen, Nl2	5.0	2.5	0.5	0.25	0.15	0.15	0.15
Light litter carbon, Cl1	4.0	2.0	0.5	0.25	0.1	0.1	0.1
Heavy litter carbon, Cl2	200	100	15	10	5.0	5.0	5.0
Nitrate, NO3	0.3	0.3	0.3	0.3	0.25	1.0	1.0
Ammonium, NH4	0.01	0.01	0.01	0.01	0.01	0.05	0.05

Table A3.15: Initial values for silt, Auli.

g N m^{-2} \ layers	1	2	3	4	5	6	7
Humus nitrogen, Nh	278	278	62	24	11	6.0	0.6
Light litter nitrogen, Nl1	0.5	0.25	0.1	0.1	0.05	0.05	0.05
Heavy litter nitrogen, Nl2	5.0	2.5	0.5	0.25	0.15	0.15	0.15
Light litter carbon, Cl1	4.0	2.0	0.5	0.25	0.1	0.1	0.1
Heavy litter carbon, Cl2	200	100	15	10	5.0	5.0	5.0
Nitrate, NO3	0.3	0.3	0.3	0.3	0.25	1.0	1.0
Ammonium, NH4	0.01	0.01	0.01	0.01	0.1	0.05	0.05

Table A3.16: Initial values for clay, Mørdre.

g N m^{-2} \ layers	1	2	3	4	5	6	7	8
Humus nitrogen, Nh	415	415	70	22	14	6.0	0.6	0.6
Light litter nitrogen, Nl1	0.5	0.25	0.1	0.1	0.05	0.05	0.05	0.05
Heavy litter nitrogen, Nl2	5.0	2.5	0.5	0.25	0.15	0.15	0.15	0.15
Light litter carbon, Cl1	4.0	2.0	0.5	0.25	0.1	0.1	0.1	0.1
Heavy litter carbon, Cl2	200	100	15.0	10.0	5.0	5.0	5.0	5.0
Nitrate, NO3	0.3	0.3	0.3	0.3	0.25	4.0	10	20
Ammonium, NH4	0.01	0.01	0.01	0.01	0.01	0.05	0.2	0.2

Table A3.17: Initial values for sand, Mørdre.

g N m^{-2} \ layers	1	2	3	4	5	6	7
Humus nitrogen, Nh	420	420	70	24	11	8.0	0.6
Light litter nitrogen, Nl1	0.5	0.25	0.1	0.1	0.05	0.05	0.05
Heavy litter nitrogen, Nl2	5.0	2.5	0.5	0.25	0.15	0.15	0.15
Light litter carbon, Cl1	4.0	2.0	0.5	0.25	0.1	0.1	0.1
Heavy litter carbon, Cl2	200	100	15	10	5.0	5.0	5.0
Nitrate, NO3	0.3	0.3	0.3	0.3	0.25	1.0	1.0
Ammonium, NH4	0.01	0.01	0.01	0.01	0.01	0.05	0.05

Table A3.18: Initial values for silt, Mørdre.

g N m^{-2} \ layers	1	2	3	4	5	6	7
Humus nitrogen, Nh	325	325	70	15	10	8.0	0.6
Light litter nitrogen, Nl1	0.5	0.25	0.1	0.1	0.05	0.05	0.05
Heavy litter nitrogen, Nl2	5.0	2.5	0.5	0.25	0.25	0.15	0.15
Light litter carbon, Cl1	4.0	2.0	0.5	0.25	0.1	0.1	0.1
Heavy litter carbon, Cl2	200	100	15	10	5.0	5.0	5.0
Nitrate, NO3	0.3	0.3	0.3	0.3	0.25	1.0	1.0
Ammonium, NH4	0.01	0.01	0.01	0.01	0.01	0.05	0.05

A3.3.3.2 Abiotic parameters

Abiotic parameters are included in the abiotic response functions that are an integral part of the SOILN-NO model. The abiotic response functions account for the response of microbial activity to soil temperature and water content. Table A3.19 list the values used in ECEC, their units, a reference and a short explanation.

Table A3.19: Abiotic parameters. Values for MOS(1) are separate for clay, silt and sand, respectively.

Parameter[1]	Units	value	Ref[2]	Description
TEMPQ10 (Q_{10})		3.8	[1]	Response to a 10 °C temperature change.
TEMBAS (t_b)	°C	15	[1]	Base temperature at which temperature effect = 1.
MOSSA (e_s)		1.0	[1]	Activity in soil moisture response function in saturated soil.
(θ_s)	%	[46.4-55.3]	[2]	Soil porosity.
(θ_w)	%	[20.6-33.5]	[2]	Wilting point.
MOS(2) ($\Delta_2\theta$)	%	1	[1]	The moisture range where activity is negatively affected by increasing moisture (irrelevant when MOSSA=1)
MOS(1) ($\Delta_1\theta$)[3]	%	10, 9, 8	[1]	The moisture range where activity is positively related to moisture.
(θ_{lo})	%	$\Delta_1\theta$ - θ_w		Lower limit of optimal moisture.
(θ_{ho})	%	θ_s - $\Delta_2\theta$		Upper limit of optimal moisture (irrelevant when MOSSA=1).
MOSM (m)		1.0	[1]	Coefficient in soil moisture function.
MOSDEN (θ_d)	%	10	[1]	Denitrification takes place if $\theta_d > \theta_s - \theta$.
DEND (d)		5	[1]	Empirical constant (response of denitrification to water content.)

1: Symbols given in parentheses are those used by Johnson et al. (1987).
2: Reference numbers are: [1] Bakken and Vold (1995), [2] Section A3.2 (this report).
3: Separate values for clay, silt and sand, in that order.

A3.3.3.3 Parameters governing microbial N transformations

The core of the SOILN model and the core of the SOILN-NO model are essentially identical, except for the inclusion of the routine of splitting plant litter into a light (= easily decomposable) and a heavy (=recalcitrant) litter fraction. This was found crucial for the model to adequately simulate the mineral N-dynamics during decomposition of plant materials (Vold, Bakken and Søreng 1994, Bakken and Vold 1995). The relevant parameter values are listed in table A3.19 to A3.21.

Here, we will briefly present the reasoning behind the faeces decomposition rate, since the others are well documented in working papers that are assumed to be published soon. The faeces decomposition rate is based on data by Kirchman (1991, 1994), and Castelanos and Pratt (1981). To determine the decay rate of the faeces material, we are interested in the stable net N-mineralization occurring after the initial rapid fluctuations. For pig and cow faeces, the stable net mineralization rate during the late phase (2-10 weeks) of the incubation experiment was equivalent to 0.15-0.2% of the total N per day (with some exceptions). These experiments were conducted at 23-25 °C. Running the SOILN-NO model for this temperature range, we find that the faeces decomposition rate (FECK) must be 0.0012 day^{-1} (base temp=15 °C, Q_{10}=3.8) to obtain equivalent net mineralization rates, given that the C/N ratio of the biomass is 4.8, the growth efficiency (LITEFF) is 0.34 and the humification fraction (LITHF) is 0.37 (as determined earlier, Vold, Bakken and Søreng 1994).

Table A3.20: Parameters governing the mineralization/immobilization (base temp= 15 °C).

Parameter[1]	Units	Value	Reference[2]	Description
HUMK (k_h)	day^{-1}	$9.9*10^{-5}$	[1]	Humus specific mineralization rate.
(k_{l1})*	day^{-1}	0.169	[2]	First-order decay rate constant for light litter .
(k_{l2})*	day^{-1}	0.0063	[2]	First-order decay rate constant for slow litter .
LIEFF (f_e)		0.37	[2]	Microbial growth yield efficiency.
LITHF (f_h)		0.34	[2]	Humification coefficient.
CNORG (r_0)		4.8	[2]	C-N ratio of microbial biomass.
FECK	day^{-1}	0.0012	[4]	Faeces specific decomposition rate.
FECEFF		0.5	[3]	Efficiency of the internal synthesis of microbial biomass in faeces.
FECHF		0.2	[3]	Faeces carbon humification fraction.
CNFEC		4.8	[4]	C-N ratio of faeces.
NITH (k_n)	day^{-1}	0.2	[2]	Specific rate of nitrification.
NITR (n_q)		56	[2]	Nitrate:Ammonium ratio in steady state.
UPMA (f_{ma})		0.2	[3]	Available fraction of mineral-N.

1. Parameters marked with * are explained in Vold, Bakken and Søreng (1994). They are not part of the original SOILN model. Other symbols in parentheses refers to (Johnson et al. 1987).
2. References are: [1] Bakken and Vold (1995), [2] Vold, Bakken and Søreng (1994), [3] Jansson (1994) and [4] Bakken, Vold and Vatn (1995).

This FECK value implies that the decay rate under field conditions is 0.1 y^{-1}(=1/4 of the rates under laboratory incubations at 15 °C), which is equivalent to a half life of 7 years. We can also roughly calculate the percent of faeces N mineralized per year, assuming that remineralization of assimilated N is completed within a year, thus assimilated N is partitioned into 14% humus N and 86% mineral N (this follows from the F_e=0.37 and f_h=0.37).

Table A3.21: Calculated annual net mineralization of faeces N (as % of added faeces N)

Year	0-1	2-3	4-5	6-7	8-9	10-11	12-13	14-15	16-17
Mineralization %	9.8	7.7	6.0	4.7	3.7	2.9	2.3	1.8	1.4

The quality of the manure (animal and treatment) appears to have a significant influence on the mineral N level in faeces amended soil during the first 2-3 weeks after incorporation (Kirchman 1994), but the slow mineralization occurring thereafter was less dependent on the animal type or pretreatment (Castellanos and Pratt 1981). Bedding and type of storage/treatment (aerobic or anaerobic) affects the amounts of available carbon, which may stimulate a rapid microbial N-assimilation immediately after incorporation of the manure into soil (Kirchman 1991). Anaerobic storage results in transient accumulation of VFA (= volatile fatty acids) which is a C source available for the soil microflora as soon as the manure becomes aerobic (in soil).

The partitioning of the manure nitrogen in ammonium and faeces N for the different animal types is shown in chapter A4.2.4, where the manure N is split between faeces-N and ammonium N. The quality of the bedding material is given by the C/N ratio and the fraction of light litter (table A3.12). The amounts of bedding in the manure is expressed by the parameter for nitrogen in bedding (MANLN). The nitrogen content of the bedding material is not interesting in itself, but given the C/N ratio and the % light litter, MANNLN is of importance.

Table A3.22: Denitrification.

Parameter	Units	Value	Description
DENPOT (k_d)	g N m^{-2} day^{-1}	0.08	Potential denitrification.
DENHS (e_s)	mg l^{-1}	12	Half saturation constant (K_s).

Source: (Bakken and Vold 1995)

Denitrification is an important factor in the N-budget of cultivated soil under extreme conditions (Bakken, Børresen and Njøs 1987, Bakken 1988). The model routines for denitrification are extremely simple, taking only temperature, moisture and nitrate concentrations into account. Model calibrations against laboratory and field data (ibid) resulted in the parameters given above (table A3.22). Data of nitrogen deposition at the sites are given in table A3.23.

Table A3.23: Deposition.

Parameter	Units	Value	Description
DEPWC	gram/liter	0.00083	Wet deposition of mineral N.
DEPDRY	gram/day	0.00075	Dry deposition of mineral N.
GWCONC	gram/liter	0.000	Concentration of nitrate in deeper groundwater.

Source: (Bakken and Vold 1995)

A3.3.4 Driving variables

The driving variables needed for the SOILN-NO simulations where obtained by using the SOIL model. Driving variables from SOIL include certain parameter values that characterize soil structure, sowing date and root depth at specified dates. A comprehensive description of the driving variable generating SOIL model simulations is given in section A3.2. The SOILN-NO model can be used to simulate the effect of different agronomic practices on nitrogen plant uptake and leaching. The ideal framework for such studies would involve simultaneous simulation of the SOIL model and the SOILN-NO model. However, the present model structure does not allow such simulations. The driving variables have to be generated in advance of SOILN-NO simulations. This is actually a consistent procedure as long as the cropping systems we are simulating are equal in both model simulations. Inconsistencies, due to different sowing dates, root depth and harvest date, can occur if the cropping system that is simulated by the SOILN-NO model is different from the cropping system in driving variable generating SOIL simulations. The reason is that root depth, sowing date and harvest date influence the hydrology of the soil. It would be extremely time consuming to generate consistent driving variables for every agronomic scenarios to be simulated within the ECEC program. As a consequence, we decided to create a single hydrological drive data file for each soil type.

Data describing the agronomic practice are also categorized as driving variables. Input to the SOILN-NO model that describe agronomic practice constitutes manure application, plowing, type of crop, nitrogen content of the yield (year specific function of N-level), root distribution, fertilization and green manuring. The inputs specify the combination of agronomic operations for each year of the period to simulate.

It is possible to specify three fertilizer and manure applications in a year. Each application is specified by the date of application and by the amount of nitrogen in ammonium, bedding and faeces. Each fraction is input to the respective nitrogen pools in the soil.

Green manure is usually considered as clover. It is possible to specify an amount of clover nitrogen to be plowed down in the autumn. Nitrogen fixed by peas which is returned to the soil as plant litter is also modelled as green manure.

Both spring plowing and autumn plowing have the effect of incorporating plant residues, roots, weeds, catch crop material or green manure into the litter pools of the soil. Also, plowing has the effect of mixing the uppermost two layers of the soil-profile. Since fertilizer application can be specified three times per year, it is also possible to simulate split fertilization.

The nitrogen content of yields harvested or plowed down are specified for each year, according to the harvest level (N) and a fixed distribution of plant C and N between grains, leaves, stubbles and roots (see below). The plant uptake model simulates nitrogen uptake according to a logistic growth curve that coincide with the specified nitrogen content at harvest.

A3.3.5 Plant production, N-uptake in plants and the distribution of C and N in plants

The distribution of plant N between roots, stubbles and shoots determines the amount of N exported from the soil-plant system with harvest. For grains, the following distribution of the assimilated N has been used: Roots 30%, stubbles 10%, straw 10% and grains 50%, primarily based on the results from the Swedish Project Ecology of Arable Land (Hansson and Andren 1987, Paustian et al 1990, Petterson and Hansson 1990). According to these results, however, straw should contain a larger pool of N than 10% of the total (and stubble an equally smaller proportion). This does not conform with the average distribution between N in grain and straw for long term field experiments, however, although falling well within the range of variation between years for the same experiments (Uhlen and Lyngstad, unpublished). We decided to compromise to ensure internal consistency: The N in straw was assumed to be 10% of plant N (hence 20% of N in grains), conforming with the distribution measured in the empirical material used to estimate the parameters for equation A3.2). Further, stubble was assumed to represent another 10% of the total plant N uptake, to ensure conformity with the swedish observations between above ground and belowground N in plants.

The same Swedish studies were used to estimate the C/N ratios of the various root types (table A3.12). As described in Chapter A5, the nitrogen in straw+grains was calculated as a function of grain yield and nitrogen level:

$$g = a*NT*Y/(b*NT+Y) \qquad [A3.1]$$

where:

- g is the N-content in grains+straw
- NT is the available nitrogen (fertilizer N + mineralized soil organic N)

- Y is the yield (derived as a function of fertilizer level, the function being a year specific yield function based on a combination of agronomic experiments, yield statistics, and the specific agronomic operations on each single field, see section A5.1)
- a and b are parameters specific for each grain species (see table A5.13)

The total N uptake in plants is thus g/0.6 (assuming that g represents 60% of the total N uptake, according to the N-distribution between grains, straw, stubble and roots given earlier).

The calculation of nitrogen uptake in perennial plants is a bit more complicated. The harvested dry weight and harvest-N is determined based on a yield function and a constant nitrogen content of grass. The estimate used for calculation of nitrogen uptake is corrected for clover N, since the latter is assumed to get its nitrogen from the air (N-fixation). The harvested N is then used to calculate the total N in the plants, assuming the following distribution of plant N: Harvest 63%, stubble 16% and roots 21%, based primarily on the estimates by Hansson and Petterson (1989), Andren et al. (1990). The next step in the modelling is to decide a death rate of plant N at each harvest time: a fraction of the roots are assumed to survive the harvesting. Likewise, a fraction of the stubble may be supposed to survive. The roots dying off are entered into the litter pools (according to their C/N ratio and the percentage of light litter, table A3.12). The stubble which dies off is accumulating at the soil surface and not entered into the litter pools before tillage (NB: this is the model's imitation of a slightly more complicated reality). Thus, "death rate" at harvest for roots has implications for the microbial delivery of plant N for microbial decay and N-mineralization during the life time of the ley, whereas the "death rate" of the stubble determines the amount of organic N accumulating to be "activated" (i.e. entered into the litter pools for decay) at the time of plowing. Based on a number of studies of root dynamics (Hansson and Petterson 1989, Andren et al. 1990), we have decided to assume 100% death of stubbles and 90% death of roots at each harvest. The 100% death rate in stubble is in line with the original SOILN model (which implicitly assumes 100% death). The 90% death rate in roots is equivalent to setting $f_{lr}=0.1$ in equation 1 (Johnsson et al 1987). The high percent death rate in roots is questionable from a mechanistic point of view, but is legitimate in ensuring that a substantial fraction of the unharvested plant N is recirculated through litter) during the life time of the ley. This represents a "trick" to mimic the partial decomposition of surface litter in the ley.

The death rate also affects the estimated uptake of mineral N from the soil as modelled in ECEC, since this uptake is the net increase in total plant N between two harvests (thus the amount of plant N at the beginning of this period will affect the amount of N needed taken from the soil). Thus a low death rate would result in a relatively low total plant uptake of mineral N from the soil.

The partitioning of N in catch crops is assumed to be like the ley, but with slightly different qualities (table A3.12). In all the scenarios modelled, we have assumed that the whole catch crop is plowed in, thus 100% enters the litter pools at the time of plowing.

A3.3.6 Output

A system for specifying a selection of state variables to write to file has been implemented in SOILN-NO. Each state variable has a unique code. The code and a specification of layer are given for each state variable to write to file. A list of the state variables is given in table A3.24.

Output from the SOILN-NO model can be a state variable from a specified layer or the sum of the state variable from all layers. The model has utility programs for transformation of state variables to flow variables with units of flow per day, per year or with units of irregular time intervals. The latter is useful in comparison of flow-variables with corresponding measurements that are taken irregularly in time. Output files are easily read and presented graphically by MATLAB. A complete description of how to handle input and output data is given in (Vold and Søreng 1995).

Table A3.24: State variables in the SOILN-NO model.

C_l	Carbon in litter.
N_{l1}	Nitrogen in light litter.
N_h	Nitrogen in humus.
NH_4	Ammonium in soil.
NO_3	Nitrate in soil.
CO_2	Accumulated CO2.
C_{l1}	Carbon in light litter.
C_{l2}	Carbon in heavy litter.
N_p	Nitrogen in plants.
N_{leach}	Accumulated nitrogen leaching.
N_f	Undissolved nitrogen fertilizer.
N_d	Accumulated denitrification.
$N_{mineral}$	Total nitrogen mineralization.
N_{l2}	Nitrogen litter 2.
C_{faeces}	Carbon in faeces.
N_{faeces}	Nitrogen in faeces.

A3.4 Soil erosion modelling in ECECMOD

This section describes how erosion is estimated in ECECMOD including the shift from one dimensional to three dimensional simulation, i.e. from point to landscape. Two models, operating on two different spatial scales are applied in sequence to obtain the desired results.

A3.4.1 Choice of modelling system

Hydrology, nitrogen dynamics and losses of nitrate through leaching are simulated with the one dimensional models SOIL and SOILN-NO that only consider the vertical movement of water and mass transport with these flows. The amount of surface runoff generated is estimated, but no horizontal flow is included. The erosion processes to be simulated consists of three different elements; a) soil detachment by raindrop impact, b) soil detachment by overland flow and c) net soil transport by the overland flow. Two of these processes are related both to the overland flow´s velocity and the hydraulic radius of the flow.

The European soil erosion model EUROSEM was selected as the deterministic erosion model. One of the scientists in ECECMOD has been involved in the development of that model. The model package GRIDSEM was chosen for erosion analyzes at the watershed level. In this section first a separate description of the two models is presented. Thereafter an explanation is given for how the two models have been integrated.

A3.4.2 Description of the modelling system

A3.4.2.1 Description of EUROSEM

The European soil erosion model (EUROSEM) is a process-based erosion prediction model designed to predict erosion in individual events and to evaluate soil protection measures (Morgan 1994). The model is developed by a team of scientist from ten European countries. A detailed description of the model is found in Morgan et al. (1996) The model uses a process-based approach to predict erosion for individual storms from fields and small catchments. A flow chart of the model is given in figure A3.9. The basic inputs that describe the system to be simulated are the length and width of the individual fields or slope segments to which the model is being applied and the rainfall depths for successive time periods in the storm within which rainfall intensity is more or less uniform. The model simulates the volume of rainfall reaching the ground surface as direct throughfall, leaf drainage and stemflow. The rate of detachment of soil particles by raindrop impact is computed as a function of the energy of the direct throughfall and leaf drainage, the detachability of the soil and the depth of surface water. Values for soil detachability are related to soil texture and taken from a review of soil detachment experiments by Poesen (1985). Runoff is generated as a flow depth using the KINEROS model (Woolhisher et al.1990), modified to deal with rainfall interception and surface depression storage depending on the roughness of the soil surface. Soil tillage affects the roughness. The detachment of soil particles by runoff is determined as a function of the difference between transport capacity and existing sediment concentrations in the flow, simultaneous deposition of sediment from the flow and the cohesion of the soil. The model uses a mass balance equation to compute sediment transport, erosion and deposition over the land surface. EUROSEM simulates tillage and crop cover effects in a dynamic way and accounts for soil protection measures by describing the soil microtopographic and vegetation conditions associated with each practice.

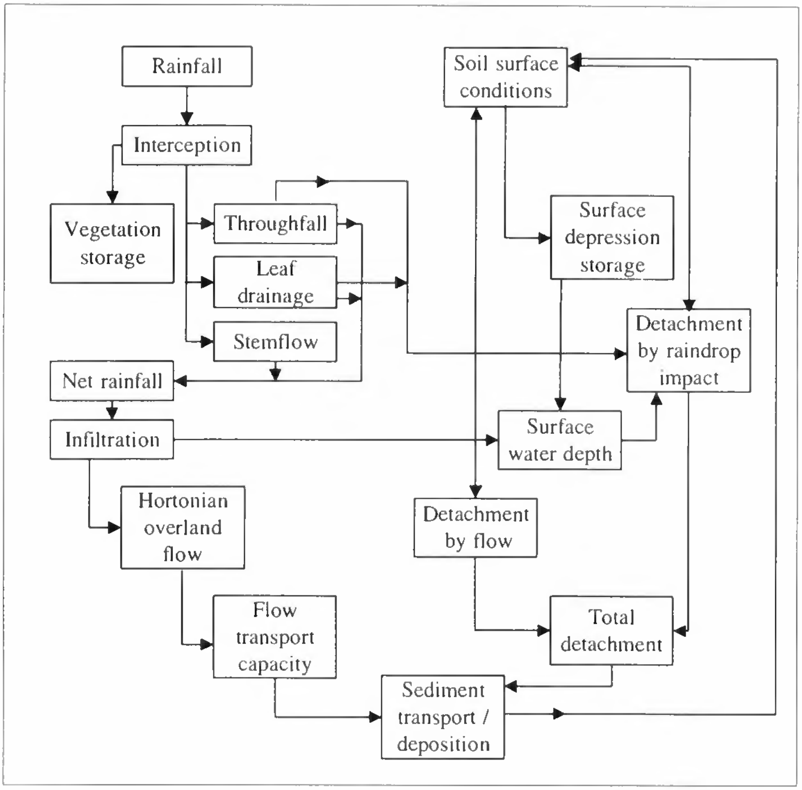


Figure A3.9: Flow chart for the deterministic erosion model EUROSEM, applied in ECECMOD (from Morgan et al. 1996).

Application of EUROSEM for ECECMOD requires the simulation of erosion also by snowmelt. Figure A3.10 shows where and how winter conditions affect erosion processes. As shown by Botterweg (1994;1996) erosion under winter conditions is possible to simulate with EUROSEM when for an event of snowmelt, runoff depth is given as input instead of time series with rainfall depths. Infiltration into the soil must then be zero and soil detachability for rain drop impact is zero too. In the model the depth of a non erodible layer can be defined to represent a frozen layer. Soil cohesion decreases during winter depending on the number of frost-thaw cycles. The parameter values that need to be estimated for running EUROSEM for ECECMOD are described in section A3.4.3.

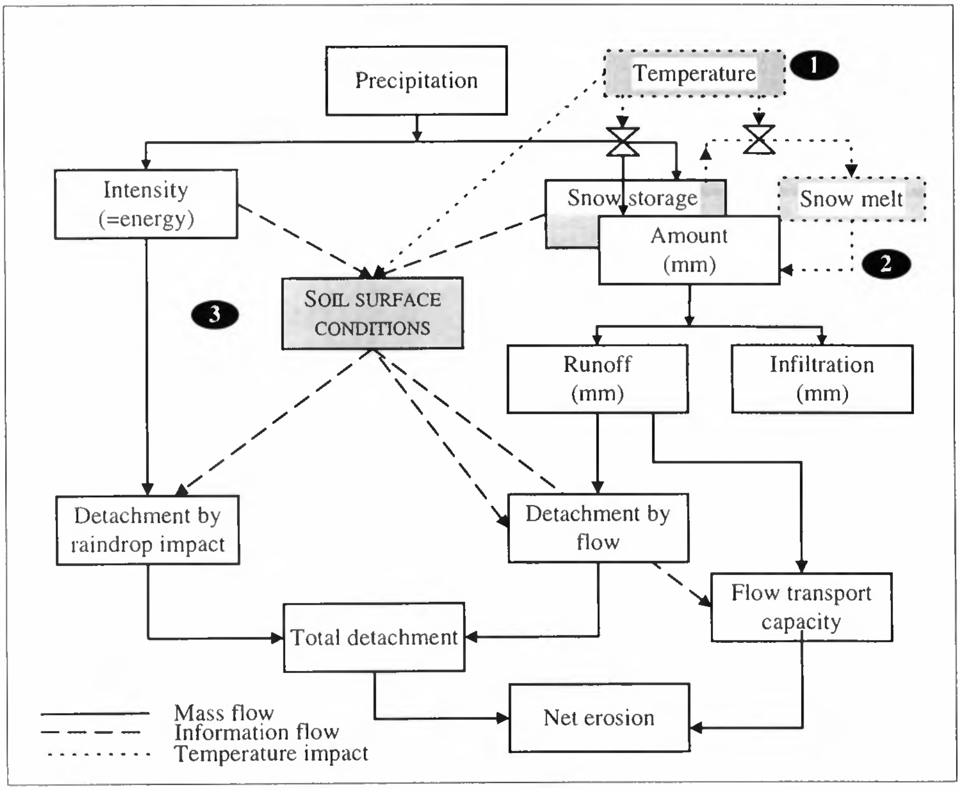


Figure A3.10: A schematic presentation of how winter conditions affect soil erosion. 1) temporary storage of precipitation on the surface, 2) snowmelt runoff instead of precipitation as driving input and 3) change of soil surface characteristics as the result of frost.

A3.4.2.2 Description of GRIDSEM

The GRIDSEM modelling system (Leek 1993) was originally used with USLE (Universal Soil Loss Equation), but with the intention of extension to other erosion models at a later date. The GRIDSEM concept forms a data management and general computation platform. It can apply the principles of various erosion models to individual grid cells (small rectangular areas) of a catchment or slope, as it takes account of some of their global interdependencies. In ECECMOD's application erosion values derived by EUROSEM are used directly as a grid cell factor. This in contrast to e.g. applying USLE where erosion is calculated for each cell based on the different factors for that cell.

The digital elevation model (DEM) in GRIDSEM represents the surface and forms the basis for several parts of the modelling process. It is important that the area's topography is accurately simulated. Examples of the importance of the accurate representation of the surface include modelling of sediment generation, export from cells and the possibility of deposition in others. The following demands are made on the DEM: a) high resolution, b) high degree of accuracy in representing the 3-dimensional surface and c) fast algorithm.

a. High resolution

Erosion levels can differ in serious degree over very short distances. Studies on erosion have also often been conducted on quite small (1 to 2 m^2) trial areas or standard USLE plots (88 m^2). Initially it was felt that it would be most appropriate if the resolution for the model was as fine as possible, while still being of a size compatible with the capacity of the computer. In the end we settled for cells of 30x30 m, which gave about 180.000 cells for Mørdre area and about 600.000 cells for Auli area, including cells with non-arable land (see A4.2).

b. High degree of accuracy for surface

To achieve a high degree of accuracy, all of the data points available are used in the model. Interpolation is done by piece wise linear functions orthogonally on the Z/X, and Z/Y axis, in the Euclidian space bounded by the minimum/maximum values of the 3 axes. Representation of the slopes, their length, gradient and direction of slope, have a higher priority than relative height differences.

c. Fast algorithm

The model has been built such that an optimal utilization of available data storage capacity and calculation capacity is assured. During the adjustment of the model to the two study areas with their large number of cells, it was found that the choice of fast algorithm become vital.

The use of EUROSEM means that erosion mapping units must be defined. The erosion mapping units are operationally defined here as the cells of the model. These are areas or elements which have spatial homogeneity with respect to soil series, slope gradient and length, crop rotations and tillage. In the application for ECECMOD a by EUROSEM beforehand estimated erosion value is given to each erosion mapping unit or grid cell (see fig. A3.11). For ECECMOD routines for finding flow paths for overland flow in the landscape are implemented and the distance from each cell to the nearest downslope flow path is calculated.

Numerical analysis is concerned with approximating solutions to mathematically expressed problems. GRIDSEM consists of a raster of square grid cells, of size defined by the user, covering a particular area, delineated by the user in a perimeter data file. The shape of the cell can in fact be irregular, with the important advantage over other raster models, that there is no “dead” area of redundant cells between the actual perimeter and the rectangular limit of the raster. This saves computer and storage space, and cuts out search operations on redundant cells. The model is relatively simple, with certain intra- and inter-cell relationships to give a more efficient numerical model. The model uses as input, or can generate internally, the following attributes for each cell:

SPATIAL:	Coordinates X, Y of the center of the cell.
TERRAIN:	Coordinate Z (height).
FACTOR1:	Erosion (as simulated with EUROSEM).
FACTOR2:	Slope (segment attribute)
FACTOR3:	Soil type (segment attribute)
FACTOR4:	Downslope distance to nearest flow channel
Road:	Whether the cell is road surface (or other special type)
Channel:	Whether the cell is a water channel
Deposition:	Whether the slope is conducive to deposition in the cell
Direction:	The direction of slope
Class:	The model farm field the cell belongs to (see also section A4.2.2)

The model is organized as a database with data objects representing the cells of the model. This enables the model to be processed and updated, without unnecessary re-computation of the respective information layers each time. As previously stated, the structure of the model system is modular. The modules are independent of each other, but pass parameters and/or data.

A3.4.3. The application of EUROSEM and GRIDSEM

An overview of the information stream from the economic model ECMOD (see section A2), to estimated total erosion in the watershed is presented in figure A3.11. The agronomic practice is output from ECMOD and together with information about daily weather, topography and soil type, the potential daily erosion levels are estimated by EUROSEM for grid cells with equal characteristics. Grid cells are the smallest homogeneous spatial units in ECECMOD only used for erosion modelling (see also section A1.4). In the next step GRIDSEM uses all the information to allocate potential erosion to each individual grid cell in the watershed and estimates total erosion in the landscape.

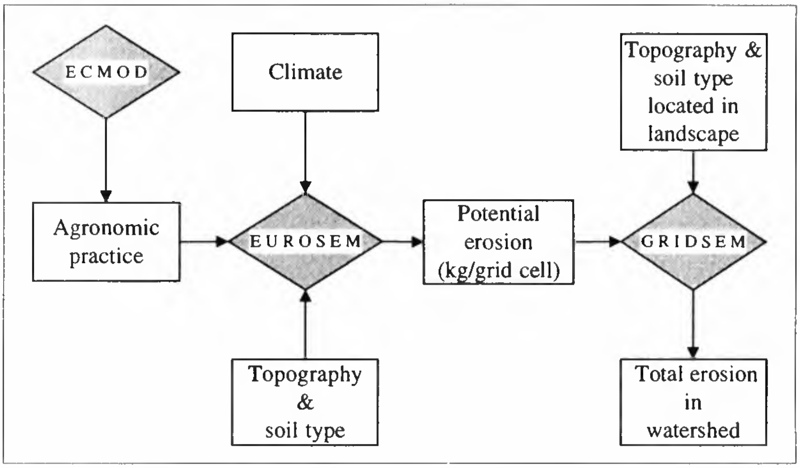


Figure A3.11: Overview of the information flow from ECMOD to the watershed, to estimated erosion.

A3.4.3.1 Building a database for potential erosion

For data technical reasons it is not possible to run EUROSEM for each ECMOD output and runoff event during the 20 years simulation period. It was decided to run EUROSEM beforehand for all the possible combinations of agronomic practices, soil type, topography (as slope) and precipitation or snowmelt runoff classes. These results were stored in a database. Then potential daily erosion levels could be selected from the database based on the actual daily combination of agronomic practices, soil type, slope, and precipitation or snow melt event. GRIDSEM includes the location of all the grid cells belonging to a specific model farm field and so each grid cell in the watershed was equipped with the right potential erosion level (see section A3.4.3.2). Finally GRIDSEM calculates actual erosion for the whole watershed (see section A3.4.3.3).

The way the database for potential erosion levels has been built is schematically shown in figure A3.12. The contents of the different inputs will be discussed.

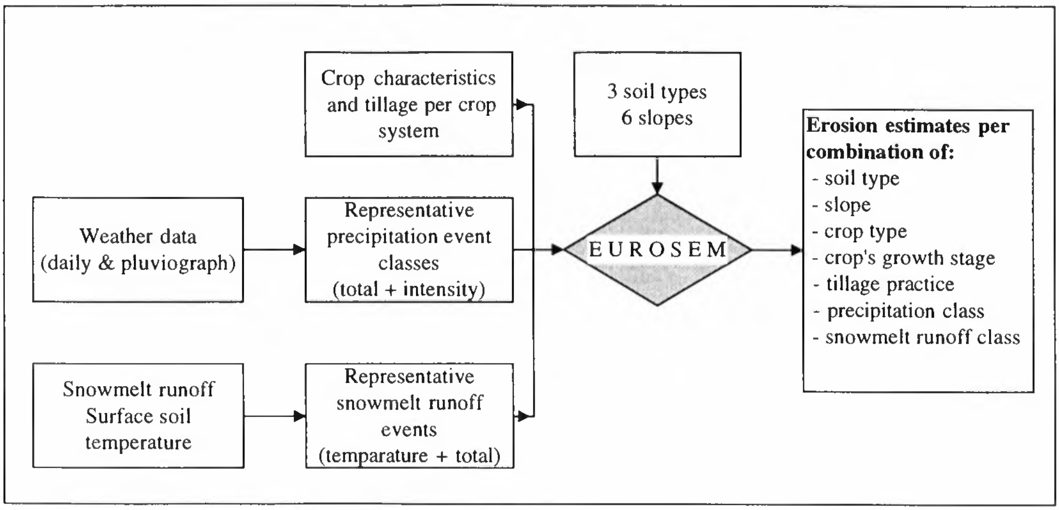


Figure A3.12: An overview of the inputs needed by EUROSEM to build a database with potential erosion values.

Crop characteristics and soil tillage per crop system

EUROSEM needs input related to the crop grown and the soil tillage practiced (see next section). Plant related input parameters are plant height and plant cover. To reduce the number of EUROSEM runs, continuous variables are divided into classes and the median values are used as input into EUROSEM. Soil tillage practice affects several input parameters and it is distinguished between classes of sow bed, harrowed and ploughed. Each class is further divided into fresh tilled surface and surface affected by weather for more than 4 (sow bed) or 10 weeks. The agronomic practices chosen by ECMOD are grouped into a set of crop systems. For each of the 58 annual systems possible, the daily values for plant height, plant cover and tillage are estimated and as class values combined in one variable called PLS_CODE. These values are independent of crop system sequence or year and stored in a database. Spring crops have a variable start of their growing season and PLS_CODE's are estimated in real time based on the sow date given by ECMOD (see section A3.4.5). From the created data base the unique combinations of plant height, plant cover and soil tillage for a given crop system and day of the year can be selected. One series of PLS-CODE values covers the whole year and one series covers the period October-May, when in addition to precipitation also snow melt runoff may occur.

Weather data: precipitation

EUROSEM has to be run with precipitation given as a time series with cumulative depths of rainfall for the length of the precipitation period. These data can be derived directly from pluviograph data, but this type of data was not available for the whole ECECMOD simulation period. The only pluviograph observation available were from the Gardermoen climate station for the summer seasons 1987-1992 (see table A4.4).

A comparison is made between the different observation series to decide if the pluviograph data could be used as input for EUROSEM. A frequency distribution of 8 daily precipitation classes for the different observation series is shown in table A4.24. The frequencies of Gardermoen daily values calculated from pluviograph observations, Gardermoen daily values (excluding snow) and Melsom daily values (excluding snow) for the precipitation classes did not differ much. It is concluded that precipitation input series for summer precipitation could be created from the available pluviograph observations.

Table A3.25: Frequency distribution (%) over 8 precipitation (mm/day) classes of precipitation registered at Gardermoen and Melsom climatic station as daily values, and daily precipitation based on registrations with a pluviograph during 6 summer seasons at Gardermoen. Registered daily values are split for periods with and without snow.

Precipitation class	Precipitation (mm/day)	Gardermoen Snow	Gardermoen No snow	Melsom Snow	Melsom No snow	Gardermoen Pluviograph
1	<0.5	19.3	23.8	24.8	19.9	24.2
2	0.5-2.5	28.8	26.9	27.7	28.8	26.7
3	2.5-5.0	15.5	16.2	16.2	16.0	14.4
4	5.0-7.5	10.1	10.0	10.2	9.4	8.6
5	7.5-10.0	6.9	6.9	7.2	6.5	8.0
6	10.0-15	7.7	8.4	7.6	7.2	9.0
7	15-20	5.1	5.4	3.4	5.4	3.6
8[1)]	>20	6.5	4.0	2.9	6.7	5.4

[1)] Later this class was divided in two: class 8: 20-35 and class 9: >35.

Precipitation events with varying total amount and intensity were selected from the pluviograph data following the procedure described her. First the pluviograph data were summed per 10 minutes periods and divided into 3 precipitation events series such that events are separated by at least 2, 4 or respectively 6 hours without precipitation. Based on total precipitation the events were then grouped in 9 classes as described in table A3.25 (the first 7 classes listed + 2 classes after splitting class 8). The mean precipitation intensity per 10 minutes is calculated for events within one class. Then from each class, 3 events are selected to represent low, medium and high precipitation intensity for total amount of precipitation for that class. The following rules were applied to secure an objective selection of events:

intensity class 1: mean intensity = MEC - 1*STD.MEC
intensity class 2: mean intensity = MEC
intensity class 3: mean intensity = MEC + 3*STD.MEC

where MEC=mean precipitation intensity for an event class, and STD.MEC=standard deviation of MEC. If several events within a class had the same statistics, the event with shortest duration was chosen. For class 1, with the lowest total amount of precipitation, no high intensity sub-class was found and the final result was 26 precipitation classes, each represented by a real precipitation event from the pluviograph observation series. (table A3.26).

Table A3.26: Total amount, duration and maximum 10 minutes intensity of natural precipitation events representing 26 precipitation classes with varying total amount (see table A3.25) and intensity (see text). The mean intensity for a class is based on all the events within the class.

Precipitation class	Precipitation intensity mean for class	(mm/10 min) max for event	Total per event (mm)	Duration (hh:mm)	
1.1	0.07	0.2	0.4	0 : 50	
1.2	0.13	0.4	0.4	0 : 20	
2.1	0.09	0.2	1.4	2 : 20	
2.2	0.12	0.4	1.4	2 : 20	
2.3	0.22	1.4	2.0	2 : 20	
3.1	0.11	0.2	3.8	8 : 20	
3.2	0.19	0.8	2.8	2 : 50	
3.3	0.50	2.8	3.0	1 : 50	
4.1	0.19	0.4	6.8	7 : 20	
4.2	0.37	1.4	6.6	4 : 20	
4.3	0.53	4.0	6.4	3 : 20	
5.1	0.16	0.4	8.4	12 : 00	
5.2	0.37	1.6	8.8	4 : 50	
5.3	0.89	6.0	8.0	1 : 50	
6.1	0.16	0.2	10.2	13 : 50	
6.2	0.43	2.0	11.6	5 : 50	
6.3	0.57	5.2	10.2	5 : 50	
7.1	0.16	0.6	15.8	15 : 50	1)
7.2	0.35	3.2	17.0	15 : 20	1)
7.3	0.43	6.0	16.8	9 : 50	
8.1	0.35	0.8	22.0	10 : 20	
8.2	0.33	2.2	24.6	12 : 50	
8.3	0.76	10.8	22.9	10 : 50	
9.1	0.29	1.0	39.8	28 : 50	1)
9.2	0.63	2.6	74.0	23 : 50	1)
9.3	0.44	3.2	34.8	21 : 20	1)

1) Later these duration had to be reduced to about 12 hours because EUROSEM could not treat such long events.

Weather data: snowmelt runoff

Snowmelt runoff events cannot be derived from available standard meteorological data and they are identified from the output of SOIL. The variables used are listed in table A3.27. In the first step, the days with runoff caused by snowmelt or a combination of snowmelt and precipitation are selected following the rule (abbreviations as in table A3.27):

if $\{(SR>0) \text{ and } [(P>0 \text{ and } SD>0) \text{ or } (SD\ \text{day}_{(n)} < SD\ \text{day}_{(n-1)})]\}$ then snowmelt event.

Table A3.27: Variables imported from SOIL output (1-6) and measured precipitation used to estimate snow melt runoff events.

Variable description	Abbreviation	Dimension
1. Depth of snow cover on the soil surface	SD	m
2. Water equivalent of the snow cover	WS	mm
3. Surface runoff	SR	mm/day
4. Soil temperature in top layer	TT	^{0}C
5. Soil surface temperature	TS	^{0}C
6. Precipitation	P	mm/day

Series from simulation with grain and grass on clayey, silty and sandy soils have been used for both Mørdre and Auli and joined into one data set. The days with snowmelt runoff are divided into 8 classes independent of soil type and main crop. Botterweg (1996) and Øygarden (1989) have shown that snowmelt over frozen soil give minor erosion, while runoff over thawing soil give high amounts of soil loss. So each runoff event class is divided into two sub-classes with respectively $TS<0$ and $TS\geq0$. Finally an event in each class with a runoff value as close as possible to the mean of the class is selected to represent the class (table A3.28). Even at low soil surface temperatures ($<-5^0$C) SOIL still simulates small amounts of runoff. This is runoff from the surface pool filled foregoing days when temperature was above zero. The water in the surface storage is in the model not affected by temperature. This situation may occur at a sudden change from mild to cold weather. The runoff values selected are daily values and time series are made with duration increasing with the total runoff from 1 to 6 hours with peak discharge at about one third of the period.

Finally daily precipitation and snowmelt runoff events have to be linked to the classes described above. For snowmelt runoff this could be done directly depending on the simulated runoff amount and the soil surface temperature simulated with SOIL. Daily precipitation at summer is only linked to a precipitation class when simulated runoff for that day is >0. Simulated runoff depends on soil type and main crop and thus for each study area 6 series (2 main crops x 3 soil types) with the precipitation or snow melt class per day with runoff are created.

Table A3.28: Snowmelt runoff classes used to simulate erosion caused by snowmelt runoff with EUROSEM (see table A3.27 for an explanation of the abbreviations).

Runoff class	Real event		Class values		
	SR(mm)	TS(^{0}C)	mean (mm)	n	Std.
1.1	0.22	-20.3	0.22	1449	0.13
1.2	0.24	3.5	0.25	214	0.13
2.1	1.33	-2.5	1.33	1715	0.58
2.2	1.40	0.0	1.39	588	0.58
3.1	3.42	-1.2	3.47	693	0.69
3.2	3.63	0.0	3.64	373	0.72
4.1	6.09	-1.2	6.06	213	0.70
4.2	6.14	0.0	6.17	214	0.72
5.1	8.51	-2.9	8.58	76	0.77
5.2	8.67	0.0	8.65	127	0.69
6.1	12.17	-0.1	11.83	41	1.14
6.2	12.18	0.2	12.11	117	1.25
7.1	15.33	-3.2	15.96	10	1.22
7.2	17.43	0.0	17.46	45	1.56
8.1	22.39	-4.4	22.39	1	-
8.2	22.26	2.2	22.72	13	2.12

Soil type and slope

The three main soil types clay, silt and sand are used to run EUROSEM. Slopes are divided in six classes (table A3.29). Areas in the highest slope class are expected to be used as permanent extensive grass land.

The slopes and soil types are not evenly distributed in the two study areas (table A3.30). Mørdre is a relatively flat area with silty soils, but on areas with slopes over 10 %, as much as clayey as silty soils are found. In Auli more arable land is found on steeper slopes in class 2 and 3.

Table A3.29:Slope classes defined for simulating potential erosion levels with EUROSEM.

Slope class	Slope (%)		Parameter value (%) in EUROSEM
	from	to	
1	0	2	1
2	2	4	3
3	4	10	7
4	10	16	13
5	16	25	20
6	>25		27

Table A3.30: Distribution of the arable land in Auli A, Auli B and Mørdre on soil and slope classes, percent.

Area	Soils			Slope classes					
	Clay	Silt	Sand	1 0-2%	2 2-4%	3 4-10%	4 10-16%	5 16-25%	6 >25%
Auli A	57	4	39	14.1	18.2	42.7	16.2	6.6	2.2
Auli B	64	8	28	31.6	24.4	33.2	7.9	2.6	0.4
Mørdre	24	75	1	63.4	11.0	10.3	6.7	7.8	0.8

A3.4.3.2 Parameterization and calibration of EUROSEM

EUROSEM is run to estimate potential erosion levels for areas of 30*30 m, the grid cell dimension used in GRIDSEM. No systematic field measurements exist for single erosion events and this made calibration of the model difficult. Erosion measurement series are presented by Øygarden (1989) and Ludvigsen (1995), but these are based on mixed flow proportional samples and a clear description is not always given of the soil surface conditions over the sampling period.

Table A3.31: Measured erosion from different plots, Romerike and the Mørdre site. For Auli no plot data were available.

Area	Field size (ha)	Soil type	Erosion 1000kg/ha/year	Reference
Romerike	0.1	clay	0.1-7.0	Ludvigsen 1995
	0.8-3.2	clay	0.1-2.0	Øygarden 1989
Mørdre	0.01	silt	0.1-1.4	Ludvigsen 1995

Lundekvam (1995) has presented erosion levels in a comparison of different tillages, but also his data give total soil losses over a longer time period, covering several events. Nevertheless, the different data series indicate the mean level of erosion that may be expected and give an idea about the relative erosion levels in relation to soil type and soil surface conditions (table A3.31). In the parameterization of EUROSEM, a single event model, no direct comparison between simulated and measured values has been possible. Instead simulated values are adjusted to the estimate single event values given in table A3.31. The application of EUROSEM in ECECMOD is comprehensive and is extended into situations not earlier tested. Earlier tests of the model have been done on data from plot studies in England and Spain (Quinton and Morgan 1996). This has to be taken into account when evaluating the potential erosion levels obtained. The final parameter values and their function in the model are presented in table A3.32. Details of the parameter functions are found in the model's user guide (Morgan et al. 1993) and the extensive model description (Morgan et al. 1996).

*Table A3.32: EUROSEM parameter description and the values applied to estimation potential soil loss from homogeneous plots of 30*30 m, without channels. Model technical parameters are not included. Values for clay(=cl), silt(=si) and sand(=sa) are given respectively. When not differentiated between soil types the given value is used for all three soil types.*

PARAMETER	PARAMETER DESCRIPTION	ESTIMATED VALUE
TEMP	air temperature used infiltration function (°C)	summer[1]: 10 winter: 2
SLOPE	field slope (%)	6 classes (table A3.29)
Parameters to describe hydrology		
FMIN	Saturated hydraulic conductivity (mm/h)	summer[1]: cl=1.4; si=3.0; sa=7.0 winter: 0
G	effective capillary drive (mm)	table[2]: cl=890; si=485; sa=101
POR	soil porosity (% volume)	table[2]: cl=48; si=50; sa=44
THI	Initial volumetric water content (%)	cl=34; si=41; sa=40
THMAX	Maximum volumetric water content (%)	cl=39; si=47; sa=44
Soil mechanical characteristics		
EROD	Detachability of the soil particles by raindrop impact (g/J)	table[2]: cl=2.0; si=1.2; sa=1.9
D50	The median particle size of the soil (μm)	literature: cl=2; si=5; sa=250
COH	Soil cohesion (kPa) depending on soil-type and amount of roots (summer=figures for no roots - max roots; winter=figures for no roots)	summer[1]: cl=12-26; si=3-12; sa=2.0-3.2 winter: cl=2; si=1; sa=1
MANN	Mannings n:combined effect of soil particle roughness, surface tillage and plant cover. Minimum and maximum values	cl=0.02-0.12; si=0.018-0.12; sa=0.01-0.12
Soil surface conditions for sow bed, harrowed and ploughed		
DEPNO	Average number of rills across the width of the slope	sow bed: 30; harrowed: 30; ploughed: 70
RILLD	Average depth of the rills (m)	sow bed: 0.02; harrowed: 0.02, ploughed: 0.20

[1] Different values are used for erosion caused by precipitation and snow melt runoff.

[2] Values are taken from tables given in the user guide.

The plant parameters plant height and plant cover are taken directly from the crop characteristics data base (see section A3.4.3.1). Maximum interception storage is then a function of plant height and crop type.

A3.4.3.3 Potential erosion levels simulated with EUROSEM

A presentation of the complete data base with erosion levels is not possible, but some charachteristical relative changes depending on soil tillage and precipitation and snow melt intensities can be read from table A3.33 and A3.34.

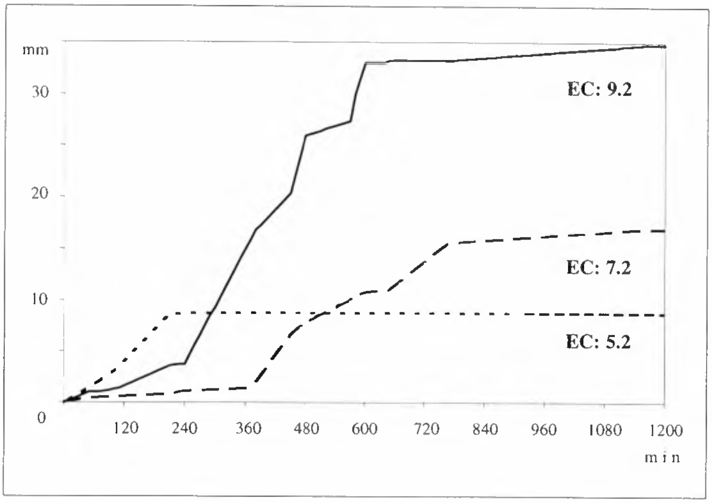


Figure A3.13: Accumulated precipitation depths (mm) for 3 precipitation classes (EC) with equal maximum intensity but different total amount of precipitation.

During summer highest precipitation level gives most erosion. The figures also show that a newly prepared seed bed on clayey soils can have an erosion rate as high as a ploughed field on that soil when exposed to heavy rain. This was not found for silty soils because the higher infiltration rate for silty soils combined with a larger surface storage capacity on a ploughed field compared to a seed bed, is able to keep runoff low. For the precipitation event 9.2, silty soil produces less runoff on the seed bed, but the higher erodability compared to clay results in a higher erosion level. The precipitation event 7.2 did not produce any erosion for the cases in table A3.33. The reason is shown in figure A3.13. The compared precipitation classes are real events and have different cumulative depth curves. The low intensity during the first 380 minutes of event 7.2 causes the soil to become dryer and the following high intensity precipitation does not result in runoff. Silt and sand have low erosion values in summer especially when compared with erosion levels for winter (table A3.34). This is caused by the higher infiltration rates for these soil types. For the snow melt runoff simulations, runoff is given directly as input and differences in infiltration rates have no effect on erosion levels.

Table A3.33: Potential soil erosion (kg/ha) from grid cell sized plots (30x30 m) simulated with EUROSEM for two summer precipitation events classes (EC), two slope classes and two soil types for different soil surface conditions. For sandy soils, no erosion was simulated for these cases.

	Slope class 2 (2-4%)				Slope class 5 (16-25%)			
	EC 5.2		EC 9.2		EC 5.2		EC 9.2	
Soil surface conditions	clay	silt	clay	silt	clay	silt	clay	silt
New prepared seed bed	1.2	0.0	1657	598.0	4.6	0.0	4352.0	4954.0
Full developed crop	0.0	0.0	25	0.1	0.0	0.0	110.0	5.4
Stubble, straw removed	0.0	0.0	265	0.2	0.0	0.0	1106.0	837.0
Stubble, with straw	0.0	0.0	16	0.1	0.0	0.0	84.0	5.5
Grass	0.0	0.0	0	0.0	0.0	0.0	0.2	2.2
Ploughed	0.1	0.0	1524	0.2	0.2	0.0	4122.0	2815.0

Table A3.34: Example figures of potential erosion levels (1000 kg/ha) during snow melt runoff events (EC) of three magnitudes over thawing soil under different soil surface conditions and two slope classes.

		Slope class 2 (2-4%)			Slope class 5 (16-25%)		
Surface condition	Soil type	EC 4.2	EC 6.2	EC 8.2	EC 4.2	EC 6.2	EC 8.2
Ploughed	clay	0	0	0	0.7	1.0	1.7
	silt	0	0.1	0.1	6.8	10.0	17.0
	sand	0	0.3	0.2	8.9	22.0	43.0
Stubble	clay	0	0	0	0.4	0.5	0.9
	silt	0	0	0	3.9	6.0	10.0
	sand	0	0	0	5.9	14.0	26.0
Harrowed	clay	0	0	0	0.4	0.6	0.9
	silt	0	0	0.1	4.3	6.7	12.0
	sand	0	0.1	0.1	8.6	20.0	37.0
Winter wheat	clay	0	0	0	0.4	0.6	0.9
	silt	0	0	0	4.2	6.5	11.0
	sand	0	0	0	8.1	19.0	35.0
Grass	clay	0	0	0	0.4	0.5	0.9
	silt	0	0	0	3.9	6.0	10.0
	sand	0	0	0	5.9	14.0	26.0

The highest erosion levels in winter on thawing soils are simulated for sand and silt that have low soil cohesion values. Here the differences between the slope classes are much larger than during summer precipitation events.

A3.4.3.4 The application of GRIDSEM in ECECMOD

The existing GRIDSEM model has been expanded with routines for finding flow channels in the digital landscape and to weight the soil loss contribution from each individual grid cell to calculate the total soil loss for the watershed or landscape. Further the data base of the model has to be filled with the basic information from the two study areas. The procedures to achieve this are described in this section.

The basic database for GRIDSEM is an overlay of a soil map representing the three main soil types (see section A4.2.1) and topography. Digital topographic information has been obtained from stereo photogrammetry, giving continuous altitude values. Each map figure is connected to a model farm field (see A1), and the area is divided in regular grid cells of 30 by 30 meters. The automatic overlay did not give appropriate digital location of the flow channels in the landscape, so in addition a combination of three routines was applied:

1. *A mask for a local operator.* The digital map model was searched for local minima under the criteria that the second derivative had to be positive for both axes within the mask for all axial directions.
2. *An interactive procedure.* The slope in the axial direction was represented in grey scale values (1:225) making it possible to identify the flow channel pattern visually, and manually digitize the channels.
3. *Digitized from maps.* From the available topographic maps streams were digitized directly.

After the flow channels were located in the digital landscape, the shortest down slope distance was calculated for each cell.

The fraction of the sediment eroded in a single grid cell that reaches the flow channel depends on the distance and slope to the stream. In GRIDSEM the procedure chosen for weighting sediment losses is similar to the segmentation procedure described by Wischmeier and Smith (1978):

$$SFL = \frac{i^{m+1} - (i-1)^{m+1}}{N^{m+1}} \qquad [A3.2]$$

where: SFL is soil loss fraction calculated for each cell
i is segment sequence number which is a function of the distance to the stream
m is slope length exponent as a function of slope
N is the number of cells along the slope.

GRIDSEM allocates potential soil erosion to each grid cell based on the farm field connection (=agronomic practice), soil type and slope of the cell. Actual soil loss from a grid cell delivered into the flow channel is then calculated by multiplying potential erosion with the SFL-value for that cell. It is assumed that the error source in GRIDSEM is linear and calibration is done by scaling the results obtained according to measured sediment losses from watersheds (table A3.35). The results from GRIDSEM are within the measured ranges.

Table A3.35: Measured erosion from different watersheds in Southern Norway, including the studied sites in Mørdre and Auli. Measurement periods: 2-5 years.

Area	Total agricultural area (ha)	Main soil type	Sediment loss (kg/ha-year)	Reference
Romerike	216	clay	1980-2630	Øygarden 1989
Romerike	148	clay	600-1100	Øygarden 1989
Mørdre	446	silt	448-720	Ludvigsen 1995
Auli (field)	44	clay-silt	270-1030	Ludvigsen 1995
Auli (forest)	12	clay-silt	63-81	Ludvigsen 1995

A3.4.3.5 Erosion levels in the landscape

The description given so far in section A3.4.3 has been independent of the input from ECMOD. This section deals with the procedures in the final step where information from ECMOD is used to estimate potential and actual erosion in the landscape (figure A3.14). Output from ECMOD is a list with the annual agronomic practice per model farm field (A2.8.2). From the crop system data base corresponding daily PLS-CODE and code for main crop (grass or grain as used in SOIL) is read for the simulation period of 20 years. For crop systems with a variable sowing date the values cannot be read for a whole year from the database. Between April 1. and harvesting the PLS-CODEs are calculated in real time based on the sowing date given by ECMOD. In the next step for each model farm field, potential soil erosion levels for grid cell sized areas are read from the erosion data base giving potential erosion for each day with runoff depending on PLS-CODE, main crop and precipitation/snowmelt runoff class for that day. A total of fifteen values are read, one for each combination of the three soil types and slope class 1-5. In GRIDSEM the 15 potential erosion values are allocated to grid cells belonging to plots that represent the model farm field in the landscape, but now with a higher resolution regarding soil type and differentiated for slope (figure A3.15).(See section A1 for a definition of the different area levels). This is repeated for each model farm fields and finally each individual grid cell has a potential erosion value for a given day where at least one combination of soil type and main crop has lead to runoff. Grid cells in slope class 6 have been defined as permanent grass land and have a daily potential erosion level independent of ECMOD output. The final step by GRIDSEM is then to calculate total erosion for the whole watershed and add up per season and year.

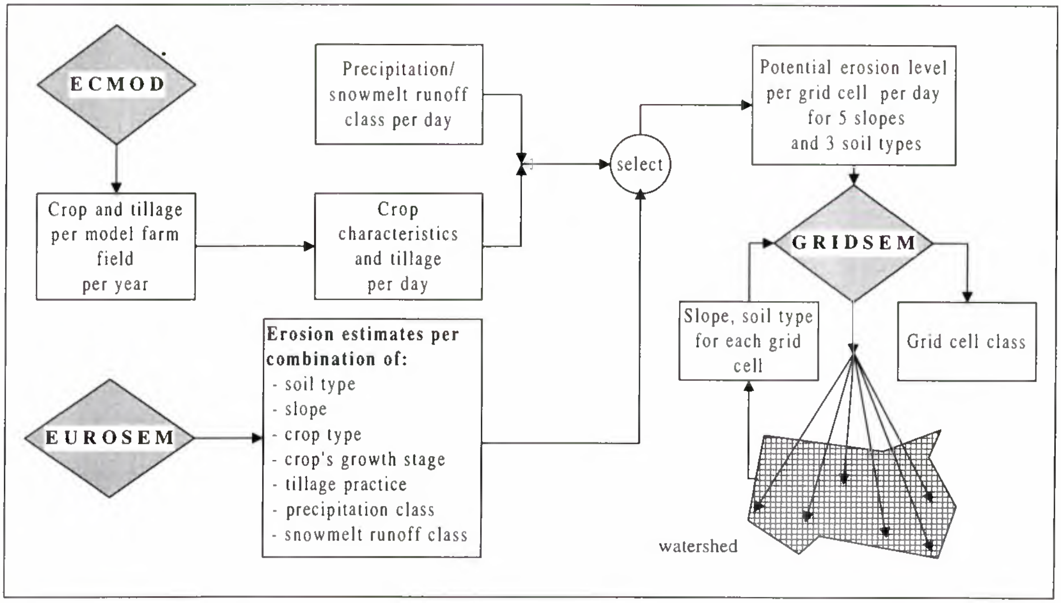


Figure A3.14: In real time estimation of potential daily erosion levels for model farms to be exported to GRIDSEM and further into the watersheds.

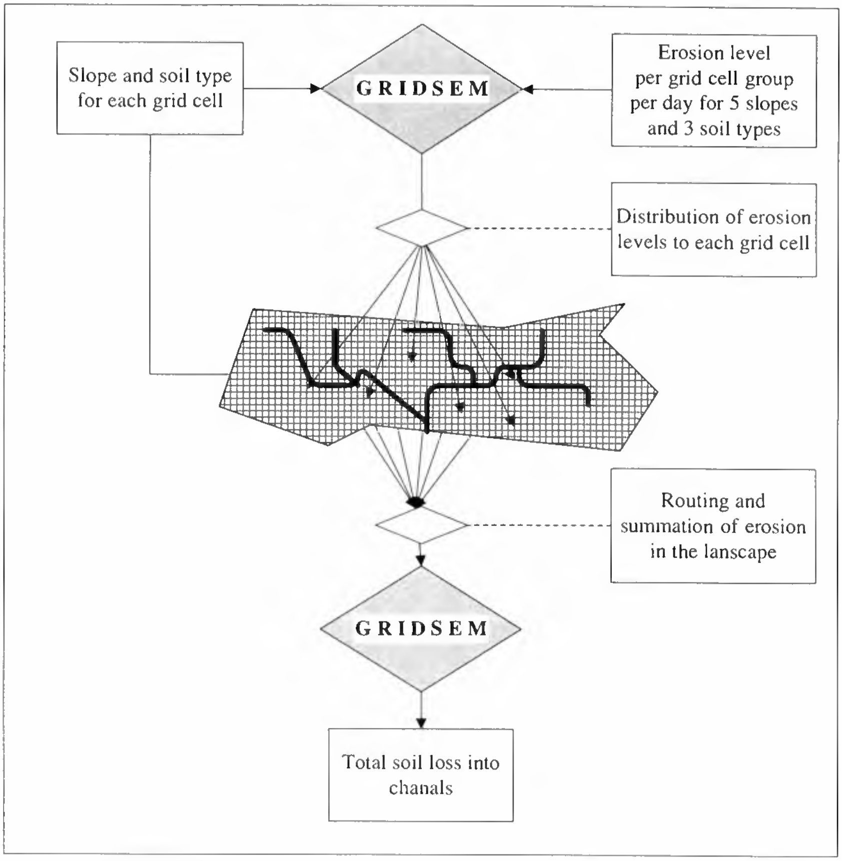


Figure A3.15: Procedure used by GRIDSEM to estimate daily actual erosion in the watersheds, based on daily potential erosion levels.

A3.5 Calculation of phosphorus losses with surface runoff and erosion

Losses of phosphorus from agricultural areas are first of all related to soil loss because of the strong adsorption of P to soil particles. In addition P-losses may occur shortly after the application of manure or fertilizers. Despite the strong bound between P and soil particles, P losses with drain water occurs (Øygarden, 1989). Most of the physio-chemical reactions of P in the soil are well understood and quantified under laboratory conditions. However, no deterministic models including all these pathways are available and in ECECMOD the losses have been estimated by using empirical functions describing phosphorus' fate in the soil. The method used in ECECMOD is mainly based on reports by Øgaard and Krogstad (1995) and

Christoffersen and Morken (1995). Standard soil chemical analyses for estimating the P-status in the soil for plant growth are available for a large amount of soil samples. The plant available P-fraction P-Al (ammonium acetate lactate extractable P) varies between the two study sites and main agricultural productions, but a large spread is found (table A3.36). Based on the available data it cannot be separated between soil type and main production within one area, but a significant higher P-Al level is found in Vestfold/Ramnes than in Akershus/Nes with respectively 8.6 and 12.7 mg P/100 g soil. There exists a weak relation between P-Al and total phosphorus (TP) in the soil, depending on mainly clay content. Also her a large range is found (table A3.37). Despite the large range of values for TP/P-AL, a separation can be made between clayey soils on one side and silty and sandy soils on the other. This reflects the stronger binding of P on clay particles compared to silt and sand particles.

Table A3.36: Average P-Al levels (mg P/100 g soil) for the three main soil types and two main agricultural productions in the two study areas Mørdre and Auli. Standard deviation in parentheses1).

Area	Main agricultural production	Total number of samples	Clay	Silt	Sand
Akershus county		6122			
	grain		8.0 (4.8)	7.9 (3.9)	10.9 (7.4)
	animal production		8.9 (5.0)	8.5 (5.2)	10.7 (6.7)
Nes municipality		757			
	grain		7.2 (4.1)	7.8 (3.6)	9.0 (4.8)
	animal production		7.8 (3.7)	9.5 (5.8)	6.6 (3.7)
Average for Akerhus:				8.6	
Vestfold county		4752			
	grain		10.3 (5.1)	11.5 (7.4)	15.5 (10.0)
	animal production		12.8 (6.8)	13.8 (8.8)	17.5 (12.5)
Ramnes municipality		273			
	grain		10.8 (5.3)	10.8 (4.1)	14.5 (7.2)
	animal production		9.0	-	13.0 (7.6)
Average for Vestfold:				12.7	

Source: Øgaard and Krogstad 1995

Table A3.37: Relation between total phosphorus (TP) and P-Al (TP/P-Al) in different soil types based on 52 soil samples from different part of Norway, and 58 samples from a clay area in Akershus county.(range in parentheses).

Soil type	Clay	Silt	Sand
TP/P-Al	14.1 (4.7-45.5) n=25	5.2 (2.9-23.8) n=15	5.7 (3.0-19.2) n=12
	14.9 (4.9-40.5) n=58		

Source: Øgaard and Krogstad 1995

The figures presented in tables A3.36 and A3.37 form the basis for estimation of P losses.

Losses are calculated separately for situations where an equilibrium between adsorbed and dissolved P fractions is assumed, and situations where this equilibrium temporarily is disturbed following manure or fertilizer applications.

A3.5.1 Phosphorus losses with runoff and erosion events

This section describes the loss of particulate and dissolved phosphorus with surface runoff and soil loss when an equilibrium situation exists between the P-fraction in the soil. Because of the enormous storage of phosphorus in the soil, it is accepted that manure or fertilizer application does not affect TP status. TP (table A3.38) is calculated from the figures in table A3.36 and A3.37:

$$TP = (TP/P\text{-}Al) \times P\text{-}Al \qquad [A3.3]$$

It has to be realized that these figures represent the best estimates from available data and represent a broad range of values.

Table A3.38: Total phosphorus (TP) (mg/100 g soil) in three different soil types in the two study areas Mørdre and Auli.

	Soil type	
Area	Clay	Silt & sand
Mørdre	125	50
Auli	185	70

During an erosion event phosphorus is transported adsorbed to particles and dissolved in runoff. Erosion is particle size dependent, such that in sediments the smallest particles are over-presented compared with the particle size distribution of the eroded soil. Further, for a given total P-concentration in a soil, the concentration per gram soil material increases with decreasing particle size. To estimate TP in sediment an enrichment factor (ER=TP in sediment/TP in field soil) has to be estimated. Experimental data show that ER is soil type and runoff intensity dependent (Sharpley, 1980). In our study information of soil loss per event and soil type was not available, and a constant ER of 2.5 is assumed for all events

The amount of dissolved phosphorus (DP) in runoff depends on the concentration of sediment in runoff, TP in the soil and time. For ECECMOD the following relation proposed by Øgaard and Krogstad (1995) is used:

$$DP=2*(a+b*\log E2) \tag{A3.4}$$

where: DP=dissolved P (mg/l),
log a=-1.631 + 0.053 P-Al
log |b|=-2.279 + 0.057 P-Al
E2=mg sediment/liter

P-Al values are mean values given in table A3.36. E2 can in principle be estimated by Eurosem/GRIDSEM, but we did not succeed to get these figures in time and a constant value is used. Runoff during winter and snow melt from fields covered with plant debris is likely to transport DP released from the debris. Quantitative data on this are rare, and in this study 25 % higher P concentration in runoff during winter/early spring from fields with overwintering grass or catch crop, compared to bare soil is assumed. The area covered by grass is nearly constant over all scenarios and DP released from debris is assumed to be equal for all scenarios. Winter wheat is not treated in the same way because the above ground biomass is low and normally does not die.

A3.5.2 Phosphorus losses related to manure and/or fertilizer application

Manure or P-fertilizer applied on the soil surface creates a situation that cannot be analyzed based on the assumptions presented in the foregoing section.Until the equilibrium situation is established again after at a maximum 10 days, the procedure described here is followed to calculate the amount of phosphorus that potential can be transported by runoff.

The concentration of solvable-P and adsorbed-P in manure and fertilizer is given by ECMOD for each field and day of application. These amounts are reduced due to infiltration on the day of application and during the following days by infiltrating water and surface runoff (figure. A3.16). The reduction factors used for the different P-fractions on the day of application depend on the technology used, soil type and standing crop. On the following days only the effect of soil type has to be considered (table A3.39). At tillage all the P-fractions are supposed to be mixed into the top soil and the equilibrium situation is reached immediately.

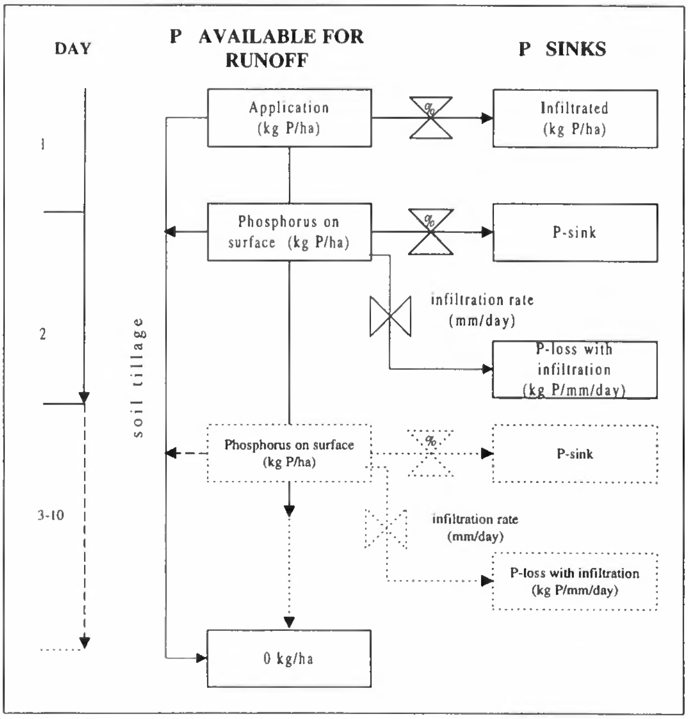


Figure A3.16: The decrease of the P-fraction in manure/fertilizer on the soil surface during the day of application and the days after.

Table A3.39: Reduction rates and final concentration of P-fractions applied with manure and fertilizer.

		Infiltration at time of application (%)						Decrease over time (%/day)[2]			Decrease at infiltration (kg/ha/mm)
		grass			bare soil / stubble						
Phosphorus fraction	Type of application[1]	soil type[2]			soil type			soil type			
		1	2	3	1	2	3	1	2	3	
Easy soluble P	A	13	20	25	25	25	30	7	10	5	10
	B	35	38	50	38	50	50	5	7	3	10
Fertilizer P	F1	0	0	0	0	0	0	5	10	5	10
	F2	0	0	0	0	0	0	0	0	0	0
Less soluble	A	6	10	12	15	12	15	5	7	3	5
organic bound P	B	20	20	25	20	25	25	3	5	2	5

[1] A= liquid manure spreader; B= semi-liquid slurry; F1=fertilizer applied in standing crop; F2=fertilizer applied directly into top soil together with seed

[2] Soil types: 1=clayey, 2=silty and 3=sandy soil

[3] reduction at incorporation/tillage 100 %, all concentrations to zero.

A4 Input data

This section covers, with one important exception, all main types of input data used by ECECMOD. The exception is data directly related to crop growth and N uptake in crops. Yield functions, timeliness costs, soil compaction effects, etc are covered by section A5.

A4.1 Economic data and data describing the political conditions

A4.1.1 Policy measures - scenario specific data

ECECMOD can be used to analyze the effect of different types of policy measures. First of all it is possible to analyze the effects of taxes or subsidies on input factors. Further the effect of changes in product prices may be studied. These are all changes that are implementable with manipulations of input data sets.

The effect of mandatory practices is more difficult to cover since they must be implemented through the way different optimization problems are formulated and constrained. The existing model is constructed to study mandatory catch crop use, spring tillage and defined levels of manure storing capacity.

Since ECMOD is constructed to solve specific farm optimization problems within given markets and prices, the model in its present form, is not capable of explicitly studying policy measures like tradeable quotas on input factors. Assuming no specific transactions costs for such markets, the results obtained for taxes can be used to discuss the effects of a quota solution though. The data referred in chapter A4.1.2 to A4.1.4 are based on Lundeby (1995a).

A4.1.2 Product prices

The prices on products sold from the farms are in all scenarios except Price33 kept at 1992 level. In Price33 the product prices are reduced by 33 %. Meat and milk prices are not included in table A4.1 since these productions are assumed fixed.

Table A4.1: Product prices, NOK/kg.

Wheat	Barley	Oats	Fodder wheat	Peas	Grass seed
2.67	2.28	1.94	2.36	2.80	24.00

Source: Landbrukets Priscentral (1993)

A4.1.3 Production costs

The total production cost is the sum of different cost components, and the main components are cost of mineral fertilizer and chemicals (herbicides, fungicides, etc), and cost in connection with manure handling and tillage. The production costs will normally vary from scenario to scenario. In the tax scenarios the price of fertilizer will increase and thereby increasing the total costs. The scenarios with mandatory requirements, like mandatory 12 month manure storage facilities, will induce investments which will increase costs. In others, like mandatory catch crops, the farmer will incur cost like the cost of an additional sowing, the cost of catch crop seeds, etc.

A4.1.3.1 Mineral nutrients

The nutrient prices are calculated on the basis of the prices for the three most sold types of artificial fertilizers. These type are NPK 21-4-10 (containing 21% N, 4% P and 10% K), NPK 22-2-12 and NPK 25-3-6. The prices pr january 1992 were 1.84, 1.84 and 1.84 NOK/kg respectively (Felleskjøpet 1992).

Table A4.2: Calculated prices on mineral nutrient, NOK/kg.

	1992	**Base***
Nitrogen	7.06	5.89
Phosphorus	9.07	6.84
Potassium	4.70	4.70

* The basis price are 1992 prices excluding taxes.

A4.1.3.2 Extra variable costs in wheat and barley production

Production of wheat and barley demand more use of input factors than oats. In table A4.3 production of oats represents the "zero level", i.e. costs in the table are costs in addition to the costs for oats production.

Table A4.3: Extra input factors use in wheat and barley compared to oats.

Crop	Cost component	Cost	Sum (NOK/ha)
Winter wheat	Sportak	0.101*414 NOK/l	41
	Tilt Top	0.081*468 NOK/l	37
	CCC 750	0.131*114 NOK/l	15
	Sumi-Alpha	0.031*438 NOK/l	13
	Yield loss (trafficking)	15kg *2.61 NOK/kg	39
		Sum	145
Spring wheat	Tilt Top	0.081*468 NOK/l	37
	CCC 750	0.11*114 NOK/l	11
	Sumi-Alpha	0.031*431 NOK/l	13
	Yield loss (trafficking)	15kg*2.67 NOK/kg	40
		Sum	101
Barley	Tilt Top	0.081*468 NOK/l	37
	Yield loss (trafficking)	15kg* 2.28 NOK/kg	34
		Sum	71

Sources: Abrahamsen (1993), Felleskjøpet Østlandet (1993) and Forsøksringene i Østfold (1992).

A4.1.3.3 Costs related to catch crops

Catch crop can be sown in grain with the help of different types of technologies. In table A4.4 two alternatives systems are calculated.

Table A4.4: Costs related to different technologies.

System I:			
	Seed, english rye-grass: (14 NOK/kg*10kg/ha)		= 140 NOK
+	Labor expenses pr ha.: (1 hour*80 NOK/hour)		= 80 NOK
+	Variable machine costs pr. working hour		
	maintenance cost :(0.09*250000/1000)	= 22.5	
	fuel: (6 l*2.36 NOK/l)	= 14.2	
	oil: (15 % of ordinary fuel costs)	= 2.1	
	total machine costs pr ha		= 39 NOK
=	Total annual costs pr ha		**= 259 NOK**
System II:			
	Annual capital cost ((7000 NOK/12+0.007*7000 NOK/2)/10ha)		= 83 NOK
+	Seed, english rye-grass (14 NOK/kg*10 ha)		= 140 NOK
=	Total annual costs pr ha		**= 223 NOK**

Source: Statens fagtjeneste for landbruket (1993), Bøe (pers. com.)

In ECECMOD the costs of sowing catch crops are the average of the two systems. For the first system, no extra investments are needed, but the catch crop is sown separately, leading to extra costs. Under system II there is a need for investment in extra seeding equipment at price 7000 NOK. Depreciation period is 12 years, and yearly catch crop area is assumed to be 10 ha.

A4.1.3.4 Manure storing

Storing in outdoor pits is normally the most reasonable solution when the manure storage capacity is to small. The investment costs pr m^3 varies substantially with the volume of the pit. On basis of Gjerde (1994) and Berg (1994) the following function for the investment cost pr m^3 is formulated.

$$FC_m = 890 - 1.97V + 0.0016V^2 \qquad [A4.1]$$

where V is total storage volume. It is assumed that precipitation and manure left after emptying reduces effective storage height with one meter.

A4.1.3.5 Manure spreading

The livestock farms can choose between two different manure spreading technologies, tank trailer and pipeline system. The prices for the necessary equipment are given in table A4.5. A 5% discount rate is used.

Table A4.5: Equipment prices.

Equipment	Depreciation time (years)	Investment cost (NOK)	Annual capital cost (NOK/year)
Centrifugal pump, small	10	30500	3812
Centrifugal pump, large	10	44500	5563
Tank trailer, small	10	40000	5000
Tank trailer, large	10	52500	6563
High pressure centrifugal pump, small	10	26100	3263
High pressure centrifugal	10	36200	4525
Propeller mixer, small	10	15000	1875
Propeller mixer, large	10	20000	2500
Hose reel with spray organ	10	30000	3785
Flexible pipe, 350 m * 90 NOK/m	7	31500	5288
Flexible pipe, 500 m * 90 NOK/m	7	45000	7554
Building cost, mix tank 50 m^3	30	40000	2333
Building cost, mix tank 100 m^3	30	71000	4142

Source: Daling (1994), Gjerde (1994) and Berg (1994).

The fixed costs for each of the technologies are shown in table A4.6 and A4.7. The costs are also grouped by the amount of manure pr farm and year.

Table A4.6: Capital costs in connection with manure handling on farms with less than 500 m^3 manure.

Tank trailer system			Pipeline system		
Equipment	Ownership	Annual capital cost	Equipment	Ownership	Annual capital cost
Centrifugal pump, small	1/1	3812	Propeller mixer, small	1/1	1875
Tank trailer, small	1/2	2500	High pres. pump, small	1/2	1632
			Hose reel	1/2	1893
			Flexible pipe	1/2	2644
			Mix tank	1/1	2333
Total annual capital cost		6312	Total annual capital cost		10377
Difference					4065

Table A4.7: Capital costs in connection with manure handling on farms with more than 500 m^3 manure.

Tank trailer system			Pipeline system		
Equipment	Ownership	Annual capital cost	Equipment	Ownership	Annual capital cost
Centrifugal pump, large	1/1	5563	Propeller mixer, small	1/1	2500
Tank trailer, large	1/2	3282	High pres. pump, small	1/2	2163
			Hose reel	1/2	1893
			Flexible pipe	1/2	3777
			Mix tank	1/1	4142
Total annual capital cost		8845	Total annual capital cost		14575
Difference					5730

A4.1.4 Time use in different tillage processes

The time used in different tillage operations is the sum of the time used in the processes constituting the operations. In the present study the following the different operations and the processes in these are:

Fall plowing:	One soil leveling with float, and one to two harrowing before sowing.
Spring plowing:	After ploughing, one soil leveling with float and one harrowing.
Fall harrowing:	One to two times harrowing before sowing.
Spring harrowing:	First one stubble/rotor harrowing and then one ordinary harrowing.
Direct drilling:	No preparations before sowing.

In table A4.8 and A4.9 the time use for the different processes and operations are given. Since machinery differs among farms time use is given for the different categories of size of machinery.

Table A4.8: Time use (hours/ha) in different processes with different equipment sizes.

	Small machine capacity	Medium small machine capacity	Medium large machine capacity	Large machine capacity
Plowing	3.0	2.2	2.3	2.0
Level floating	1.2	1.1	0.9	0.8
Stubble harrowing	1.5	1.4	1.2	1.0
Harrowing	1.0	0.9	0.8	0.6
Combi seeding	1.8	1.7	1.6	1.4
Rolling	0.5	0.5	0.4	0.4
Field spraying	0.4	0.4	0.3	0.3
Direct drilling				1.4

Table A4.9: Time use (hours/ha) for farming operations incl. spraying

	Small machine capacity	Medium small machine capacity	Medium large machine capacity	Large machine capacity
Fall plowing	5.40	5.05	4.40	3.80
Spring plowing	7.90	7.20	6.30	5.50
Fall harrowing	5.20	4.90	4.30	3.70
Spring harrowing	5.70	5.35	4.70	4.00

A4.2 The landscapes and farm data

A4.2.1 The landscapes

As described in appendix A1, the modelling may be divided into different levels of aggregation, with the watersheds as the "top" level. The analyses undertaken are based on rather detailed information about the landscapes. The information needed are of the following types:

- A division of the watershed/landscape into cultivated and not cultivated areas.
- A specification of the topography of the areas.
- A classification of the cultivated land into soil classes.
- A separation of the arable land into fields and a demarcation and classification of the farms these fields belongs to.

The classification of farms is based on size, type of production and volume of animal manure per ha. In our case all the information necessary could be provided by utilizing soil data from the Norwegian Institute of Land Inventory and farm data from a data base belonging to Statistics Norway. The data are compiled by the Norwegian Institute of Land Inventory.

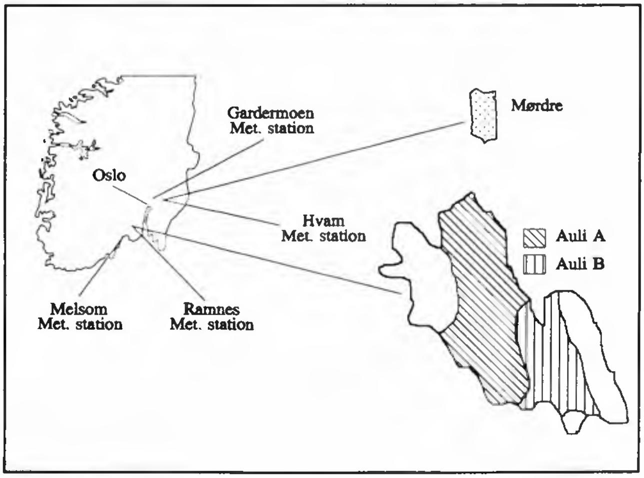


Figure A4.1: The location of Auli-A, Auli-B and Mørdre.

Two areas are chosen for the study reported in this volume. Auli is a watershed west of the Oslo fjord. Two subareas of this watershed, both in the municipality of Ramnes are chosen. The more hilly part in the north-west is named Auli-A and the flat area in south-east is named Auli-B. Mørdre is a small watershed north and east of Oslo, consisting of a rather flat plateau (levelled) with steep slopes down to a creek. A brief description of the watersheds are given in table A4.10.

Table A4.10: Some characteristics of the watersheds.

Watershed	Topography	Total agricultural land (ha)	Number of farms	Soil distribution (%)		
				clay	silt	sand
Auli A	hilly	1304	92	57	4	39
Auli B	flat	1293	84	64	8	28
Mørdre	flat	446	18	24	75	1

A4.2.2 The model farms

The modelling is based on a set of model farms representing the actual farms in the landscapes analyzed. In order to construct the model farms the following information is needed:

- A geographical demarcation of each production unit/farm.
- Information about farm size, number of animals and types of crops.

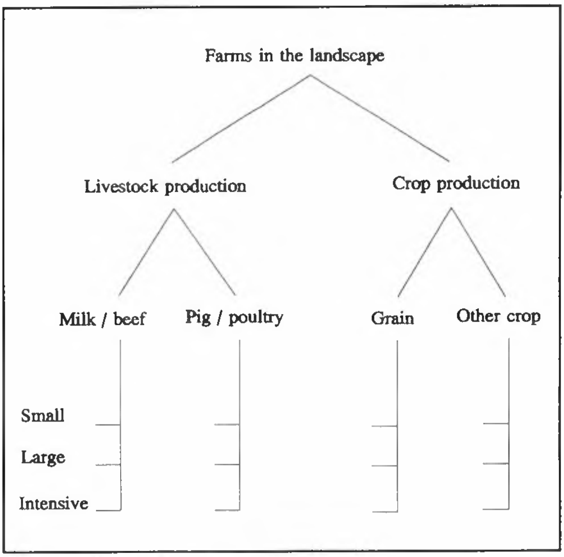


Figure A4.2 The farms are grouped by a set of criterias illustrated in this figure.

The model farms are constructed so as to represent the variation in production patterns and farm sizes in the different landscapes. On the basis of the existing variation, a set of criterias illustrated in figure A4.2 groups the farms by structure and production. If the amount of total N in manure pr. ha is less than 40 kg, the farm will be classified as a livestock farm. Within this group the farms are divided into two groups. One where the meat production is based on concentrate feed and one where milk/beef production dominates. Finally the farms are divided into groups by intensity (more than 150 kg manure-N/ha), small (less than 1,5 man year) and large (more than 1,5 man year).

The other group (less than 40 kg manure-N/ha) are classified as plant production farms. These farms are split into grain farms (grain area > 75% of total area) and other crop farms. This group covers farms with seed and pea production. The grain and crop production farms are also divided further by intensity and size.

Since some land always will be rented, there is a distinction between the farm as a property unit and as a production unit. In constructing the model farm system, we have faced the problem that while information about production is given for production units, information about position in landscapes are given for property units. Since each production unit has a main property unit defined, we were able to connect almost 80% of all arable land in the landscapes to the production units. For the remaining 20%, we have assumed that the production is distributed in the same way as for the rest of the landscape.

A4.2.2.1 Model farms in Auli

The 176 farms in Auli are grouped into 10 different model farms, six livestock farms and four with mainly plant production. Information about each model farm is given on the next pages. The model farms are fully described in Lundeby (1994).

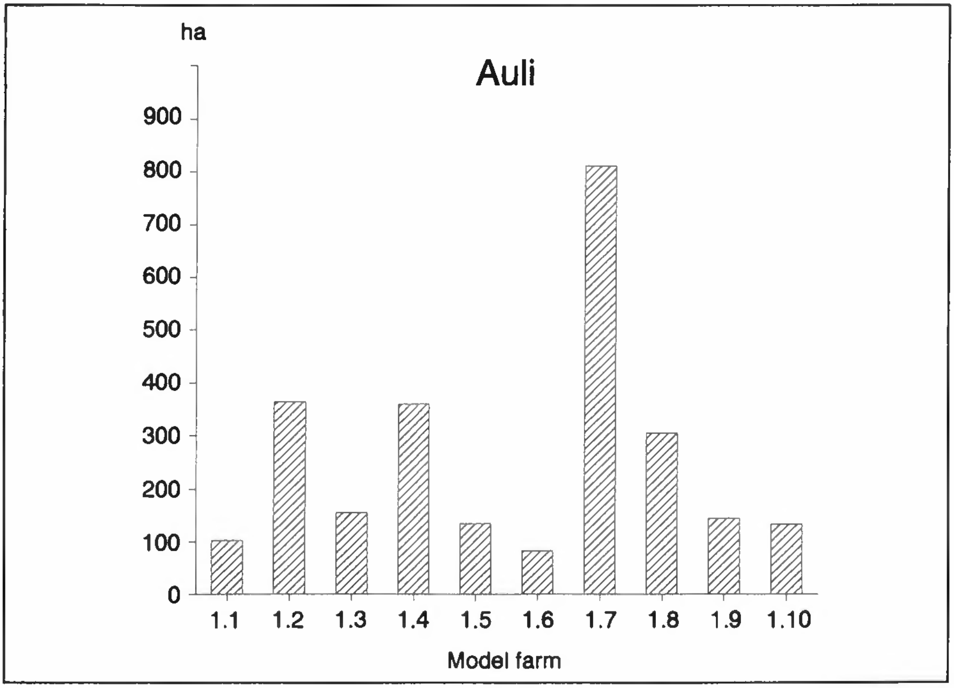


Figure A4.3: The total agricultural land represented in each model farm group in Auli.

Model 1.1: Milk/beef production; size: Small

Livestock and manure.

	Number	Volume
Milk cows	3,8	68
Suckler cow	1,4	7
Bull > 12 month	1,6	16
Heifer > 12 month	2,9	29
Bull < 12 month	4,4	22
Heifer < 12 mnd	2,5	13
Total		155 *

Soil class and model field size

1. clay	3.0 ha
2. clay	3.0 "
3. sand	2.5 "
4. sand	2.5 "
5. sand	2.0 "
Total	13.0 ha

Soil preparation machines. Small machine capacity (see chap A4.1.4). Tanktrailer 3700 l
* water and litter 28 %

Model 1.2: Milk/beef production, Large and extensive

Livestock and manure.

	Number	Volume
Milk cows	16,7	300
Suckler cow	3,2	10
Bull > 12 month	10,3	103
Heifer > 12 month	11,7	117
Bull < 12 month	10,7	54
Heifer < 12 mnd	11,3	57
Total		641

Soil class and model field size	
1. clay	4.0 ha
2. clay	6.0 "
3. clay	7.0 "
4. silt	2.0 "
5. sand	4.0 "
6. sand	4.0 "
7. sand	4.0 "
Total	31.0 ha

Soil preparation machines. Medium large machine capacity (see chap A4.1.4). Tanktrailer 5800 l

Model 1.3: Milk/beef production, Intensive

Livestock and manure.

	Number	Volume
Milk cows	22,1	398
Suckler cow	0,5	3
Bull > 12 month	7,4	74
Heifer > 12 month	13,2	132
Bull < 12 month	8,4	42
Heifer < 12 mnd	12,8	64
Total		713

Soil class and model field size	
1. clay	4.0 ha
2. clay	4.0 "
3. clay	3.0 "
4. silt	4.0 "
5. sand	3.0 "
Total	18.0 "

Soil preparation machines. Medium small machine capacity (see chap A4.1.4) Tanktrailer 5800 l

Model 1.4: Pig production, Small and extensive

Livestock, manure

	Number	Volume
Sow	5,6	25
Fattening pig	216,0	175
Young sow	2,1	10
Piglets	95,0	8
Total		218

Soil class and model field size	
1. clay	7.0 ha
2. clay	3.0 "
3. sand	2.0 "
4. sand	2.0 "
Total	14.0 ha

Soil preparation machines. Medium small machine capacity (see Chap. A4.1.4). Tanktrailer 3700 l

Model 1.5: Pig production, Large and extensive

Livestock, manure

	Number	Volume
Sow	17,2	25
Boar	0,5	2
Fattening pig	543,8	435
Young sow	5,8	26
Piglets	293,0	23
Total		564

Soil class and model field size

	1. clay	5.0 ha
	2. clay	5.0 "
	3. clay	8.5 "
	4. silt	2.0 "
	5. sand	6.0 "
	6. sand	2.0 "
Total	28.5 "	

Soil preparation machines. Medium large machine capacity (see Chap. A4.1.4). Tanktrailer 5800 l

Model 1.6: Pig production, Intensive

Livestock, manure

	Number	Volume
Sow	23,0	108
Fattening pig	639,2	522
Young sow	6,3	27
Piglets	392,0	32
Total		709

Soil class and model field size

1. clay	2.5 ha
2. clay	2.5 "
3. silt	2.0 "
4. sand	2.5 "
Total	9.5 ha

Soil preparation machines. Small machine capacity (see Chap. A4.1.4). Tanktrailer 5800 l

Model 1.7: Grain production, Small and extensive

Soil class and model field size

1. clay	3.0 ha
2. clay	3.5 "
3. sand	2.5 "
4. sand	2.0 "
Total	11.0 ha

Soil preparation machines. Medium small machine capacity. (see chap. A4.1.4)

Model 1.8: Grain production, Large and extensive

Soil class and model field size

1. clay	2.0 ha
2. clay	9.5 "
3. clay	7.5 "
4. silt	4.0 "
5. sand	6.0 "
6. sand	3.0 "
Total	32.0 "

Soil preparation machines. Medium large machine capacity (see chap. A4.1.4)

Model 1.9: Grain/grass-seed production

Soil class and model field size

1. clay	3.0 ha
2. clay	5.0 "
3. sand	3.0 "
4. sand	2.0 "
Total	13.0 ha

Soil preparation machines. Small machine capacity (see chap. A4.1.4)

Model 1.10: Grain / pea production

Soil class and model field size

1. clay	4.0 ha
2. clay	4.0 "
3. silt	2.0 "
4. sand	3.0 "
Total	13.0 ha

Soil preparation machines. Medium small machine capacity (see chap. A4.1.4)

A4.2.2.2 Model farms in Mørdre

The 18 farms in Mørdre are grouped into four model farms, two livestock farms and two farms with mainly plant production. Information about each model farm is given in the next pages. The model farms are fully described in Lundeby (1994).

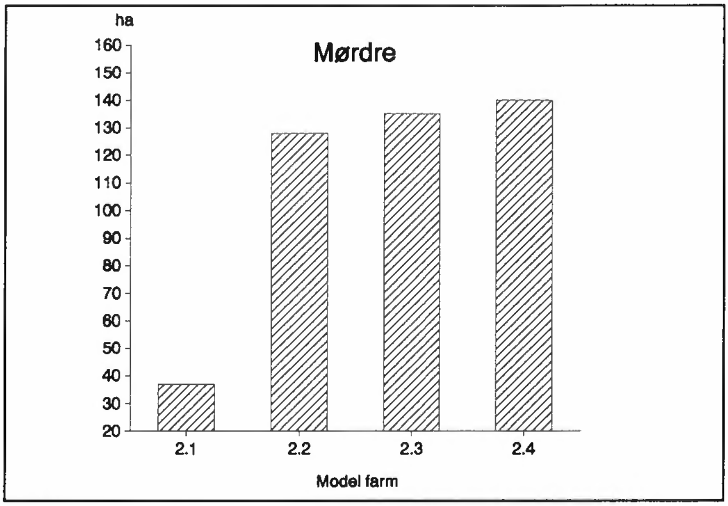


Figure A4.4: The total agricultural land represented by each model farm in Mørdre.

Milk production farms, model farm 2.1, represents a quite small area in Mørdre, see figure A4.4. The three other model farms represents almost 130 ha each.

Model 2.1: Milk/beef production size: Large

Livestock and manure.

	Number	Volume
Milk cows	20,78	374
Bull > 12 month	3,04	30
Heifer > 12 month	16,71	167
Bull < 12 month	5,32	23
Heifer < 12 mnd	12,0	61
Total		655

Soil class and model field size

1. clay	5.0 ha
2. clay	8.0 "
3. silt	5.0 "
4. silt	6.5 "
5. silt	6.0 "
6. silt	4.0 "
7. silt	4.0 "
Total	38.5 "

Soil preparation machines. Medium large machine capacity (see chap A4.1.4). Tanktrailer 5800 l.

Model 2.2: Pig production, size: Large

Livestock, manure

	Number	Volume
Sow	4,1	19
Fattening pig	490,0	392
piglets	69,0	60
Total		416

Soil class and model field size

clay	3.0 ha
clay	10.0 "
clay	11.0 "
clay	5.0 "
silt	12.5 "
silt	7.0 "
Total	48.5 "

Soil preparation machines. Large machine capacity (see Chap. A4.1.4). Tanktrailer

Model 2.3: Grain production, size: small

Soil class and model field size

1. clay	2.0 ha
2. silt	2.0 "
3. silt	4.0 "
4. silt	3.0 "
Total	11.0 ha

Soil preparation machines. Medium small machine capacity. (see chap. A4.1.4)

Model 2.4: Grain production, size: Large

Soil class and model field size

1. sand	3.0 ha
2. clay	3.0 "
3. clay	6.5 "
4. silt	14.0 "
5. silt	15.0 "
6. silt	6.0 "
Total	47.5 ha

Soil preparation machines. Large machine capacity (see chap. A4.1.4)

A4.2.3 Aggregation coefficients

The simulation of nitrogen leaching at the model farm level is linked back to the landscapes via aggregations coefficients attached to each model farm field. Each model farm field represents a certain proportion of the total area in the watersheds, and by multiplying the leaching from model farm field by this proportion and summing over all fields, we get the total leaching in the watershed. In the case of phosphorus and soil loss the aggregation is more complex due to dependency of topography, distance to water ways, etc. This is described in A3.4.

A4.2.4 Animal manure

A4.2.4.1 Nitrogen and phosphorus excretion from animals

The analyses of manure handling in ECECMOD is based on a set of nutrient excretion coefficients for various classes of animals. Separate sets for different feeding practices may be included. In the existing version of the model two sets of feeding practices are used:

- Feeding A: These coefficients are calculated on the basis of existing feeding practices in Norwegian animal production as it was in 1992. They are calculated as the difference between N and P in the feed and N and P in the products produced by the animal.
- Feeding B: This set of coefficients is constructed to reduce excretion of N and P in a way not affecting production or health. For N a system based on a new protein evaluation system and new formulas for con-

centrates is used. For P the English ARC (minimum) norm with a 20 % safety margin is used. The calculations are undertaken in the same way as for Feeding A.

The method and empirical basis for the various coefficients are documented in Bolstad (1994). In ECECMOD only coefficients for cattle and pigs/sows are utilized since the number of other animals in the analysis areas are relatively low and without any potential errors could be converted to cattle or pigs through a system of manure weights developed by Sundstøl and Mroz (1988).

Excreted N and P are split in different fractions relevant for the analysis. This is done on the basis of an analysis by Bruce (unpubl.) based on the work of Bolstad (1994). The fractions are:

Nitrogen:
N-f1: Ammonia N (the mineral N component)
N-f2: N in faeces (the organic N components)

Phosphorus:
P-f1: Soluble P
P-f2: Adsorbed P

The coefficients calculated are per animal and year, except in cases where standard age or length of a defined stage of the animals life is less than one year. Then the unit is per animal like in the case of a piglet or a fattening pig. These definitions are the same as the ones used in the animal data set of each model farm register – see A2.2.

Table A4.11: Coefficients (kg/animal) for different fractions of nitrogen and phosphorus in manure. Feeding A: The 1992 situation.

	N-fl	N-f2	P-fl	P-f2
Cattle:				
Milk cow	61.61	32.26	5.29	9.53
Suckler cow	44.39	22.20	2.54	5.34
Bull 0-12 mo.	16.33	8.27	1.84	2.37
Bull 12-24 mo.	12.68	9.93	1.24	2.06
Heifer 0-12 mo.	19.09	7.16	1.20	1.04
Heifer 12-24 mo.	30.85	15.43	1.31	2.75
Pigs:				
Sow	12.82	5.38	3.73	2.52
Young sow*	3.21	1.35	0.93	0.63
Fattening pigs*	3.54	1.09	0.58	0.57
Piglets*	0.30	0.14	0.02	0.01

* Lifetime < 1 year. Excretion coefficients are for the total lifetime. For the rest coefficients are per year.

Table A4.12: Coefficients for different fractions of nitrogen and phosphorus in manure. Feeding B: An alternative with reduced N and P excretion.

	N-fl	N-f2	P-fl	P-f2
Cattle:				
Milk cow	53.83	31.87	3.36	8.16
Suckler cow	44.14	16.16	2.29	5.59
Bull 0-12 mo.	16.29	7.97	0.67	1.41
Bull 12-24 mo.	12.58	7.02	0.80	1.86
Heifer 0-12 mo.	19.10	7.06	0.73	0.79
Heifer 12-24 mo.	30.80	15.46	1.39	3.40
Pigs:				
Sow	12.82	5.38	3.73	2.52
Young sow*	3.21	1.35	0.93	0.63
Fattening pigs*	2.73	1.23	0.32	0.31
Piglets*	0.30	0.14	0.01	0.01

* Lifetime < 1 year. Excretion coefficients are for the total lifetime. For the rest coefficients are per year.

In addition to the N and P coefficients separate figures for N in litter and feed remnants is calculated. This organic fraction is more interesting for its carbon than for its N content though. SOILN-NO uses the information about organic N components together with standard C/N coefficients for litter and faeces. The total volume of manure per animal is also calculated. It is needed to determine storage capacity and the time necessary for spreading with the different technologies.

A4.2.4.2 Losses of nitrogen to the air during storing and spreading

Ammonia N may be lost both during storing and spreading. In the gas form, ammonia fairly easily escapes from the surface. There is a number of factors affecting losses during and after spreading. The basic factors are weather (temperature, precipitation and wind) and ammonia concentration in the manure. Higher temperature and ammonia concentration will lead to higher losses. Increased air circulation will increase the loss, because the concentration of ammonia in the air is kept at a low level. On the other hand, out on the field ammonia does not only escape to air, but also infiltrates the soil. It is highly soluble and follows the water as it infiltrates the soil, hence reducing the potential loss. The water content of the manure and the infiltration capacity of the soil will therefore be important factors. If the manure is covered by soil, the loss will be very small (close to zero), hence the time from spreading to incorporation into the soil plays an important role.

Horlacher and Marschner (1990) have developed a model for estimating loss of ammonia after spreading under different conditions. The estimation follows a three step procedure:

1) Estimation of potential ammonia loss. The potential loss is determined by average temperature after application and infiltration capacity of the manure (which depends on water content and infiltration capacity of the soil)
2) Estimation of the fraction of the potential loss that is lost before eventual rainfall. This (actual) loss is determined by time from spreading to rainfall and average temperature.
3) Estimation of the fraction of residual potential loss lost after rainfall. This loss is a function of precipitation and temperature.

One of the shortcomings of the Horlacher and Marschner (1990) model is that it is discrete in the sense that estimates of the losses are only given for intervals of the input variables (temperature, infiltration capacity, time to rainfall and amount of rain). In order to surpass this problem, Christoffersen and Morken (1995) have developed a continuous model on the basis of Horlacher and Marschners (1990) procedure and results. For all the submodels a Richards growth function is fitted to the data. The Richards growth function can be described as:

$$\gamma = \frac{\gamma_0 \gamma_f}{\left[\gamma_0^n + \left(\gamma_f^n - \gamma_0^n\right) e^{-kt}\right]^{1/n}} \qquad [A4.2]$$

The total percentage loss of ammonia is found by:

$$\gamma_t = \gamma_p \gamma_b + (\gamma_p - \gamma_p \gamma_b) \gamma_a \qquad [A4.3]$$

where γ_p is potential percentage loss, γ_b is the fraction that is lost before rainfall and γ_a is the fraction of residual potential loss lost after precipitation.

In the case of potential percentage loss, γ_p, the variables and parameters in [A4.2] are n = c+dI, where c and d are coefficients and I is infiltration capacity, kt = (a+bI)(T+f), where a, b and f are coefficients and T is temperature, γ_0 and γ_f are parameters. There are similar expressions for the fraction that is lost before rainfall, γ_b (which is a function of time and temperature) and the fraction of residual potential loss lost after precipitation, γ_a (which is a function of temperature and precipitation).

With this model Christoffersen and Morken (1995) estimated the loss of ammonia after spreading for:

1) Three different time periods for spreading of manure (spring, summer (on meadows) and fall),
2) three different technologies for manure spreading (spreading of semi liquid manure with tank trailer, semi liquid manure + 100% water spread with tank trailer and semi liquid manure + 100% water spread through a system of pipes),
3) tree types of soils (clay, silt and sand), and
4) two types of crops (grain and meadows). For small grains the losses are estimated for two different periods of time between application and tillage (3 and 18 hours).

Since losses to a large degree are driven by the weather they will vary from year to year. This means that the farmer has little information about the losses at the time he applies the manure, hence bases her/his decision on expectations. Due to this, an average loss is estimated for each possible spreading day during the period 01.01.70 - 12.31.88 based on historical climatic data (temperature and precipitation). A possible spreading day is defined to be a day with water content in the soil below a given level. The water content is estimated using the SOIL-model, with soil characteristics, temperature and precipitation as input variables. A graphical presentation of losses throughout the year for all combinations of 2)-4) is given in Christoffersen and Morken (1995).

The next step in order to get the desired estimates, is to divide the year into spreading seasons. The actual spreading day will differ with a number of factors, but there are rather "stable" intervals where spreading will take place. These seasons are found by consulting State advisory representatives in the study area, and they are

- spring season:	April 20 - May 20
- summer season:	June 15 - June 28
- fall season:	October 1 - October 31

The estimates for each season are now found by taking the average of the losses each day in each season. The estimated losses are presented in table A4.13.

Table A4.13: Estimated losses of ammonia after spreading. Explanation is given in the text.

Crop	Soil type	Spreading technology	Time to incorporation	Fraction lost in spring	summer	fall
Grain	Clay	semi liquid	3	0.0827	N.A.	0.0345
			18	0.2012	N.A.	0.0941
		+100% water	3	0.0585	N.A.	0.0244
			18	0.1421	N.A.	0.0665
	Silt	semi liquid	3	0.0769	N.A.	0.0328
			18	0.1892	N.A.	0.0893
		+100% water	3	0.0331	N.A.	0.0143
			18	0.0814	N.A.	0.0392
	Sand	semi liquid	3	0.0694	N.A.	0.0298
			18	0.1694	N.A.	0.0807
		+100% water	3	0.0349	N.A.	0.0153
			18	0.0853	N.A.	0.0415
Meadow	Clay	semi liquid	-	0.4427	0.7484	0.2578
		+100% water	-	0.2438	0.4560	0.1416
		pipe/hose	-	0.1842	0.4560	0.1416
	Silt	semi liquid	-	0.3925	0.6946	0.2281
		+100% water	-	0.2422	0.4572	0.1413
		pipe/hose	-	0.1792	0.4572	0.1413
	Sand	semi liquid	-	0.3403	0.6131	0.1997
		+100% water	-	0.1466	0.2710	0.0885
		pipe/hose	-	0.1151	0.2710	0.0885

N.A. = non-applicable, since no manure is applied on grains in summer.

As to the losses during storing, the physical processes behind are of course the same as those driving the losses after spreading. Among the more important factors are (Rom 1993): the ammonia concentration in the manure and the gas phase above the manure, air circulation in the storage, ratio between the surface area and the volume in the storage, the acidity of the manure and temperature. It is evident that the loss of ammonia in relative terms (e.g. measured as percentage loss of total amount of ammonia in storage) will vary over the year.

In summer the percentage loss of ammonia will be higher than in winter, due to higher temperatures, more need for ventilation and higher ratio between surface area and volume. However, in absolute terms, losses will not be that high due to a low amount of manure in storage. Therefore, the difference in losses between summer and winter may not influence the average percentage loss much.

It has been beyond the scope of this project to model the loss from storage in great details. First, the loss from a given farm is dependent on characteristics of the housing and storage facilities, for which we lack data. Second, in our model we do not model the choice of storage technology, only the size of storage. If the loss does not depend on the size of the storage, which we find reasonable to believe, the loss will not bias the choice of storage size. Third, and maybe most important, there has been little empirical research on this issue in Norway. Our aim has therefore been to find an estimate of a typical (average) loss for a typical farm.

Morken (1994) incorporates a literature survey giving estimates for losses of ammonia during storage for different technologies under Norwegian conditions. Based on this survey the following estimates have been used for average losses during storage:

13% of total ammonia on farms with cows/cattle as primary production

17% of total ammonia on hog farms.

A4.3 Weather data and weather characteristics

For the analyses in ECECMOD different series with meteorological data have been used as basic input for the ecological part of the modelling system. The data series are described here together with a characterization of the study areas with respect to climate.

A4.3.1 Weather data series

The 20 year long simulation period used in ECECMOD restricted the choice of meteorological stations to those with long enough series with observation of the variables needed. Despite the dense network of observation stations found in Norway to day, no station fulfilling this criteria was found inside neither the Mørdre nor the Auli area. For Mørdre the station at Gardermoen, situated west of the site was decided used (see map in figure A4.1). However, for calibration of SOIL for silty soils, also weather data from the meteorological station at Hvam could be used. For the Auli area the station at Melsom was selected, but snow observations could be taken from the precipitation station at Ramnes. In addition to the series with daily observations, a series of precipitation measurements with a pluviograph (resolution 0.1mm/min) was available for Gardermoen. All the weather data series are obtained from the Norwegian meteorological institute and summarized in table A4.14.

Table A4.14: Series of weather data used in the ecological models in ECECMOD

Meteorological station	Resolution of data series	Length of data series	Variables available[1)]
Gardermoen	pluviograph	1987-05-04 to 1987-10-29	D
		1988-05-03 to 1988-10-28	D
		1989-05-27 to 1989-10-17	D
		1990-05-16 to 1990-11-19	D
		1991-05-08 to 1991-11-13	D
		1992-05-08 to 1992-10-26	D
Gardermoen	daily values	1970 to 1993	A - G
Melsom	daily values	1970 to 1993	A - E
Ramnes	daily values	1970 to 1995	F, G
Hvam	daily values	1991 to 1994	A, D

[1)] A = temperature; B = wind speed (m/s); C = relative air humidity(%); D = precipitation;
E = cloud cover; F = snowdepth (m); G= snow cover (scale 1-4);
A, B, C, E: mean value per day; D: total per time period; E, F: observation at 08.00 GTM).

Since 1980 precipitation observations have been available from Hvam station, showing that the annual precipitation is about 250 mm less then at Gardermoen. This difference is acceptable because ECECMOD primarily evaluates relative changes between scenarios and does not compare simulated results directly with measurements. However, local measurements have been used in calibration.

A4.3.2 Weather conditions during the ECECMOD simulation period

Table A4.15 shows the average annual values for the main meteorological variables temperature and precipitation together with snow related observations. At average over the 20 years of simulation, the Mørdre area has a colder and dryer climate than Auli, with a longer period with snow cover.

To get an idea about the weather conditions in the simulation period, each year has been divided into three seasons, respectively from May 1. to September 15., September 16. to December 1. and December 1. - May 1., representing the main growing season or summer, autumn and winter respectively. A year is now defined as the period from December to December. On average the distribution of precipitation over three seasons differs between Gardermoen and Melsom (table A4.15). At Melsom the highest mean precipitation is measured during winter, but at Gardermoen during summer. So the two areas not only differ in total amount of precipitation, but also in the distribution of total precipitation over the seasons. The distribution of precipitation within individual years varies considerable (figure A4.6). At Gardermoen as well as at Melsom the winter and summer of 1975 have been dry, but in autumn precipitation was above normal. However, in 1988 the opposite can be observed, a wet winter and summer but a dry autumn. The extreme differences between years stress the need for long time series when evaluating effects on runoff and nutrient losses.

Table A4.15: Average annual and seasonal values (1973-1992) for the main climatological variables for the meteorological station at Gardermoen and Melsom. σ in parentheses.

Meteorological station	Observation period[1]	Temperature °C	Precipitation (mm)	Maximum snow depth (cm)	Days with snow cover[2]
Gardermoen	calendar year	4.20 (1.2)	809 (119)		
	winter	-3.15 (2.3)	261 (73)	68 (27)	157 (27)
	summer	13.33 (0.7)	319 (90)		
	autumn	3.14 (1.2)	227 (82)		
Melsom	calendar year	6.29 (1.2)	1009 (138)	---	---
	winter	-0.41 (2.4)	354 (110)		
	summer	14.36 (0.7)	335 (88)		
	autumn	5.41 (1.1)	315 (118)		
Ramnes	winter	---	---	66 (35)	125 (34)

[1] See text for definition of the seasons

[2] Only days with snow cover >0 included in calculations

The mean temperature during summer varies between 11.7 and 14.1 °C at Gardermoen and between 12.7 and 15.5 °C at Melsom (figure A4.5). The differences with standard normal values are minor and no extreme years can be made out. For the winter season the differences in mean temperature between the years are larger; -6.7 to +0.6 °C at Gardermoen and -4.0 to +3.3 °C at Melsom. For the winter seasons the differences with normal temperature are larger, too. Especially the winter of the years 1989, 1990 and 1992 show to have been milder than normal. The number of days with rain on bare soil is high for these years, too (table A4.16). It has to be realized that higher winter temperatures may have a tremendous effect on both hydrology and erosion, because precipitation is not temporarily stored on the surface as snow (Botterweg 1994; 1996).

Table A4.16: Number of days with rain on bare soil during January, February and March at Gardermoen and Ramnes meteorological station. (in the years not listed the number is 0 for both stations).

Year	Days with precipitation on bare soil		Year	Days with precipitation on bare soil	
	Ramnes	Gardermoen		Ramnes	Gardermoen
1973	10	10	1988	14	0
1974	9	0	1989	31	15
1975	11	1	1990	38	34
1976	4	1	1991	4	0
1981	4	0	1992	35	19
1983	14	0			

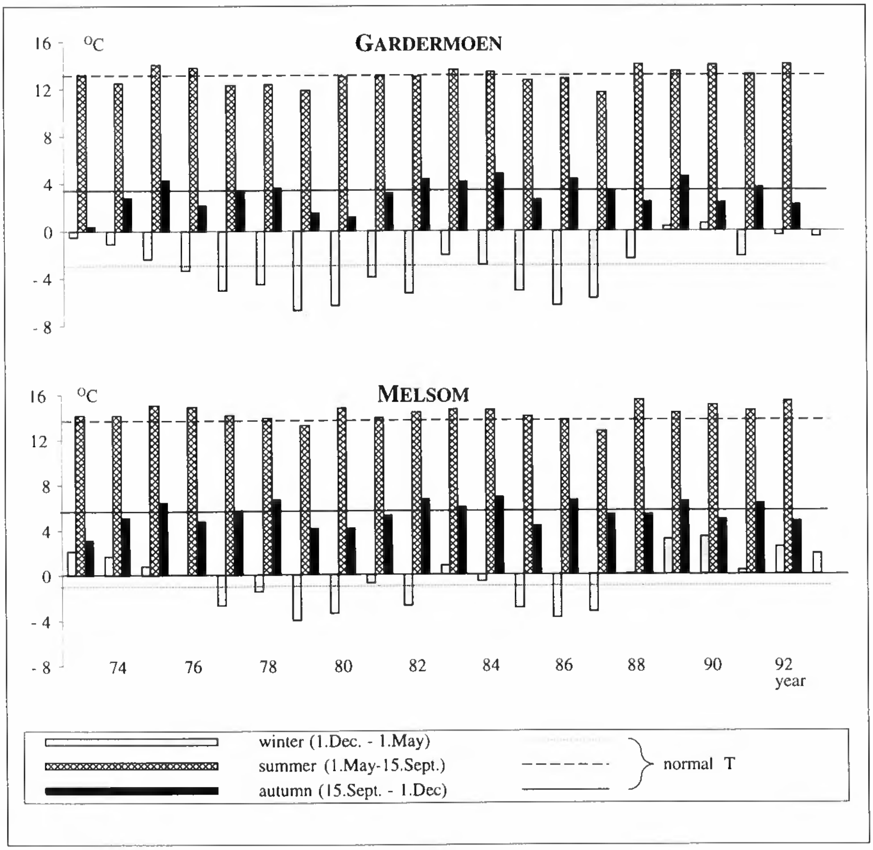


Figure A4.5: Annual mean seasonal temperature observed at Gardermoen and Melsom meteorological station for winter, summer and autumn 1973-1992. The horizontal lines are the local standard normal temperatures for the three seasons.

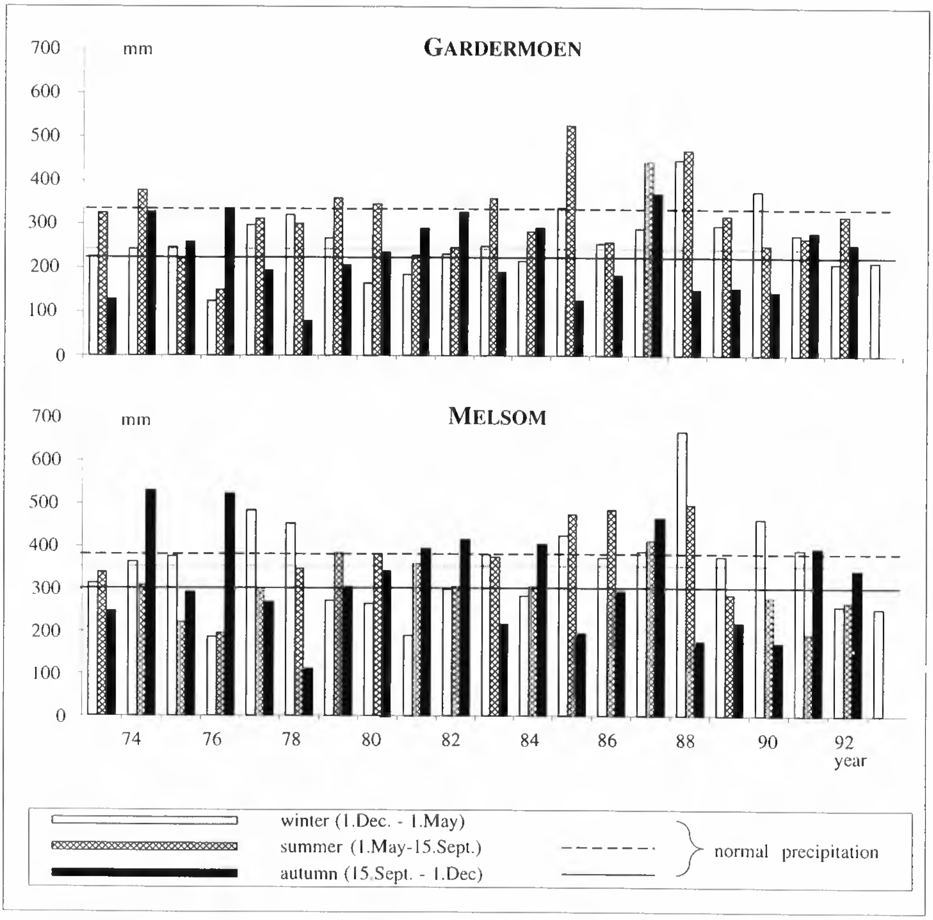


Figure A4.6: Annual total precipitation observed at Gardermoen and Melsom meteorological station for the winter, summer and autumn season 1973-1992. The horizontal lines are the local standard normal precipitation for the three seasons.

A4.4 Hydrology data

The hydrology data described in this section are the result of simulations with SOIL with the meteorological data described in section A4.3 as input. A detailed description of the application of SOIL is given in section A3.2 together with the type of data exported to other models in ECECMOD.

Describing the hydrology data both the differences between the soil types, representing the spatial variation and the temporal variation over the years are of interest. A variation not taken into account in the hydrology simulations is the variation in daily weather conditions within the watersheds introducing an extra spatial variation because of shifting initial conditions at the start of a precipitation event. Because of the size of the areas studied, this will be less important for Mørdre with 450 ha arable land in a watershed of about 500 ha, then it will be for Auli with 2 500 ha arable land spread out over a watershed of about 36000 ha). A summary of the main hydrological variables is given in table A4.17. As can be expected, surface runoff decreases from clay to silt to sand and is for all soil types higher for grain then for grass. Drain flow is higher for grass because in the middle of the summer when potential evapotranspiration is at its maximum, the grass is cut while grain reaches the maximum of its active leaf area.

Table A4.17: Mean annual precipitation, surface runoff and drain flow or percolation to groundwater for clay loam and sand, as simulated with SOIL.

Watershed	Precipitation (mm) [1]	Soil type	Surface runoff (mm) [2]		Drain flow /percolation[2]	
			grass	grain	grass	grain
Mørdre	809	clay	85.9	129.6	470	249
		silt	43.4	61.4	474	261
		sand	11.1	17.3	441	381
Auli	1009	clay	111.7	217.7	648	369
		silt	49.3	103.0	668	423
		sand	8.3	29.6	646	567

[1] Measured input data(table A4.15)
[2] Simulated with SOIL

The difference in drain flow between grass and grain is caused by a lower annual evapotranspiration of the perennial crop during summer. Further infiltration is better in the permanent crop, resulting in lower surface runoff. Figure A4.7 shows the relation between the three water flows for one year.

To show more details, the annual hydrology data series have been split into the same seasonal series as the meteorological observations (summer: May 1 to September 15; autumn: September 16 to December 1; winter: December 1 - May 1). In figure A4.8 - A4.9 total surface runoff and drainage runoff (percolation for sand) is presented per season, per year for an annual crop for both study areas. The graphs show that surface runoff during summer is rare and if it occurs, it happens only in small amounts. Both winter and autumn runoff vary considerably over the years as can be expected from the variation in weather data (figures A4.5-6). It can be seen that in Mørdre more surface runoff is generated during winter in the last 5 years of the simulation period, but some of these years have low runoff in autumn. Some of the winters in this period were also characterized as being mild (see section A4.3). In contrast to runoff in Mørdre, high runoff amounts are also found in the winters in Auli

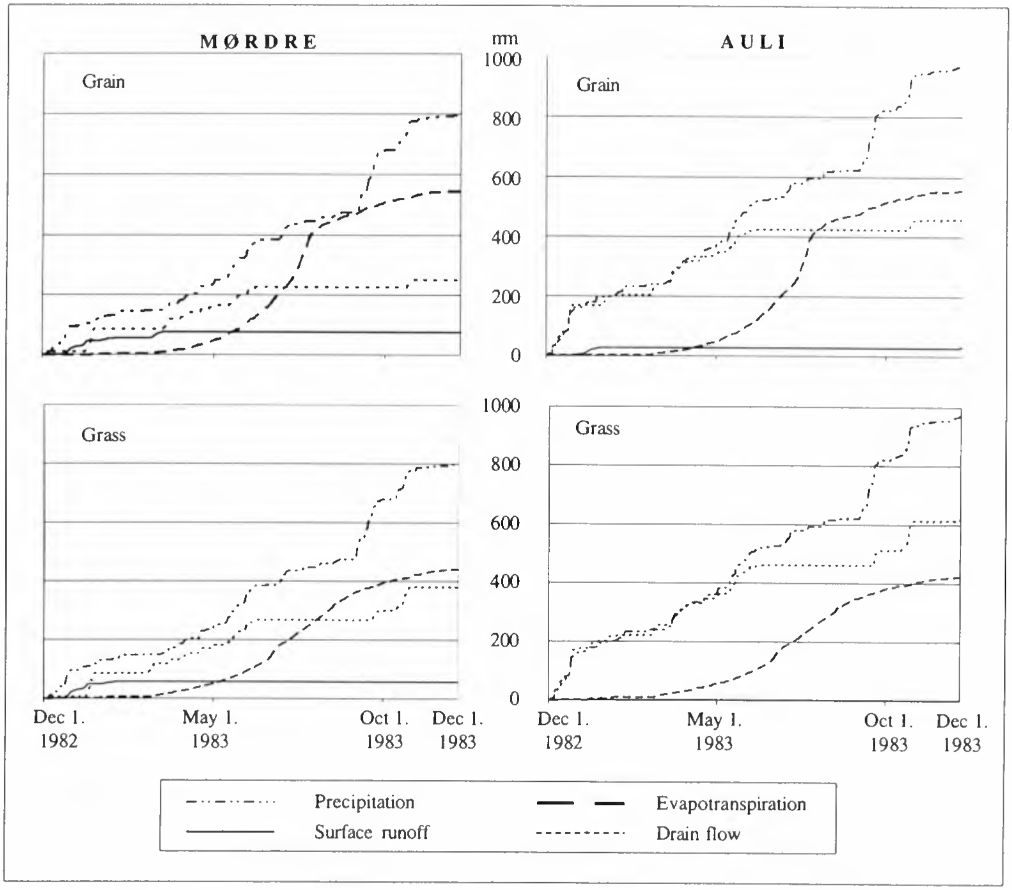


Figure A4.7: Precipitation, surface runoff, drain flow and evapotranspiration for 1983 as simulated with SOIL for a silty soil with grain or grass in Mørdre and Auli.

during the first years of the simulation period. The sandy soils in Auli have generated more runoff than in Mørdre. Runoff through drain pipes is generated nearly for all seasons and all years, but at the end of the simulation period both in Mørdre and Auli, low values can be registrated during summer and autumn. Percolation in the sandy soils is found through all seasons with maximum values for winter and minimum values for summer. The results obtained are in itself not that important to discuss, but are a basis to explain variation in nutrient losses and erosion between years and between scenarios.

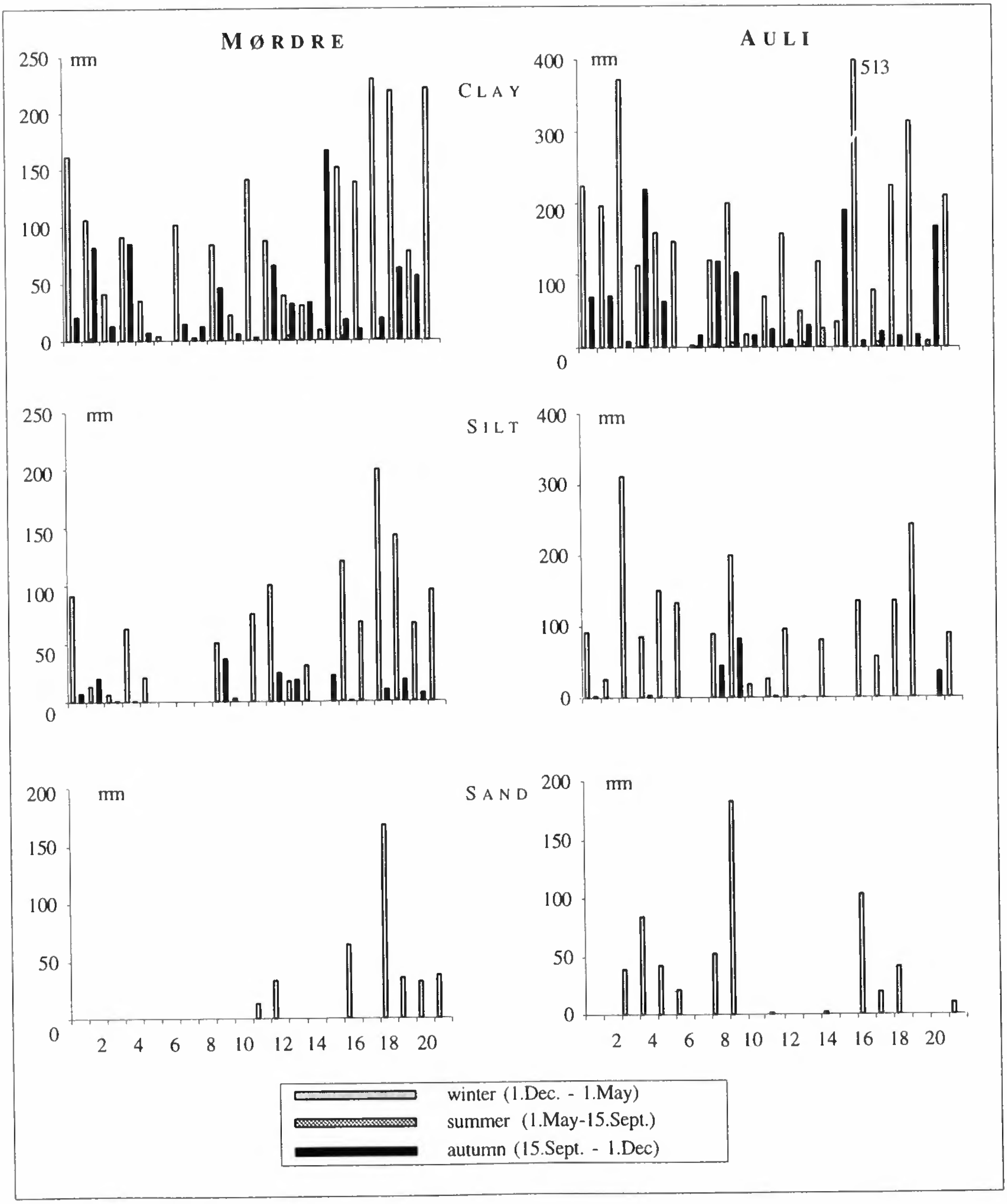


Figure A4.8: Total seasonal surface runoff (mm) from the three main soil types under an annual crop in the Mørdre and Auli watershed. Results are based on daily values as simulated over a 20 year period with SOIL.

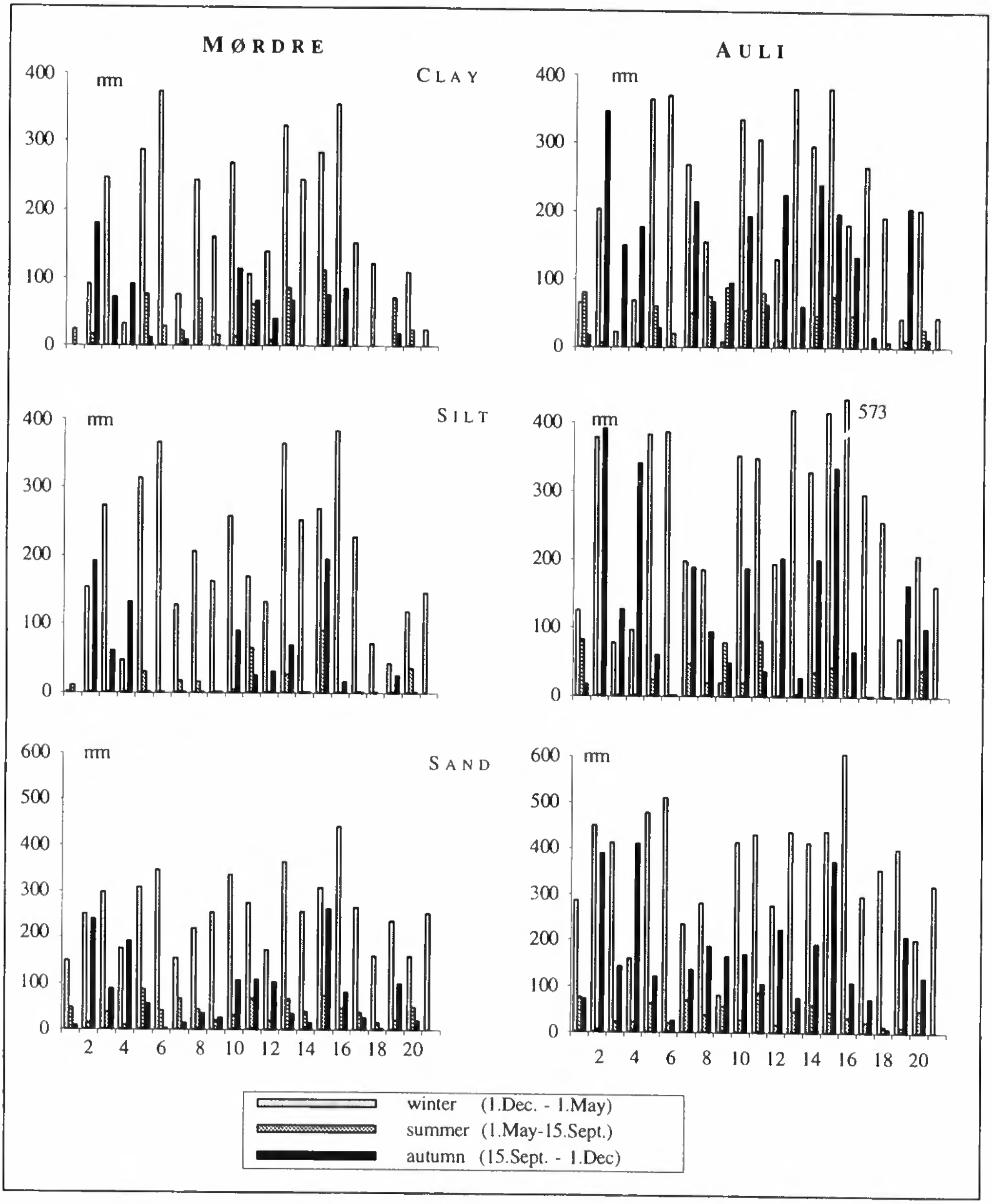


Figure A4.9: Total seasonal drainage (mm) from clayey and silty soils and percolation in sandy soils under an annual crop in the Mørdre and Auli watershed. Results are based on daily values as simulated over a 20 year period with SOIL.

A5 Production functions – yields and nitrogen uptake

A5.1 Yield production functions in the model structure

Crop growth constitutes an important cross road for the disciplines involved in this study. The following general production function is formulated:

$$Y = f(N \mid P) = f_{ijt}[(N_1, N_2, N_3) * \Omega_{lkdmo} \mid P] \qquad [A5.1]$$

where Y denotes yield, plant mass in dry matter,
f_{ijt} denotes a production function for soil type i, crop j and time period t,
N is mineral N $(= \Sigma_q^3 N_q)$,
N_1 is nitrogen in mineral fertilizers,
N_2 is nitrogen from manure in the form of ammonia,
N_3 is mineralized N from the different organic components of the soil,
Ω denotes an operator capturing the influence of different elements of the agronomic practice like:
  l plant succession,
  k soil preparation methods,
  d sowing date,
  m soil compaction, trafficking,
  o competition effects of catch crops, and
P denotes phosphorus in fertilizers.

Time t is measured in years or for some purposes in harvesting seasons, capturing variations in weather over time. The model demands production functions for each type of crop, soil and for each year or cutting season. These production functions are estimated for a standard agronomic practice with tillage in fall and use of mineral fertilizers only. Thus $N_2 = 0$. N_3 is also set to 0, incorporating mineralization under these standard conditions into the function f. This means that N_3 really is ΔN_3 – i.e. the change in mineralization following from an agronomic practice different from the standard as defined above. Finally it is assumed that [A5.1] gives the yield if the crop sowed at the optimal time in spring – i.e. the date securing the highest expected yield.

If the model chooses other practices than the ones defined as standard or the crop is sown at another time than the optimal, the relationship is modulated with the help of the operator Ω. This structure makes it possible to utilize existing trial data that often are organized as factorial trials. Moreover, the system makes if fairly simple to update the model with the effect of a specific change in practice as it also makes it possible to divide the analyses into parts that can be practically handled, still securing consistency throughout the whole study.

In modelling nitrogen turnover, it is N-uptake and not dry matter yield that is of interest. Therefore relationships between dry matter and the amount of N in the crop is developed. For grain the level of N is determined as a function of both dry matter and the level of mineral N in fertilizers. This is not done so far for grass – i.e. N-uptake is here proportional to dry matter yield.

A5.2 Production functions for grain

A5.2.1 Background

Previous work on yield curves in Norway (for example Simonsen, 1989) have primarily focussed on fertilization as the explanatory variable. In a comment to Simonsen's work Vagstad (1990) notes that only 30 % of the variation in leached nitrogen can be explained by Simonsen's yield curve (and the ensuing implicit leaching curve for nitrogen).

One approach that would capture more of this variation is to estimate year specific yield curves for each grain type (barley, oats, spring and winter wheat) for each of the three main soil types (clay, silt and sand). A difficulty with this approach is that the necessary data for this approach is non-existent, as data for some grain and soil types are missing for several years (the ECMOD modeling period use data from the period 1973-92). Year specific yield curves in these instances are therefore estimated using meta analysis.

In addition to estimating the year specific yield curves, expected yield curves for each grain and soil type – the informational base for the ECMOD expected profit maximizing decision maker – need to be estimated. The principal steps in estimating yield curves in ECMOD are:

- estimating year specific yield curves for grain and soil types where yield-fertilization data is available,
- estimating year specific yield curves for grain and soil types where yield-fertilization data is not available using meta analysis, and
- on the basis of the year specific yield curves, estimating expected yield curves for each grain and soil type.

Romstad (1995) provides a more detailed description of these steps.

In the next sections the chosen functional forms are briefly discussed, the yield data that form the base for the estimation are briefly presented before the results from the estimations are displayed and discussed.

A5.2.2 Functional form

Choice of functional form is the key factor in parametric estimation of yield curves, and hence important for good estimates of the expected effects of many policy instruments. For a research program like this one it is therefore important that the estimated yield curves reflect the connections between grain yields and nitrogen fertilization, both theoretically and empirically. Earlier works within EcEc/RMPA (see Bakken and Romstad 1992, Romstad and Rørstad 1994) indicate considerable variability in the functional relationship for fertilization and yields between years. Possible ways of capturing this variability include (i) switching regression, (ii) use of flexible functional forms or (iii) estimating several functional forms and choosing the functional form based on statistical performance criteria. The latter approach was chosen in ECMOD.

The approach of "flexible functional forms" is not chosen because of difficulties interpreting the functional relationships, and possible convergence problems in the non-linear estimation routines that would have to be used. In switching regression the functional form with the best fit (leased squared error) is chosen. This favors functional form with many parameters. In the chosen approach the statistical fit is corrected by the number of parameters using the *final prediction error* criterium (which corresponds to Scwartz's Bayesian information criterium in maximum likelihood estimations, see Schwartz (1978) for details).

The functional forms estimated are (1) Spillmann, (2) 2nd degree polynomial, (3) 2nd degree polynomial with a plateau at the estimated maximum yield fertilization level, (4) "von Liebig" type and (5) 3rd degree polynomial. These functional forms were estimated as they:

- they span a broad specter of the connection between fertilization and yields,
- they are frequently used in production economics to depict the connection between fertilization and yields (functional forms (1), (2) and (5), confer with Debertin, 1986).
- they approach the expected maximum yield level as fertilization increases (functional forms (1) and (3),
- they reflect von Liebig's minimum law, which has received regained attention in production economics the last ten years (functional form (4), confer with Ackello-Ogutu, Paris and Williams (1985), Paris and Knapp (1989), Berck and Helfand (1990)).

Romstad (1995) presents the mathematical specification for the five functional forms, while figure A5.1 shows typical curves for the five functional forms.

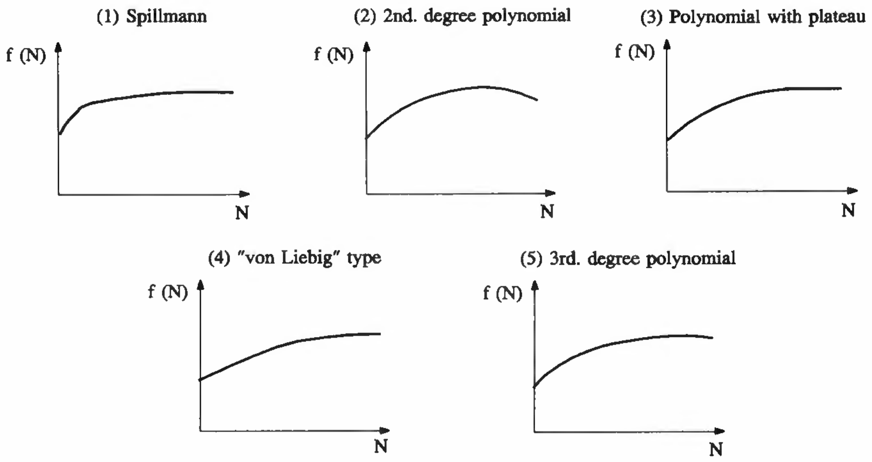


Figure A5.1: Typical connections between fertilization and yields for the five functional forms.

A5.2.3 Data

The yield curves are estimated on the basis of three research series for the connection between fertilization and yields:[13]

- Lyngstad's and Stabbetorp's data with farm trials in the period 1974-83.
- Uhlen's data from Ås on clay for the period 1978-91 (the yield part of Uhlen's lysimeter trials).
- Three data sets from Øsaker (barley: 1973-88, 1973-88 and 1979-90).

The data was merged to one data set and sorted after soil type (clay, silt and sand), crop (barley, oats, spring and winter wheat). Table A5.1 shows the magnitude of the data which forms the basis for the estimations.

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[13] This research was made possible by the cooperation of professors Ingvar Lyngstad and prof. emeritus Gotfred Uhlen, all at the Department of Soil and Water Sciences, Agricultural University of Norway, who allowed us to use their material. The data was organized by Nils Harry Vagstad and Hans Olav Eggestad, Center for Soil and Environmental Research. We extend our gratitude to these persons.

Table A5.1: Years where primary data are available for soil and crop type (bold face numbers indicate the number of years with data available, years with available data are indicated by 2 digits).

Soil type	Grain type			
	Barley	Oats	Spring wheat	Winter wheat
Clay	**18** 73-88, 90-91	**17** 73-89	**17** 74-90	**1** 78
Silt	**2** 75, 77	**0**	**1** 74	**0**
Sand	**6** 74, 76-79, 81	**3** 74-75, 78	**17** 75	**0**

The table shows that data are missing for several years for the various grain and soil types, in particular for the grain type winter wheat and the soil type silt. The meta analysis is used to "fill these holes" in the primary data.

A5.2.4 Estimation

For each grain and soil type year specific yield curves are estimated where primary data are available. All the five functional forms are estimated using non-linear multiple regression[14] (PROC NLIN in SAS). For each grain and soil type the functional form that provides the least squared error in the interval 60-160 nitrogen per ha, corrected for the number of parameters in the model (*final prediction error* criterium).

Meta analysis was undertaken for years where primary data were missing for any soil and grain type combination. Two types of meta analysis was undertaken:

(i) *Meta analysis on individual observations*. By using Statistics Norways year specific yield statistics, the year with the most similar yields to the year with missing primary data was found, and the estimated parameters for these years were transferred and multiplicatively adjusted.

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[14] For the polynomial functional specifications, ordinary linear least square regression could have been applied. With the large amount of data to be estimated, all estimations where done in the same standard procedure to facilitate automated selection of the functional form. Romstad (1995) provides more details on the estimation procedures.

(ii) *Meta analysis on groups of observations* was carried out to obtain year specific yield curves for winter wheat on clay (by copying over parameters for the respective year for winter wheat), and for years where primary data were missing for the soil types silts and sand (by multiplying the yields for the crop on clay with estimated yield correction factors for silt and sand, and adjusting intercept parameters additively).

Tables A5.2-A5.5 show the distribution of the chosen functional forms after the estimation and the meta analysis had been carried out.

Table A5.2: Distribution of chosen functional forms for barley.

Soil type	Chosen functional form				
	Spillmann	2nd degree. polynomial	Polynomial & plateau	"von Liebig"	3rd degree polynomial
Clay	2	3	3	0	12
Silt	2	3	0	0	12
Sand	2	6	3	0	9

Table A5.3:Distribution of chosen functional forms for oats.

Soil type	Chosen functional form				
	Spillmann	2nd degree. polynomial	Polynomial & plateau	"von Liebig"	3rd degree polynomial
Clay	2	2	5	0	11
Silt	2	2	5	0	11
Sand	2	3	6	0	9

Table A5.4: Distribution of chosen functional forms for spring wheat.

Soil type	Chosen functional form				
	Spillmann	2nd degree. polynomial	Polynomial & plateau	"von Liebig"	3rd degree polynomial
Clay	5	5	4	4	2
Silt	5	5	4	4	2
Sand	5	5	4	4	2

Table A5.5: Distribution of chosen functional forms for winter wheat.

Soil type	Chosen functional form				
	Spillmann	2nd degree. polynomial	Polynomial & plateau	"von Liebig"	3rd degree polynomial
Clay	6	5	4	4	1
Silt	6	5	4	4	1
Sand	6	5	4	4	1

A5.2.5 Expected profit maximizing fertilization

By the time of fertilization the decision maker does not know how good or bad the coming growing season will be. This implies that the fertilization decision on each plot needs to be based on expectations. In ECMOD these expectations are calculated by estimating a 3rd degree polynomial with a maximum yield plateau on the basis of predicted values from the estimated year specific yield functions for each soil and grain type (Romstad (1995) provides a more detailed discussion of alternative approaches and presents the arguments for the chosen approach). The mathematical specification for the estimated expected yield curve is given by:

$$\begin{aligned} f_{ij}(n) &= \beta_0 + \beta_1 n + \beta_2 n^2 + \beta_3 n^3 + e_{f_{ij}} \text{ for } n \leq n_{Y_{max}} \\ f_{ij}(n) &= \beta_0 + \beta_1 n_{Y_{max}} + \beta_2 n_{Y_{max}}^2 + \beta_3 n_{Y_{max}}^3 + e_{f_{ij}} \text{ for } n > n_{Y_{max}} \end{aligned} \qquad [A5.2]$$

where $n_{Y_{max}}$ denotes the maximum yield fertilization level, and superscripts i and j denotes crop and soil type respectively.

The detailed parameter estimates can be found in Romstad (1995). Figure A5.2 shows – as an example – a selection of the year specific yield curves (1987-92) and the estimated expected yield curve for barley on clay.

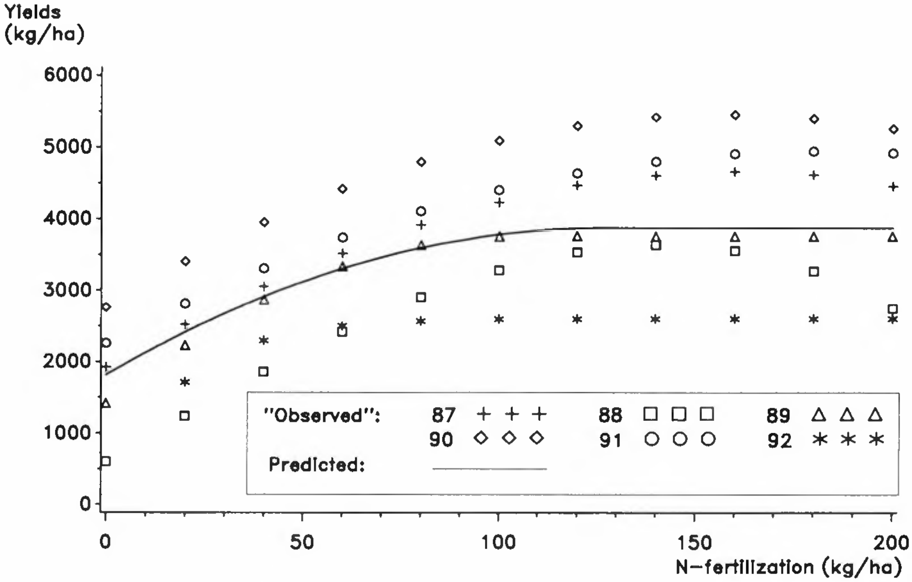

Figure A5.2: A selection of "observed" and predicted values (clay on soil). Estimated function $\hat{y} = 1820 + 32.68\,n - .0131\,n^2 + 0.0000001\,n^3$, *with* $n_{Y_{max}} = 126$ *N/ha.*

An interesting question is how well the estimated curves would predict fertilization on grains for an expected profit maximizing decision maker with actual behavior. Table A5.6 shows the predicted fertilization levels for the 1992 grain prices, and nitrogen fertilizer prices and taxes.

Table A5.6: Expected profit maximizing fertilization levels with 1992 base prices (price + tax on nitrogen fertilizers = NOK 7.07 per/kg, product prices given in the table).

Soil type	Expected profit maximizing fertilization level (kg/ha)			
	Barley (2.28 NOK/kg)	Oats (1.94 NOK/kg)	Spring wheat (2.67 NOK/kg)	Winter wheat (2.61 NOK/kg)
Clay	114	101	125	128
Silt	114	101	124	128
Sand	114	101	118	120

These fertilization levels are only off by a few kg per hectare compared to actual observed behavior among Norwegian grain farmers in comparable regions (South Eastern

Norway), and must therefore be considered good estimates. For a more detailed discussion, see Romstad (1995),

A5.2.6 Closing remarks

Due to the lack of data for some years, some judgement choices had to be made – in particular related to the meta analysis part. This constitutes a possible source for errors with respect to the estimated year specific yield curves, and consequently also for the expected yield curves. The good fit between the predicted fertilization behavior and actual fertilization, as exemplified by the comparison with actual fertilization data for 1992, indicates that these errors are minor. This is certainly the case for the expected yield curves. The possibilities for errors for single years are larger. In this connection it should be noted that the estimated curves should not be viewed as an exact replication of the real connections between fertilization and grain yields, but as an effort to clarify these connections.

One of the most important contributions of the chosen approach is that it embodies the stochastic effects of climate variations between years. As such the chosen approach visualizes the variability in actual yields between years, and presents strong indications that the functional relationship between fertilization and yields may vary between years, crops and soil types.

An additional benefit of the chosen approach in ECECMOD is that it also makes it easier to calibrate the nitrogen leaching models, as year specific yield curves provides better estimates of the nitrogen removed through the yields than what would be possible using aggregate curves.

A5.3 Production functions for grass

A5.3.1 The modelling principles

Grass is in some respects a more complicated crop to model than grain. It consists mostly of several grass varieties and it may contain clover with its ability to fix nitrogen. Further it is cut two or three times a year and the meadow lasts normally for several years, in itself causing variation in yields over time.

To fit the overall modelling, the production functions for grass has to cover the following needs:

- They must be specific for each year and soil type.
- They must give information at least about how large a proportion of the total yearly yield is harvested each season.
- They must be able to describe the substitution from fertilizer N to clover N fixation as either fertilizer or clover seed levels are changed.

The existing empirical data for the type of climate we have been interested in, are too few and scattered to utilize the regression method developed for grain. Only a few years of our analysis period – 1973 to 1992 – are covered, while there exists some series of data from the 1960's. The following two stage method has been applied. First, a plant growth model was utilized to produce estimates for dry matter yields for different N levels, soils, cutting seasons and years. Second, these data were used to construct yearly and average production functions principally along the same line as for grain. As will be shown later, the loss of variation from observations to model estimates occurred almost entirely in the first step.

The plant growth modelling is based on a model developed by Torssell et al. (1982). Data used for the estimations are mainly from the counties Akershus and Østfold:

$$\Delta A_t = A_{t-1} \; R_s \; ALD \; SI \; TI \; VI \qquad [A5.3]$$

where ΔA_t denotes daily growth in harvestable yield, day t, kg dry matter pr ha,
A_{t-1} standing plant mass day t−1, kg dry matter pr ha,
R_s relative growth rate,
ALD ageing factor (function of standing plant mass),
SI index for daily global radiation,
TI index for air temperature, and
VI index for plant available water in the rote zone.

Nitrogen fertilizer is not an explanatory variable in [A5.3]. This element is incorporated into the model by making R_s a function of N as in [A5.4]. The estimation is done for each harvest season separately.

$$R_{stT} = a + b\,N + c\,N^2 + d\,E + e\,E\,N + f\,E\,N^2 \qquad [A5.4]$$

where R_{stT} R_s value for season t in year T,
N nitrogen fertilizer in kg pr ha,
E age of meadow (1-4 years), and
a-f parameters.

Information about the choice of functional form in [A5.4] is given in Baadshaug, Grønnerød and Skjelvåg (1995). Their study documents the difficulties with defining a good model relating R_s to N. For [A5.4] R^2 varies between 0.3-0.5.

Based on [A5.3] and [A5.4], a relationship between nitrogen fertilizing and yields was established for each meadow age group, year and season. Results were produced both for a standard meadow with timothy and meadow fescue and a meadow with 20 % clover together with timothy and meadow fescue. By varying the values for VI in [A5.3], estimates were obtained for different soil types with water capacities of 60, 90 and 120 mm set as representative values for sandy, clayey and silty soils respectively.

The trials providing the data on yields and nitrogen use were conducted under a system with three cuts per year and with a meadow plowed every three years. Further the trials were conducted with a fixed relation between N given for each season; 47 %, 32 % and 21 % for the tree seasons respectively. Thus it gave no sense to produce independent production functions for each season. But the estimates gave information about the distribution of the total yield between seasons given the level of nitrogen supplied. This information is utilized to distribute the total yield for each year between the three seasons which is of importance for the nitrogen modelling.

On the basis of the estimates produced by Baadshaug, Grønnerød and Skjelvåg (1995), a set of yearly production functions for the period 1973-1992 were estimated for both types of meadow. Following the fact that the relationship between N and Y is shown to be more smooth in grasses than in grain, and that [A5.4] already determines a certain functional form on the relationship between Y and N, only a second degree polynomial is used. This functional form is utilized also for the expected yield function being estimated on the observations for all twenty years together.

Normally there is very little clover in Norwegian meadows. It is not always part of the seed mix used, as it often dies out fairly early as an effect of the relatively high level of nitrogen fertilization. If the price of N in mineral fertilizer increases, it may become more economical to utilize clover better. This may be modelled as a switch from the timothy/fescue meadow to the one with clover as in the two series of estimates in Baadshaug et al. (ibid.). The problem with this method though, is that such a transition will probably be gradual rather than momentaneous. Further the meadow with clover is supposed to be much more productive in trials than what the average farmer is normally able to produce.

Based on this reasoning, we have taken the average of the parameters from the meadow with timothy/meadow fescue and the one with clover and let this new function represent meadow in ECECMOD. Tests show that the two types of meadows differ very little in yields if we compare at the levels of N normally used. But the difference is fairly substantial at lower N levels.

The effect of clover is not dependent only upon the use of mineral fertilizer N as captured the described production functions. Also the amount of clover in the seed mix will have some influence. As to the last issue though, Grønnerød (1992) concludes that the relationship is rather weak at least beyond a level of about 10 % in the seed mix, which is the average level of today's use. Thus we have chosen to concentrate only on the effect of nitrogen use.

The data available made it possible to produce yield functions dependent upon age of the meadow. Still we have used the average for the whole rotation period since differentiating at this level would have given only very small gains. The age of meadows is in practice though, somewhat higher than in the trials (Lundeby and Vatn 1994). This is taken into account by letting the third year in the succession count twice producing a more standard four year succession.

There is one more adjustment related to the difference in response between trials and actual agriculture. Even though the difference is supposed to be extra large for meadow with clover, the problem exists also for the timothy/meadow fescue type. Thus the average functions estimated as above, gave yields about 10 % above the average as measured in practice. Calculating this deviance, we have corrected for the relative distribution of the soil types in the areas modelled. Practice is defined as the average yield for the period 1984-1992 for the two counties Akershus and Vestfold. When comparing with the modelled yields the mean level of fertilizer use in grass production as given by Statistics Norway (see Lundeby and Vatn 1994) is used. The correction is done multiplicatively.

A5.3.2 Documentation of the production functions used

The production functions are estimated using non-linear multiple regression (PROC NLIN in SAS). Details about the functions estimated are given in Vatn (1994). While the F- and R^2-values are very high for the estimated yearly functions – both for the timothy and clover meadows – they are modestly high for timothy and low for clover meadows as we look at the average functions. This tells us that the year – i.e. weather – influences the yields substantially. Especially in the case with clover, fertilizer N has a low influence on yields compared to other factors for which the year serves as a "proxy." Some examples presented in table A5.7 illustrates this. We have chosen production functions estimated for timothy/meadow fescue and timothy/meadow fescue/clover on clay. The functions represents the whole period (1973-92) and the year 1988 respectively. The yield is estimated in kg per ha. The standard deviations are given in parentheses:

Table A5.7: Estimated yield functions for timothy/fescue on clay for the period 1973-92 and 1988.

$\hat{y}_{\text{tim., clay, 1973-92}}$	=	2230.8 +	$38.63{*}N$ −	$0.074{*}N^2$	
		(194.0)	(2.59)	(0.007)	(F-value: 218 R^2: 0.74)
$\hat{y}_{\text{clov., clay, 1973-92}}$	=	6055.9 +	$11.88{*}N$ −	$0.028{*}N^2$	
		(241.1)	(3.22)	(0.009)	(F-value: 7.6 R^2: 0.09)
$\hat{y}_{\text{tim., clay, 1988}}$	=	2165.9 +	$41.75{*}N$ −	$0.078{*}N^2$	
		(74.9)	(1.00)	(0.003)	(F-value: 1810 R^2: 0.99)
$\hat{y}_{\text{clov., clay, 1988}}$	=	6448.3 +	$12.49{*}N$ −	$0.030{*}N^2$	
		(4.4)	(0.06)	(0.000)	(F-value: 25610 R^2: 0.99)

The situation is similar for the other soil types. The variation between years is rather substantial. The following table illustrates the situation for timothy/meadow fescue where 1976 and 1984 are worst respectively best year in the actual period. This is the situation for all soil types:

Table A5.8: Estimated yield functions for timothy/fescue on sand, clay and silt for 1976 (year with the lowest yield) and 1984 (year with the highest yield)

$\hat{y}_{\text{tim., sand, 1976}}$	=	1421.5 +	$22.44{*}N$ −	$0.045{*}N^2$	
		(36.4)	(0.49)	(0.001)	(F-value: 1843 R^2: 0.99)
$\hat{y}_{\text{tim., sand, 1984}}$	=	2965.8 +	$50.28{*}N$ −	$0.096{*}N^2$	
		(12.9)	(0.17)	(0.000)	(F-value: 83585 R^2: 0.99)
$\hat{y}_{\text{tim., clay, 1976}}$	=	1651.1 +	$26.68{*}N$ −	$0.055{*}N^2$	
		(22.2)	(0.30)	(0.001)	(F-value: 6934 R^2: 0.99)
$\hat{y}_{\text{tim., clay, 1984}}$	=	3104.9 +	$52.82{*}N$ −	$0.101{*}N^2$	
		(8.0)	(0.11)	(0.000)	(F-value: 238871 R^2: 0.99)
$\hat{y}_{\text{tim., silt, 1976}}$	=	1806.2 +	$29.44{*}N$ −	$0.059{*}N^2$	
		(15.2)	(0.20)	(0.001)	(F-value: 17986 R^2: 0.99)
$\hat{y}_{\text{tim., silt, 1984}}$	=	3127.5 +	$53.66{*}N$ −	$0.102{*}N^2$	
		(10.1)	(0.13)	(0.000)	(F-value: 156457 R^2: 0.99)

The functions used in ECECMOD are the average of the timothy/fescue and timothy/ fescue/clover functions. Figure A5.3 shows the results for expected yields – i.e. the ones based on the estimated yields for whole period – for sand, clay and silt respectively.

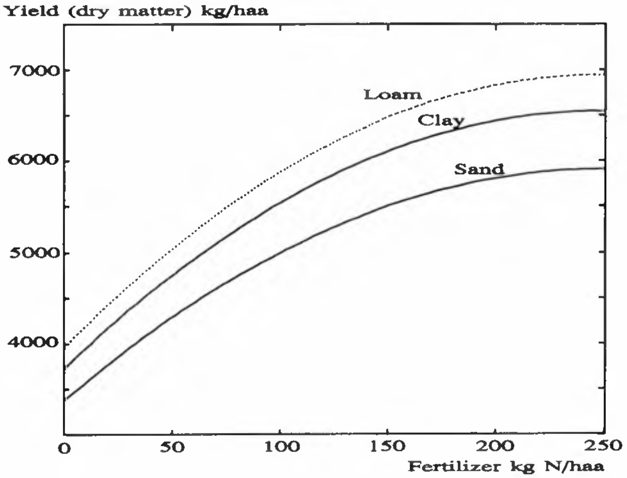

Figure A5.3: Production functions for meadow on different soils – average response for the period 1973-1992.

The functions are as follows:

$$\hat{y}_{sand} = 3373.7 + 20.30*N - 0.041*N^2$$

$$\hat{y}_{clay} = 3727.0 + 22.73*N - 0.046*N^2$$

$$\hat{y}_{silt} = 3951.6 + 24.13*N - 0.049*N^2$$

As to the distribution of the total yield per year on harvesting seasons, the analyses produced the following results:

Harvest mid June:	average 57.4 %	max: 85.1 %	min: 33.5 %
Harvest early August:	average 27.1 %	max: 53.2 %	min: 5.8 %
Harvest mid September:	average 15.4 %	max: 20.1 %	min: 6.9 %

A5.4 Changes in crop growth due to changes in agronomic practices

A5.4.1 Timeliness costs

Changes in agronomic practices may result in changed sowing dates. As an example, a change from fall to spring tillage, will normally delay sowing. This alters the plant uptake period as it induces changes in yields. Since nitrate leaching is so dependent upon plant uptake, the effect on leaching may be substantial.

There exists some studies on the relation between sowing date and yields relevant for Norwegian conditions (Strand 1984; Christoffersen 1988 and Ekeberg 1987). In all cases, the change in yield is a function of delayed sowing date only. In the case of Strand and Christoffersen, the loss function is further linear.

Vatn and Romstad (1994) discuss the arguments in the literature. They conclude that there are reasons to believe that the timeliness costs are lower early than late in spring. Moreover, these costs must be supposed to vary whether the spring is late or not. To capture these mechanisms, functions were estimated where yield loss depends upon both "earliest possible" sowing date of the year and actual sowing date. Different functional forms were tested (Vatn and Romstad 1994) – both types assuming the earliest possible day to give the highest yield, and types able to capture losses while sowing too early. All functions tested were non-linear.

Certainly there are problems related to consistent operationalization of the concept "earliest possible sowing date." We have used data from a series of trials where the first sowing date was set deliberately early and where there was an aim to secure as equal conditions as possible from year to year (Ekeberg, pers. com.). The available data did not differentiate between soils – i.e. the trials were conducted exclusively on a moraine deposited soil. The trials differentiated between the grain species though, but evaluating the results we found that such partitioning added little information. There were too few years in the trial to determine any clear patterns here.

On the basis of the results gained, the simplest of all functional forms tested was the one finally chosen. The choice was made both upon standard statistical measures and how well the function reflected the underlying physiological mechanisms (Vatn and Romstad 1994):

$$h = \alpha - \beta d_{0t}(d_t - d_{0t})^2 \qquad [A5.5]$$

where h is relative yield, d_{0t} is "earliest possible sowing date" in year t and d_t is actual sowing date the same year, all dates counted from the April 20.

The estimation gave the following result:

$$\hat{h} = \underset{(1.05)}{93.8} - \underset{(0.0002)}{0.0014}\, d_{0t}(d_t - d_{0t})^2 \qquad \text{F-value: } 37.9 \quad R^2 = 0.16 \qquad [A5.6]$$

where the highest observed yield of the each year is set to 100. All observed yields in the material are made relative to that level. To make [A5.5] fit our needs, it is multiplicatively transformed to make the yield of day 0 become 100.

A5.4.2 Soil preparation system and relative yields

Four methods for soil preparations have been considered. They are;

Fall plowing (FP): One soil level floating, and one to two harrowing before sowing.
Spring plowing (SP): After ploughing, one soil level floating and one harrowing.
Fall harrowing (FH): One to two times harrowing before sowing.
Spring harrowing(SH): First one stubble/rotor harrowing and then one ordinary harrowing.
Direct drilling (DD): No preparations before sowing.

Within these system there will be some variation depending on soil class.

Table A5.9: Relative yields in different soil preparation systems.

	AP	**SP**	**AH**	**SH**	**DS**
Heavy clay	100	89	91	88	95
Silty clay loam	100	96	93	92	82
Clay loam	100	102	103	99	96
Silty loam < 90 % silt	100	98	99	94	77
Loam	100	97	96	99	99
Silt	100	104	83	84	76
"Sandy silt/Silty sand"	100	96	94	89	85

Table A5.4 is based on Hansen (1991) and updated with experimental results from 1991 to 1994.

Table A5.10: Annual capital costs pr. farm in different soil preparation systems and farm size. Numbers i NOK.

	Small farms	Medium small farms	Medium large farms	Large farms
Fall plowing	10156	12695	19449	21985
Spring plowing	10156	12695	19449	21985
Fall harrowing	9176	11470	17354	20420
Spring harrowing	9176	11470	17354	20420

The costs in table A5.10 are excl. tractor costs. Direct drilling : rental price.

Table A5.11: Variable costs[1] pr/ha in different soil preparation systems and farm size. Numbers in NOK/ha.

	Small farms	Medium small farms	Medium large farms	Large farms
FP: clay	1081	1034	970	901
FP: sand,silt	1021	978	927	858
SP: clay	1186	1126	1048	979
SP: sand,silt	1126	1069	1005	936
FH: clay	1056	1026	970	919
FH: sand,silt	1013	983	936	876
SH: clay	1049	1019	963	903
SH: sand,silt	1006	908	929	877

[1] Maintenance costs, fuel, straw, herbicides and labor

A5.4.3 Soil compaction, trafficking and yields

Different agronomic practices result in different soil compaction and trafficking damages, influencing conditions for crop growth and N uptake. The aim of this part of the study is to find estimates for crop losses due to trafficking. As discussed below, the relevant losses are incurred in connection with spreading of manure, thus spreading technology plays an important role. Due to the complexity of the subject matter, it has not been within the scope of this study to model the crop losses in great details, but to establish reliable average figures for the losses under different technology choices.

Above a certain level of soil compaction, there is a negative relationship between soil compaction and crop growth. Below this level the soil is too loose, and may thereby inhibit the growth. Figure A5.4 (next page) shows the general relationship between relative growth and degree of compactness for barley. The dotted line to the left shows a normal state in spring on fall plowed fields. The degree of compactness is defined to be the ratio (expressed in percentage) between the dry bulk density of the plough layer and the density after a standardized uniaxial compaction test (200 kPa). The optimal degree of compactness (i.e. the compactness yielding highest yield) has largely been found to be independent of soil type. The optimal compactness tends to be high in dry years and low in years with a rainy growing season. The optimal level also varies with crop species. (Arvidsson and Håkansson 1991). The most important determinant factors for soil compaction are soil moisture content, number of passes, wheel equipment (width and inflation pressure) and weight of machinery.

In addition to losses due to soil compaction there will be losses due to damages of the plants when trafficking in growing crops. This is only relevant for meadow, and these damages will occur in all manure spreading seasons (spring, summer and fall). For meadow we do not differentiate between damages due to soil compaction and damages to the growing crop.

Production functions (yield functions) for grains used in this study are estimated from field trials (see section A5.2). In these trials standard fertilizing and preparation methods are used. Manure is normally not applied to the plots since these trials are studies of growth response to nitrogen, in which manure makes it difficult to measure the amount of nitrogen applied. In other words: the compaction effects of normal field preparation is already accounted for in the data, and the only additional losses we need to consider is the losses due to manure spreading.

Also in the case of meadows, crop losses due to "base line" practice are embedded in the production functions. Thus, the loses or gains we must take into consideration are the ones stemming from manure spreading practices different from base line. In our case, standard equipment has been manure spreading with tank trailer in all three seasons. From this it is evident that there may also be gains: if the farmer is not spreading manure in one of the seasons the loss will be avoided.

In the model the losses due to soil compaction and trafficking are modelled via the following general expression:

$$f(N)(1-\sum_{q=1}^{3}\Omega_q^z) \qquad [A5.7]$$

where f(N) is the yield function with respect to nitrogen (N) and Ω^z_q is the relative loss when spreading manure in season q using technology z. Of course, if no manure is spread in a given season, no losses occur, for meadow there may in fact be gains. In other words, Ω may be negative for meadow.

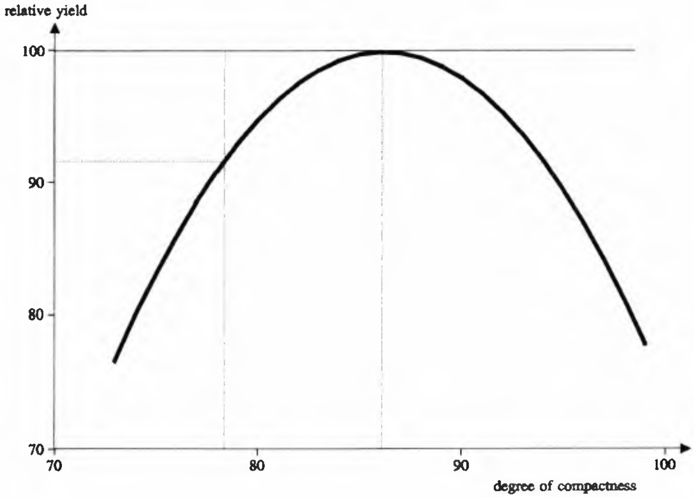

Figure A5.4: General relationship between relative growth and degree of compactness for barley (after Håkansson 1989).

Losses are technology dependent, and in our model the farmer can choose between three types of manure spreading methods. The base line case is spreading slurry with a tank trailer. The farmer may also spay semi liquid manure (slurry + 100% water) using the same tailer. The last choice is spreading semi liquid manure via a system of pipes and hoses. (The choice of spreading technology is described in section A2.5.) The losses in table A5.12 refer to base line technology. When using semi liquid manure, the traffic on the fields doubles if spraying the same amount, and we have assumed that the damage will double. If using the pipe/hose technology we have assumed that there will be no losses. We have also assumed that the losses differs between soil types in grain. The reason for this is that the water content of the soils differs, and as mentioned above, the water content of the soil is a determinant factor for soil compaction and thereby crop losses.

Table A5.12: Crop yield losses, in percentage, due to soil compaction and trafficking. All losses are related to base line technology. See text for explanation.

Crop	Soil type	Spring	Summer	Fall
Grain	Clay	1.5	N.A	0.0
Grain	Silt	1.5	N.A	0.0
Grain	Sand	1.0	N.A	0.0
Meadow	Clay	1.3	0.6	2.1
Meadow	Silt	1.3	0.6	2.1
Meadow	Sand	1.3	0.6	2.1

N.A. = no application on grain in summer

For grain the figures in table A5.9 are found by surveying the literature and adjusting for the weather and soil conditions in our study areas. The estimates for meadow are based on Arvidsson and Håkansson's (1991) model for relative yield in ley. In their model separate relative yields are estimated for each harvest. In our model all cuts are merged into one production function (even though there are three cuts in the underlying model). In order to get consistent estimates, the loss in each harvest, estimated using Arvidsson and Håkansson (1991), has been weighted using the relative yield for the different cuts in the data used to generate the annual production functions.

A5.4.4 Catch crop and competition effects

Competition between two plants occur when one of the plants reduces one of the growth factors: water, nutrition or light, and when this reduction reduces the growth of the other plant (Zimdahl 1980).

The purpose of a catch crop is to reduce N-leaching and soil erosion in periods of unvegetated fields. Because of the short growing season after grain harvest it is necessary to undersow the catch crop in spring. A disadvantage of undersowing the catch crop is the risk of reducing the grain yield. To minimize this competition effect (c-effect) between the catch crop and the main crop there has been focused a lot on cultivation methods like: establishment methods, catch crop species, seed rates, sowing date (ex. after main crop).

Not to mix the c-effect factor and the 2. year effect, the factor chosen is based on experimental results from the first year of undersown catch crop. Weather conditions, especially precipitation, will influence on the c-effect factor and cause variation from year to year. It was not possible to find any system for this variation. Therefore a constant value of the c-effect was chosen. In Lundeby (1995b) this c-effect factor is estimated to 4 %.

A5.5 Nitrogen in crops

The crop growth production functions described earlier in this chapter represents crop response by yield dry matter as a function of fertilization level. Statistical information on dry matter in yield for all the usual types of crops at different fertilization levels is available. The information is obtained from different sources and cover a wide range of years at several fertilization levels for both grains and grass. The vast amount of data quantifying yield dry matter at different fertilization levels makes it possible to create crop growth functions specific to every year during the scenarios under consideration.

One of the main ideas in the ECEC/RMPA project was to use the information in crop response functions both in the economical analyses and as driving variables in the SOILN-NO model simulations of nitrogen transformation and losses. It was mentioned in section 4.4 and appendix A3.3, however, that crop response in the SOILN-NO model is expressed in terms of nitrogen contents in yields. The nitrogen contents are interpreted as driving variables in SOILN-NO simulations by a dynamic programming approach to plant N-uptake, developed by Vold and Søreng (1995). As the crop response is given in terms of dry matter in yield, it was necessary to develop a functional relationship between nitrogen content in yields and dry matter in yield, since the SOILN-NO model require crop response in terms of nitrogen content in harvested yield. One way of making such a relationship is to determine nitrogen content as a percentage of dry matter in yield. The fact that other factors than dry matter in yield also affect the nitrogen content makes this relationship biased. One factor that affects nitrogen content in yield is the nitrogen fertilization level. This is clear from long term field experiments with grains in south-eastern part of Norway, conducted by Institute of Soil Sciences at the Agricultural University of Norway (Vold, Bakken and Vatn 1995a), where dry matter and nitrogen content of yields were measured at several fertilization levels during the period 1970-1988. Thus, in order to calculate proper nitrogen contents in grain yields from crop growth production functions, one should use both fertilization levels and dry weight of yields as explanatory variables.

The next section shows how a functional relationship between nitrogen content in grain yields, yield dry weight and fertilization level was developed. Then there is a section where the nitrogen contents of stubble, catch crop, weed and meadow are considered. Due to few available measurements of nitrogen contents together with dry weight at different fertilization levels for these yield types, it was necessary to use the rather rough assumption that nitrogen contents are fixed percentages of dry weight.

A5.5.1 Nitrogen in grains

Types of grain crops considered comprise barley, oats and wheat. We decided to use a series of long term fertilizer experiments in the south eastern part of Norway, to investigate the functional relationship between nitrogen availability, obtained yields (dry weight), and the amounts of N in grains and straw (Vold, Bakken and Vatn 1995b). A simple equation was fitted to the data by nonlinear regression (explanatory variables were N-levels and obtained yields), and its performance checked by inspecting the residuals. Particular attention was paid to the model's ability to account for the annual variability within each fertilizer level as well as the difference between the fertilizer levels.

The search for a model was based on objectives of simplicity and plant physiology. The well-known Michaelis-Menten model,

$$f = ym\ x/(K + x),$$

or alternatively

$$f = \alpha\ ym\ x/(\alpha\ x + ym),$$

where K, α and ym are constants and K and α are related by $K=ym/\alpha$, came quickly to mind. This model is used in enzyme kinetics and also in a more qualitative sense to represent aggregated processes. Vold, Bakken and Vatn (1995b) show how the Michaelis-Menten equation was used as a starting point in a physiologically based argumentation for a functional relationship between nitrogen content, yield dry weight and fertilization level. The equation arrived at is given by:

$$g = \alpha\ NT\ Y/(\beta\ NT + Y) \qquad [A5.8]$$

where $g = E[NH]$ is the expected nitrogen content in harvested yield (g N m^{-2}), Y is yield dry weight (g DW m^{-2}), NT is the maximum amount of N-uptake by the crops (g N m^{-2}) (shoot+root), i.e. soil nitrogen that is available to plants during the growth season and α and β are constants. The effective nitrogen level in the soil was expressed in terms of fertilizer application, NF (g N m^{-2}), and the soil derived plant available nitrogen, NS (g N m^{-2}), by:

$$NT=NS+NF$$

For the particular field data sets, it was evident that NS was not a constant through the experiment. Rather, it seemed to decline, thus NS being a decreasing function of time, t. A linear function of time was suggested as appropriate to represent the yearly nitrogen mineralization, NS. Thus,

$$NS = NS_0 + \gamma\ (t-t_0) \qquad [A5.9]$$

where NS_0 is the value of NS in year t_0, and γ is a constant. Now, the relationship in [A5.9] can be expressed in terms of a nonlinear fixed regressor model:

$$NH = g(NF,Y,t;\theta) + \varepsilon \qquad [A5.10]$$

where ε is assumed independent identical distributed (i.i.d) $N(0,\sigma^2)$, NH is the actual nitrogen content in the yield and $\theta = [\alpha, \beta, \gamma, NS_0, t_0]$.

A part of the data from the field experiments, $\tilde{NH}_i$, $\tilde{NF}_i$ and $\tilde{Y}_i$, i=1,...,n, were applied for the purpose of estimating the parameters in the model equation [A5.10]. Here $\tilde{NF}_i$ and $\tilde{Y}_i$ are fertilization levels and measured yield dry weights corresponding to measured nitrogen contents $N\tilde{H}_i$. The problem of estimating the parameters was formulated as a least-squares problem:

$$S(\theta) = \min \Sigma[N\tilde{H}_i - g(N\tilde{F}_i, \tilde{Y}_i, t; \theta)]^2$$

Problems of this type can only be solved by iterative solution algorithms. One such iterative algorithm is the Levenberger-Marquardt method. A MATLAB-version of this algorithm by Shrager, Jutan and Muzic (1994) was downloaded from Matlib[15].

A small MATLAB-program where the data, the model and the Levenberger-Marquardt algorithm were interconnected, was implemented. Sets of parameter estimates for oats, barley and wheat were found and cross validation against data not used in the parameter estimation, were performed. The results from parameter estimation, calculation of R^2-values and cross validations are found in Vold, Bakken and Vatn (1995b). They conclude that the model has qualities that make is suitable for prediction of the nitrogen content in grain yields. The conclusion is based on the model prediction error, which was calculated with parameter values obtained by parameter estimation against a part of the data set, the rest of the data set being reserved for the purpose of cross validation.

For application purposes, however, it would be most natural to exploit the complete dataset while estimating the parameters. Thus, sets of parameters for oat, barley and wheat were estimated by solving the least-squares problems with the complete dataset involved. The estimates arrived at are shown in table A5.13.

Table A5.13: Estimates of model parameters for oats, barley and wheat.

Parameters	Oats	Barley	Wheat
$\hat{\alpha}$	1.1384	0.9943	2.1010
$\hat{\gamma}$	26.1346	18.5209	53.9421
β	-0.3828	-0.4536	-0.3675
$N\hat{S}_0$	9.5778	9.0953	7.4052

The yearly soil derived plant available nitrogen in a plot is highly dependent on earlier - and present agronomic practice of the plot. Scenarios considered comprise plots with very different agronomic practice. It is, thus, no evidence that a certain linear model is superior to a constant value in describing the overall yearly soil derived plant available nitrogen. This was clearly demonstrated in Vold, Bakken and Vatn (1995b) where model parameters for

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[15] Matlib is found on ftp-site ftp.mathworks.com. The Levenberger-Marquardt algorithm is found in directory pub/contrib/optim/leasqr

wheat were estimated against data from a crop rotation experiment and model validation was performed against long term field experiments with wheat. It turned out that reestimation of NS_0 and γ was necessary in order to obtain good fit to validation data.

As there are no clear indications that a linear function is more appropriate than a constant value in describing the yearly soil derived plant available nitrogen, it was decided to use a constant value. This value was found from the linear function by taking average over the period under consideration. Thus,

$$NS = N\hat{S}_0 + \hat{\gamma}\ (T/2-t_0),$$

where T = 1988 and $t_0 = 1970$. This way, a constant value of NS, for oats, barley and wheat were determined to be 5.9, 7.28 and 5.37 (g N m^{-2}), respectively. The difference between measured nitrogen contents and respective model predictions for oat, barley and wheat, with α and β as given in table A5.13 and NS constant, is shown in figures A5.5, A5.6 and A5.7. Measurements of nitrogen contents in yields of oat, barley and wheat are plotted against respective model predictions in figures A5.8, A5.9 and A5.10.

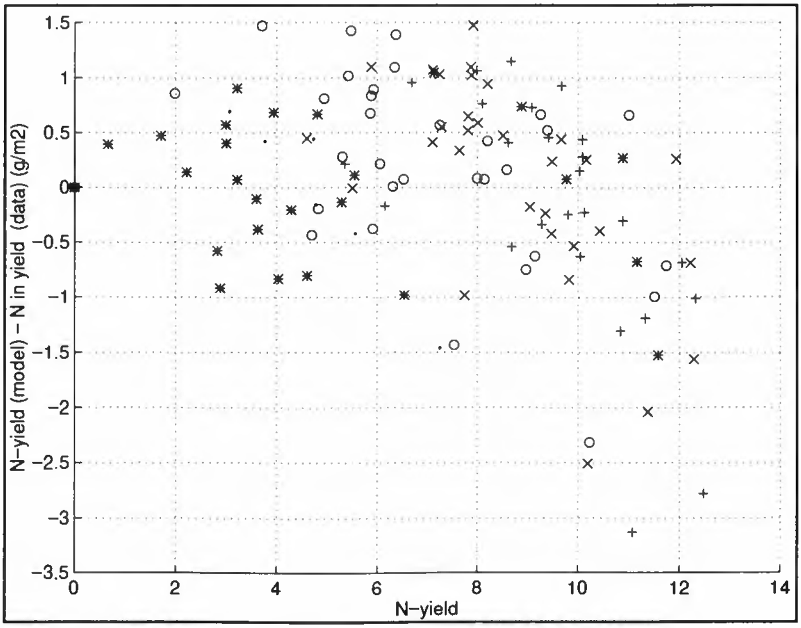

Figure A5.5: Residuals plotted against measured nitrogen content in oats yields.

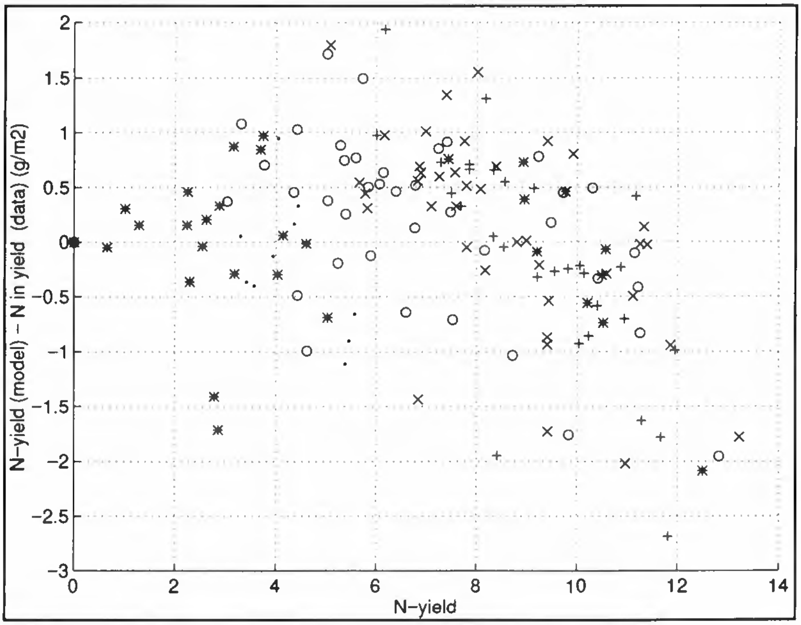

Figure A5.6: Residuals plotted against measured nitrogen content in barley yields.

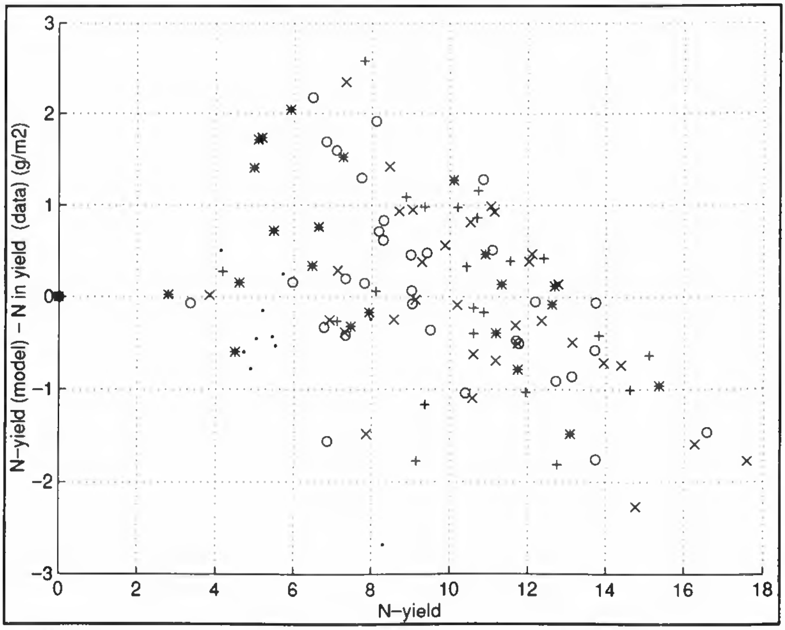

Figure A5.7: Residuals plotted against measured nitrogen content in wheat yields.

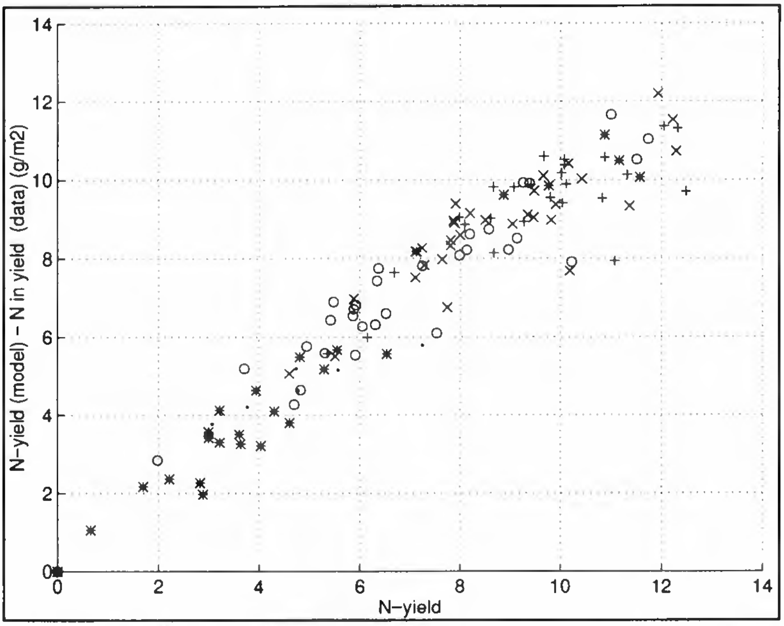

Figure A5.8: Model prediction with estimated parameter values in relation to measurements of nitrogen content in oats (grain+straw).

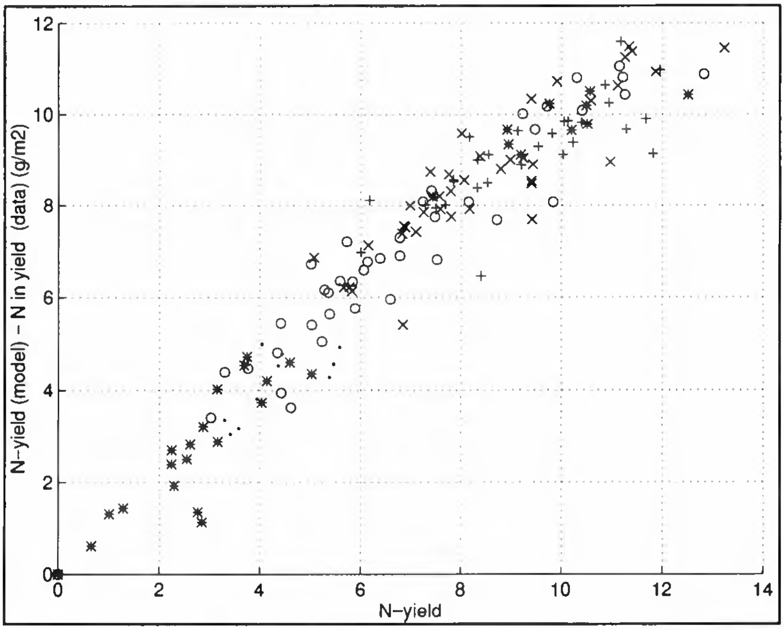

Figure A5.9: Model prediction with estimated parameter values in relation to measurements of nitrogen content in barley (grain+straw).

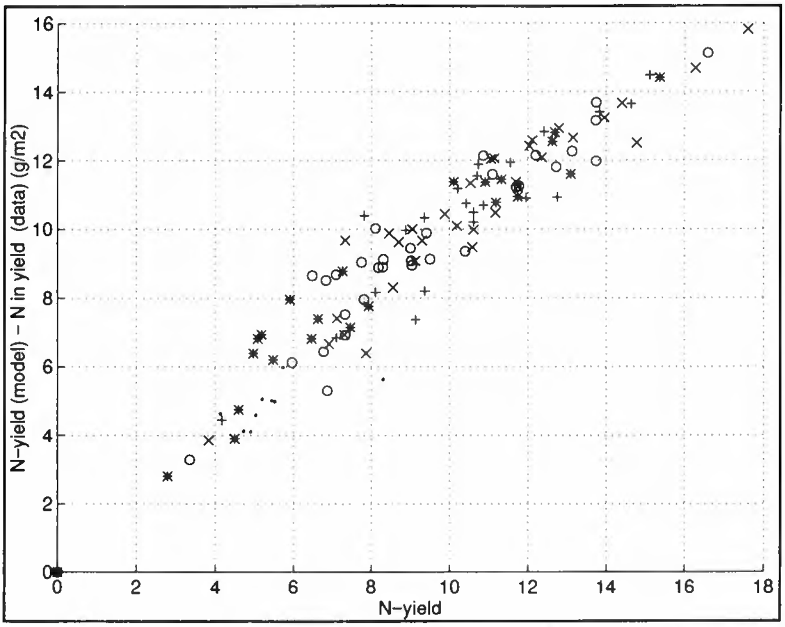

Figure A5.10: Model prediction with estimated parameter values in relation to measurements of nitrogen content in wheat (grain+straw).

Ideally, one would prefer to use the SOILN-NO model to calculate the effective nitrogen level, NT, during model simulation. This is not possible with the present version of the model, however, since the effective nitrogen level depends on the nitrogen uptake to plants that has to be specified in advance of model simulation.

A5.5.2 Nitrogen uptake in grass

The calculation of N-uptake in grass is simpler than for grains. The estimation consists of three steps. First the dry matter yield of grass and clover is estimated on the basis of the yearly production functions described in section A5.3. Then the clover part of this yield is subtracted, assuming that the uptake of N in clover is entirely based on N fixation. Finally, the N-uptake from the soil is determined as a fraction of the grass dry matter yield. The N percent relates to the number of cuts.

A5.5.3 Nitrogen uptake in catch crop, winter wheat, weeds and regrowth of grass

After the harvest of grain, weeds and catch crops will keep growing until it is ploughed or ceased to grow because of the temperature limit. Results from Norway and Sweden, show that the average amount of catch crops in late fall is ca. 800 kg dry matter/ha or 25,5 kg N/ha. Practice and experiments indicate that the amount of catch crops vary a lot and fluctuate from year to year. In order to describe this variation it is assumed that dry matter yields are a linear function of the temperature sum in the fall. This choice is made on the basis of the fact that the temperature is normally the most constraining factor for plant growth in Norway in this period of the year. Figure A5.11 shows the results of the estimations made for each of the two areas, for the period 1970- 1993. Sources and methods are further documented in Lundeby (1995b).

N-uptake in weeds and germinating grains is assumed also to be a linear function of the temperature sum, but the effect is much lower than in the case of catch crops – on average estimated to be about 15 % of catch crop effect. If there is no fall tillage, we get a maximum weed yield. Early ploughing date (15. September) reduces the N-uptake to 33 % of maximum. Medium ploughing date (5. October) reduces the N-uptake to 75 %.

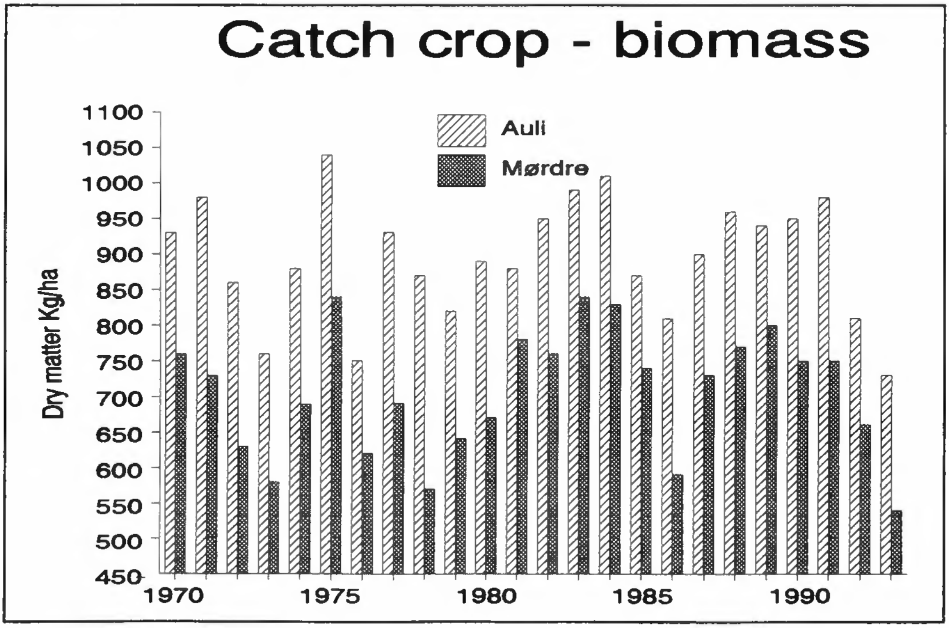

Figure A5.11: Estimated biomass for catch crops in the period 1970 - 1993.

There is some regrowth after the third mowing in fields with grass production. For physiological reasons, we have assumed that meadow is less efficient than catch crops in extracting plant available soil-N. In the model the regrowth extracts 15 kg N/ha.

The N-uptake in winter wheat will depend on the sowing date. The model assumes an average uptake of 5 kg N/ha in autumn (Lundeby 1995b).

Appendix B
Overview of the results

In this appendix the main results from all of the scenarios are presented in a table for each scenario. The tables are divided into two parts, the first presenting results regarding changes in environmental quality with the associated costs, and the second regarding agricultural practices under the different scenarios. All figures are averages over the 20 year period.

The variables in the first part of the tables are:

N-level	Optimal application of nitrogen in kg/ha (sum of effective manure N and mineral fertilizer N). This is reported in both absolute terms and relative to the Base scenario.
N-leach	Amount of nitrogen leached, kg/ha, in absolute terms and relative to Base. The maximum amount leached of all fields and years is also shown along with the estimated standard deviation.
N-air	Loss of N in ammonia to air, kg/ha. This loss occurs during spreading of manure. Estimated standard deviations are also reported.
P-leach	Amount of phosphorous lost due to erosion, kg/ha.
Soil loss	Loss of soil due to erosion, kg/ha.
Farmer cost	Costs in terms of differences in net economic result for the farmers between the given scenario and the Base scenario, i.e. negative numbers are gains to the farmers under the given scenario. These private cost are expressed in NOK per ha, and can be termed private abatement costs.
Social cost	Social abatement costs. Costs to the society from implementing the given scenario compared to Base. This is expressed in per ha and per kg reduced N-leachage terms.

For N losses "max" and $\hat{\sigma}$ are calculated on the basis of the values obtained for each model farm field and year weighed according to the representativity of the model farm fields in the landscapes. For soil loss "max" is calculated on the basis of average losses per year.

The variables in the second part of the tables are:

S-wheat	Summer wheat
W-wheat	Winter wheat
Other cr.	Other crops (pea and grass seed)
AP	Autumn ploughing
SP	Spring ploughing

Percentages are percentages of the total area in the different landscapes. As can be seen, AP and SP do not add up to unity. The remaining areas are meadows.

The name and main characteristics of each scenario are given in infobox B1. More details about the scenarios and the chosen structure are given in chapters 5 and 7 of the main text.

Infobox B1: Scenario descriptions

S-1992	1992 political and economic conditions – short run adaption
Base	1992 political and economic conditions except environmental taxes/ subsidies
Tax50	50 % tax on N in mineral fertilizers
Tax100	100 % tax on N in mineral fertilizers
Tax200	200 % tax on N in mineral fertilizers
Tax100M	100 % tax on N in mineral fertilizers, including a market for manure
Price33	33 % price reduction on grains
Catch50	50 % arable land requirement on catch crops/grass cover
Catch100	100 % arable land requirement on catch crops/grass cover
Catch50Tax100	Catch50 and Tax100 combined
Catch100Tax100	Catch100 and Tax100 combined
Storage12	12 months manure storage requirement
Catch50Storage12	Catch50 and Storage12 combined
Soil-sub	Subsidy to abandon fall tillage
Soil-50	Mandatory requirement: < 50 % of the acreage with fall tillage
Soil-subTax100	Soil-sub and Tax100 combined
Soil-subStorage12	Soil-sub and Storage12 combined
Soil-subTax100Storage12	Soil-sub, Tax100 and Storage12 combined
FeedingB	Changed feeding practices reducing excretion of N and P in manure
Early-Plow	Plowing shortly after grain harvest

In addition to this a split fertilization scenario was run for a selection of model farms (see chapter 7).

Table B1 : S-1992 (1992 political and economical conditions - short run adaption)

	N-level kg/ha	N-leach [max] $(\hat{\sigma})$ kg/ha	N-air $(\hat{\sigma})$ kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	123.8	38.9 [249] (25.7)	7.0 (12.4)	2.15	494 [1562]			
Δ Base	-3.6	-1.4	0.5	-2.82	-686	-24	149	104
Grain	111.8	39.4 [249] (28.0)						
Δ Base	-2.3	-1.4						
Meadow	179.5	39.7 [106] (18.3)						
Δ Base	-9.5	-1.7						
Other cr	89.6	17.5 [44] (6.7)						
Δ Base	-0.1	-1.8						
Auli-B								
All crops	121.0	40.3 [249] (27.0)	7.7 (14.8)	2.68	611 [1772]			
Δ Base	-3.2	-1.0	-0.1	-1.96	-447	-190	127	132
Grain	113.2	41.2 [249] (30.0)						
Δ Base	-2.4	-1.0						
Meadow	183.4	38.1 [106] (15.7)						
Δ Base	-8.8	-0.7						
Other cr	53.3	20.7 [44] (8.1)						
Δ Base	-0.1	-1.7						
Mørdre								
All crops	116.3	28.5 [95] (15.1)	1.1 (2.3)	0.55	276 [787]			
Δ Base	-2.9	-1.0	-0.8	-0.01	-4	-380	34	35
Grain	113.5	28.6 [86] (16.0)						
Δ Base	-2.5	-0.9						
Meadow	173.6	26.2 [95] (9.8)						
Δ Base	-10.6	-1.7						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3600 kg/ha	23% 3660 kg/ha	21% 4060 kg/ha	5% 4100 kg/ha	18% 6110 kg/ha	3%	29%	50%
Auli-B	30% 3570 kg/ha	24% 3780 kg/ha	22% 4080 kg/ha	8% 4270 kg/ha	13% 6240 kg/ha	3%	43%	43%
Mørdre	34% 3900 kg/ha	28% 3910 kg/ha	19% 4460 kg/ha	14% 4230 kg/ha	5% 6630 kg/ha	0%	41%	54%

Table B2 : Base (1992 political and economic conditions except environmental taxes/subsidies)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	127.3	40.4 [249] (26.1)	6.5 (9.3)	4.97	1180 [3282]			
Δ Base	00.0	0.0	0.0	0.00	0	0	0	0
Grain	114.1	40.8 [249] (28.3)						
Δ Base	00.0	0.0						
Meadow	189.0	41.4 [109] (19.2)						
Δ Base	00.0	0.0						
Other cr	89.7	19.3 [47] (7.4)						
Δ Base	00.0	0.0						
Auli-B								
All crops	124.2	41.2 [249] (27.2)	7.8 (10.0)	4.64	1058 [3658]			
Δ Base	00.0	0.0	0.0	0.00	0	0	0	0
Grain	115.5	42.2 [249] (30.1)						
Δ Base	00.0	0.0						
Meadow	192.1	38.8 [109] (16.2)						
Δ Base	00.0	0.0						
Other cr	53.4	22.4 [47] (8.9)						
Δ Base	00.0	0.0						
Mørdre								
All crops	119.2	29.4 [100] (15.7)	1.9 (2.8)	0.56	281 [853]			
Δ Base	00.0	0.0	0.0	0.00	0	0	0	0
Grain	116.0	29.5 [89] (16.6)						
Δ Base	00.0	0.0						
Meadow	184.1	27.9 [100] (10.3)						
Δ Base	00.0	0.0						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	**Oats**	**S-wheat**	**W-wheat**	**Meadow**	**Other cr.**	**AP**	**SP**
Auli-A	30%	23%	21%	5%	18%	3%	79%	1%
	3680 kg/ha	3760 kg/ha	4170 kg/ha	4110 kg/ha	6230 kg/ha			
Auli-B	30%	24%	22%	8%	13%	3%	83%	2%
	3630 kg/ha	3870 kg/ha	4170 kg/ha	4280 kg/ha	6390 kg/ha			
Mørdre	34%	28%	19%	13%	5%	0%	48%	47%
	3950 kg/ha	3900 kg/ha	4460 kg/ha	4250 kg/ha	6690 kg/ha			

Table B3 : Tax50 (50 % tax on N in mineral fertilizers)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	119.0	37.4 [249] (25.6)	5.7 (9.1)	4.92	1175 [3238]			
Δ Base	-8.3	-3.0	-0.8	-0.05	-5	310	28	9
Grain	108.5	38.2 [249] (28.1)						
Δ Base	-5.6	-2.5						
Meadow	167.9	36.2 [96] (17.2)						
Δ Base	-21.1	-5.2						
Other cr	89.4	18.7 [45] (7.1)						
Δ Base	-0.4	-0.7						
Auli-B								
All crops	116.5	38.5 [249] (26.8)	5.8 (9.4)	4.51	1042 [3514]			
Δ Base	-7.6	-2.7	-2.0	-0.13	-17	270	24	9
Grain	109.7	39.8 [249] (30.0)						
Δ Base	-5.9	-2.4						
Meadow	172.3	33.5 [96] (14.3)						
Δ Base	-19.9	-5.3						
Other cr	53.2	21.6 [45] (8.5)						
Δ Base	-0.2	-0.8						
Mørdre								
All crops	112.2	27.0 [89] (14.4)	1.1 (2.3)	0.56	279 [840]			
Δ Base	-7.0	-2.4	-0.8	0.00	-1	330	29	12
Grain	109.9	27.2 [83] (15.2)						
Δ Base	-6.2	-2.4						
Meadow	161.3	24.3 [89] (9.3)						
Δ Base	-22.8	-3.5						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	**Oats**	**S-wheat**	**W-wheat**	**Meadow**	**Other cr.**	**AP**	**SP**
Auli-A	30%	23%	21%	5%	18%	3%	79%	1%
	3660 kg/ha	3740 kg/ha	4140 kg/ha	4080 kg/ha	6090 kg/ha			
Auli-B	30%	24%	22%	8%	13%	3%	83%	2%
	3630 kg/ha	3830 kg/ha	4160 kg/ha	4250 kg/ha	6270 kg/ha			
Mørdre	34%	28%	20%	13%	5%	0%	48%	47%
	3900 kg/ha	3900 kg/ha	4450 kg/ha	4200 kg/ha	6550 kg/ha			

Table B4 : Tax100 (100 % tax on N in mineral fertilizers)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	111.1	34.5 [249] (25.2)	4.0 (7.7)	4.88	1171 [3218]			
Δ Base	-16.3	-5.9	-4.5	-0.09	-9	570	77	13
Grain	103.5	36.0 [249] (27.8)						
Δ Base	-10.6	-4.8						
Meadow	146.3	30.3 [82] (15.5)						
Δ Base	-42.7	-11.1						
Other cr	89.0	18.2 [43] (6.9)						
Δ Base	-0.7	-1.2						
Aull-B								
All crops	109.3	35.9 [249] (26.6)	4.9 (8.7)	4.59	1055 [3618]			
Δ Base	-14.9	-5.3	-2.9	-0.05	-3	510	64	12
Grain	104.2	37.7 [249] (29.9)						
Δ Base	-11.4	-4.5						
Meadow	152.2	28.1 [82] (12.6)						
Δ Base	-39.9	-10.7						
Other cr	53.0	21.0 [43] (8.2)						
Δ Base	-0.4	-1.4						
Mørdre								
All crops	105.8	25.0 [83] (13.4)	1.1 (2.3)	0.56	281 [850]			
Δ Base	-13.4	-4.4	-0.8	0.00	0	610	51	12
Grain	104.2	25.2 [83] (14.1)						
Δ Base	-11.8	-4.3						
Meadow	139.6	21.6 [81] (8.6)						
Δ Base	-44.6	-6.3						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	**Oats**	**S-wheat**	**W-wheat**	**Meadow**	**Other cr.**	**AP**	**SP**
Aull-A	30% 3640 kg/ha	23% 3710 kg/ha	22% 4100 kg/ha	5% 4090 kg/ha	19% 6030 kg/ha	3%	79%	1%
Aull-B	30% 3600 kg/ha	24% 3840 kg/ha	22% 4110 kg/ha	8% 4220 kg/ha	14% 6210 kg/ha	3%	83%	2%
Mørdre	35% 3850 kg/ha	28% 3920 kg/ha	20% 4390 kg/ha	13% 4200 kg/ha	5% 6340 kg/ha	0%	48%	48%

Table B5 : Tax200 (200 % tax on N in mineral fertilizers)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	95.3	29.6 [249] (24.5)	3.9 (7.5)	4.83	1168 [3225]			
Δ Base	-32.1	-10.8	-2.6	-0.14	-13	1040	237	22
Grain	93.3	31.3 [249] (27.5)						
Δ Base	-20.8	-9.5						
Meadow	104.2	24.1 [64] (13.1)						
Δ Base	-84.8	-17.3						
Other cr	88.3	17.0 [41] (6.4)						
Δ Base	-1.4	-2.3						
Aull-B								
All crops	95.7	29.9 [249] (25.4)	5.0 (8.6)	4.15	986 [3314]			
Δ Base	-28.5	-11.3	-2.8	-0.49	-72	930	227	20
Grain	94.3	31.5 [249] (28.8)						
Δ Base	-21.3	-10.7						
Meadow	112.7	22.1 [64] (10.5)						
Δ Base	-79.4	-16.7						
Other cr	52.6	19.7 [41] (7.7)						
Δ Base	-0.8	-2.7						
Mørdre								
All crops	93.3	20.4 [69] (10.8)	1.0 (1.7)	0.55	273 [834]			
Δ Base	-25.9	-9.1	-0.9	-0.01	-8	1130	180	20
Grain	93.0	20.5 [69] (11.4)						
Δ Base	-23.0	-9.0						
Meadow	98.4	17.0 [69] (7.4)						
Δ Base	-85.8	-10.9						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Aull-A	30% 3540 kg/ha	22% 3650 kg/ha	22% 4050 kg/ha	4% 4020 kg/ha	19% 5570 kg/ha	3%	78%	1%
Aull-B	30% 3570 kg/ha	24% 3750 kg/ha	21% 4040 kg/ha	8% 4100 kg/ha	14% 5770 kg/ha	3%	81%	4%
Mørdre	35% 3790 kg/ha	27% 3850 kg/ha	20% 4330 kg/ha	13% 4130 kg/ha	5% 6010 kg/ha	0%	37%	59%

Table B6 : Tax100M (100 % tax on N in mineral fertilizers - including a manure market)

	N-level kg/ha	N-leach [max] $(\hat{\sigma})$ kg/ha	N-air $(\hat{\sigma})$ kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	110.4	33.1 [151] (18.6)	3.2 (6.2)	4.84	1171 [3218]			
Δ Base	-16.9	-7.3	-3.3	-0.13	-9	570	73	10
Grain	102.6	34.2 [151] (19.7)						
Δ Base	-11.5	-6.6						
Meadow	146.3	30.3 [82] (15.5)						
Δ Base	-42.7	-11.1						
Other cr	89.0	18.2 [43] (6.9)						
Δ Base	-0.7	-1.2						
Auli-B								
All crops	108.5	34.4 [151] (20.0)	4.0 (7.0)	4.51	1055 [3618]			
Δ Base	-15.7	-6.9	-3.8	-0.13	-3	520	63	9
Grain	103.3	35.8 [151] (21.9)						
Δ Base	-12.3	-6.4						
Meadow	152.2	28.1 [82] (12.6)						
Δ Base	-39.9	-10.7						
Other cr	53.0	21.0 [43] (8.2)						
Δ Base	-0.4	-1.4						
Mørdre								
All crops	105.8	25.0 [83] (13.4)	1.1 (2.3)	0.56	281 [850]			
Δ Base	-13.4	-4.4	-0.8	0.00	0	610	51	12
Grain	104.2	25.2 [83] (14.1)						
Δ Base	-11.8	-4.3						
Meadow	139.6	21.6 [81] (8.6)						
Δ Base	-44.6	-6.3						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3640 kg/ha	23% 3710 kg/ha	22% 4100 kg/ha	5% 4090 kg/ha	19% 6030 kg/ha	3%	79%	1%
Auli-B	30% 3600 kg/ha	24% 3850 kg/ha	22% 4110 kg/ha	8% 4220 kg/ha	14% 6210 kg/ha	3%	83%	2%
Mørdre	35% 3850 kg/ha	28% 3920 kg/ha	20% 4390 kg/ha	13% 4200 kg/ha	5% 6340 kg/ha	0%	48%	48%

Table B7 : Price33 (33 % price reduction on grains)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	118.9	37.7 [250] (25.6)	7.6 (12.4)	4.84	1148 [3083]			
Δ Base	-8.4	-2.7	1.1	-0.13	-32	3030	22	8
Grain	108.3	38.4 [250] (28.2)						
Δ Base	-5.8	-2.3						
Meadow	168.3	37.1 [98] (17.3)						
Δ Base	-20.8	-4.3						
Other cr	89.4	18.7 [45] (7.1)						
Δ Base	-0.4	-0.6						
Auli-B								
All crops	116.2	38.8 [250] (26.6)	9.5 (14.7)	4.53	1043 [3518]			
Δ Base	-8.0	-2.4	1.7	-0.11	-16	3090	20	8
Grain	109.2	39.9 [250] (29.7)						
Δ Base	-6.4	-2.3						
Meadow	172.6	35.4 [98] (14.7)						
Δ Base	-19.5	-3.4						
Other cr	53.2	21.6 [45] (8.5)						
Δ Base	-0.2	-0.8						
Mørdre								
All crops	111.9	26.8 [90] (14.2)	1.9 (2.8)	0.56	280 [851]			
Δ Base	-7.3	-2.6	0.0	0.00	0	3100	31	12
Grain	109.5	26.9 [83] (15.1)						
Δ Base	-6.5	-2.6						
Meadow	162.1	24.4 [90] (9.4)						
Δ Base	-22.1	-3.4						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	29%	25%	21%	5%	18%	3%	79%	1%
	3650 kg/ha	3750 kg/ha	4120 kg/ha	4220 kg/ha	6040 kg/ha			
Auli-B	29%	27%	20%	9%	13%	3%	83%	2%
	3630 kg/ha	3850 kg/ha	4140 kg/ha	4280 kg/ha	6170 kg/ha			
Mørdre	33%	31%	20%	12%	5%	0%	48%	48%
	3900 kg/ha	3910 kg/ha	4450 kg/ha	4280 kg/ha	6550 kg/ha			

Table B8 : Catch50 (50 % arable land requirement on catch crops/grass cover)

	N-level kg/ha	N-leach [max] $(\hat{\sigma})$ kg/ha	N-air $(\hat{\sigma})$ kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	128.6	29.6 [249] (22.6)	6.5 (9.3)	2.81	660 [2112]			
Δ Base	1.3	-10.8	0.0	-2.16	-520	199	199	18
Grain	115.8	27.3 [249] (23.2)						
Δ Base	-1.7	-13.4						
Meadow	189.0	41.3 [109] (19.1)						
Δ Base	0.0	-0.1						
Other cr	89.7	13.9 [35] (5.6)						
Δ Base	-0.0	-5.4						
Auli-B								
All crops	125.5	29.3 [249] (24.5)	7.8 (10.0)	2.30	505 [1490]			
Δ Base	1.4	-12.0	0.0	-2.34	-553	217	217	18
Grain	117.2	28.2 [249] (26.6)						
Δ Base	1.7	-14.0						
Meadow	192.1	38.8 [109] (16.2)						
Δ Base	0.0	0.0						
Other cr	53.4	15.0 [35] (6.5)						
Δ Base	0.0	-7.4						
Mørdre								
All crops	121.0	21.5 [100] (15.0)	1.9 (2.8)	0.56	283 [843]			
Δ Base	1.8	-7.9	0.0	0.00	2	294	294	37
Grain	117.9	21.2 [83] (15.7)						
Δ Base	1.9	-8.3						
Meadow	184.1	27.9 [100] (10.3)						
Δ Base	0.0	0.0						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	**Oats**	**S-wheat**	**W-wheat**	**Meadow**	**Other cr.**	**AP**	**SP**
Auli-A	30% 3610 kg/ha	23% 3660 kg/ha	21% 4140 kg/ha	5% 4110 kg/ha	18% 6230 kg/ha	3%	79%	1%
Auli-B	30% 3560 kg/ha	24% 3760 kg/ha	22% 4140 kg/ha	8% 4280 kg/ha	13% 6390 kg/ha	3%	84%	2%
Mørdre	34% 3870 kg/ha	28% 3780 kg/ha	19% 4360 kg/ha	13% 4250 kg/ha	5% 6690 kg/ha	0%	67%	29%

Table B9: Catch100 (100 % arable land requirement on catch crops/grass cover)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	130.6	20.0 [175] (18.6)	6.2 (9.2)	2.69	652 [2091]			
Δ Base	3.3	- 20.3	-0.3	-2.28	-529	495	495	24
Grain	118.3	15.8 [175] (16.0)						
Δ Base	4.2	- 25.0						
Meadow	189.0	39.1 [109] (18.3)						
Δ Base	0.0	-2.3						
Other cr	89.7	12.5 [35] (5.3)						
Δ Base	0.0	-6.8						
Auli-B								
All crops	127.4	17.8 [175] (18.2)	6.1 (9.6)	2.09	486 [1494]			
Δ Base	3.3	- 23.4	-1.7	-2.55	-572	533	533	23
Grain	119.5	14.8 [175] (17.1)						
Δ Base	3.9	- 27.5						
Meadow	192.1	37.4 [109] (15.8)						
Δ Base	0.0	-1.4						
Other cr	53.4	14.3 [35] (6.3)						
Δ Base	0.0	-8.1						
Mørdre								
All crops	123.2	10.3 [98] (8.7)	1.4 (2.4)	0.60	302 [913]			
Δ Base	4.0	- 19.1	-0.5	0.04	21	686	686	36
Grain	120.3	9.5 [38] (7.5)						
Δ Base	4.2	- 20.0						
Meadow	184.1	26.8 [98] (10.0)						
Δ Base	0.0	-1.1						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	**Oats**	**S-wheat**	**W-wheat**	**Meadow**	**Other cr.**	**AP**	**SP**
Auli-A	30% 3480 kg/ha	24% 3590 kg/ha	24% 4020 kg/ha	1% 4400 kg/ha	18% 6230 kg/ha	3%	80%	0%
Auli-B	31% 3510 kg/ha	25% 3670 kg/ha	26% 4000 kg/ha	2% 4400 kg/ha	13% 6390 kg/ha	3%	85%	0%
Mørdre	35% 3680 kg/ha	29% 3740 kg/ha	31% 4210 kg/ha	0% 0 kg/ha	5% 6690 kg/ha	0%	95%	0%

Table B10: Catch50Tax100 (Catch50 and Tax100 combined)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	112.1	24.4 [248] (20.9)	4.2 (7.9)	2.73	662 [2115]			
Δ Base	-15.2	-15.9	-2.3	-2.24	-518	780	282	18
Grain	105.2	23.3 [248] (22.5)						
Δ Base	-8.9	-17.4						
Meadow	145.0	30.5 [81] (15.4)						
Δ Base	-44.0	-10.9						
Other cr	89.0	13.4 [33] (5.5)						
Δ Base	-0.7	-6.0						
Auli-B								
All crops	110.6	24.7 [248] (22.7)	5.0 (8.9)	2.22	503 [1428]			
Δ Base	-13.6	-16.5	-2.8	-2.42	-555	740	281	17
Grain	105.9	24.4 [248] (25.4)						
Δ Base	-9.6	-17.8						
Meadow	151.1	28.2 [81] (12.6)						
Δ Base	-41.0	-10.6						
Other cr	53.0	14.6 [33] (6.4)						
Δ Base	-0.4	-7.8						
Mørdre								
All crops	107.2	17.7 [80] (12.7)	1.1 (2.3)	0.57	287 [881]			
Δ Base	-11.9	-1.8	-0.8	0.01	6	900	333	28
Grain	105.9	17.5 [79] (13.4)						
Δ Base	-10.1	-12.0						
Meadow	134.9	21.4 [80] (8.4)						
Δ Base	-49.3	-6.5						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3570 kg/ha	23% 3600 kg/ha	22% 4070 kg/ha	5% 4090 kg/ha	18% 6000 kg/ha	3%	79%	1%
Auli-B	30% 3530 kg/ha	24% 3730 kg/ha	22% 4080 kg/ha	8% 4220 kg/ha	13% 6180 kg/ha	3%	84%	2%
Mørdre	35% 3780 kg/ha	28% 3800 kg/ha	20% 4290 kg/ha	13% 4200 kg/ha	5% 6280 kg/ha	0%	67%	28%

Table B11: Catch100Tax100 (Catch100 and Tax100 combined)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	113.7	16.1 [175] (15.8)	4.1 (7.6)	2.70	659 [2116]			
Δ Base	-13.7	-24.3	-2.4	-2.27	-521	1080	569	23
Grain	107.1	13.3 [175] (15.2)						
Δ Base	-7.0	- 27.4						
Meadow	145.0	28.5 [81] (14.2)						
Δ Base	-44.0	-12.9						
Other cr	89.0	12.3 [31] (5.2)						
Δ Base	-0.7	-7.1						
Auli-B								
All crops	112.2	14.4 [175] (16.2)	4.9 (8.6)	2.13	499 [1554]			
Δ Base	-12.0	-26.8	-2.9	-2.51	-560	1070	596	22
Grain	107.9	12.4 [175] (16.6)						
Δ Base	-7.7	-29.8						
Meadow	151.1	27.0 [81] (12.0)						
Δ Base	-41.0	-11.8						
Other cr	53.0	14.1 [31] (6.2)						
Δ Base	-0.4	-8.3						
Mørdre								
All crops	109.3	8.0 [78] (6.8)	1.1 (2.3)	0.60	302 [913]			
Δ Base	-9.9	-21.5	-0.8	0.04	21	1320	741	35
Grain	108.0	7.4 [32] (5.9)						
Δ Base	-8.0	-22.2						
Meadow	134.9	20.3 [78] (8.0)						
Δ Base	-49.3	-7.6						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3450 kg/ha	24% 3550 kg/ha	24% 3960 kg/ha	1% 4330 kg/ha	18% 6000 kg/ha	3%	80%	0%
Auli-B	31% 3480 kg/ha	25% 3610 kg/ha	26% 3940 kg/ha	2% 4330 kg/ha	13% 6180 kg/ha	3%	85%	0%
Mørdre	35% 3610 kg/ha	30% 3660 kg/ha	31% 4160 kg/ha	0% 0 kg/ha	5% 6280 kg/ha	0%	95%	0%

Table B12: Storage12 (12 month manure storage requirement)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	128.3	38.1 [249] (24.8)	6.6 (12.8)	4.82	1175 [3237]			
Δ Base	0.9	-2.3	0.1	-0.15	-5	82	82	35
Grain	115.3	39.4 [249] (27.3)						
Δ Base	1.2	-1.3						
Meadow	189.0	34.7 [95] (16.1)						
Δ Base	0.0	-6.7						
Other cr	89.7	19.3 [47] (7.4)						
Δ Base	0.0	0.0						
Aull-B								
All crops	124.9	37.5 [249] (25.2)	7.6 (14.7)	4.10	989 [3309]			
Δ Base	0.7	-3.8	-0.2	-0.54	-70	88	88	23
Grain	116.4	38.9 [249] (28.1)						
Δ Base	0.9	-3.3						
Meadow	192.1	31.6 [95] (13.1)						
Δ Base	0.0	-7.2						
Other cr	53.4	22.4 [47] (8.9)						
Δ Base	0.0	0.0						
Mørdre								
All crops	119.4	27.3 [87] (14.3)	1.3 (3.6)	0.55	275 [829]			
Δ Base	0.2	-2.1	-0.6	-0.01	-6	-1	-1	.
Grain	116.2	27.5 [83] (15.1)						
Δ Base	0.2	-2.0						
Meadow	184.1	23.6 [87] (8.8)						
Δ Base	0.0	-4.3						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Aull-A	30% 3670 kg/ha	23% 3750 kg/ha	21% 4170 kg/ha	5% 4110 kg/ha	18% 6290 kg/ha	3%	79%	1%
Aull-B	30% 3630 kg/ha	24% 3870 kg/ha	22% 4180 kg/ha	8% 4280 kg/ha	13% 6420 kg/ha	3%	82%	4%
Mørdre	34% 3970 kg/ha	28% 3910 kg/ha	19% 4480 kg/ha	13% 4250 kg/ha	5% 6870 kg/ha	0%	37%	59%

Table B13: Catch50Storage12 (Catch50 and Storage12 combined)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	129.6	27.7 [249] (21.2)	6.6 (12.8)	2.69	662 [2112]			
Δ Base	2.3	-12.6	0.1	-2.28	-518	279	279	22
Grain	116.9	26.5 [249] (22.7)						
Δ Base	2.9	-14.2						
Meadow	189.0	34.7 [95] (16.0)						
Δ Base	0.0	-6.8						
Other cr	89.7	13.9 [35] (5.6)						
Δ Base	0.0	-5.4						
Aull-B								
All crops	126.3	26.5 [249] (22.2)	7.6 (14.7)	1.97	485 [1386]			
Δ Base	2.1	-14.7	-0.2	-2.67	-574	304	304	21
Grain	118.1	26.0 [249] (24.7)						
Δ Base	2.5	-16.2						
Meadow	192.1	31.6 [95] (13.1)						
Δ Base	0.0	-7.2						
Other cr	53.4	15.0 [35] (6.5)						
Δ Base	0.0	-7.4						
Mørdre								
All crops	121.2	19.9 [87] (13.5)	1.3 (3.6)	0.50	248 [477]			
Δ Base	2.0	-9.5	-0.6	-0.06	-33	301	301	32
Grain	118.1	19.7 [80] (14.2)						
Δ Base	2.1	-9.8						
Meadow	184.1	23.6 [87] (8.8)						
Δ Base	0.0	-4.3						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Aull-A	30%	23%	21%	5%	18%	3%	79%	1%
	3600 kg/ha	3660 kg/ha	4140 kg/ha	4110 kg/ha	6290 kg/ha			
Aull-B	30%	24%	22%	8%	13%	3%	82%	3%
	3560 kg/ha	3760 kg/ha	4150 kg/ha	4280 kg/ha	6420 kg/ha			
Mørdre	34%	28%	19%	13%	5%	0%	58%	37%
	3880 kg/ha	3780 kg/ha	4370 kg/ha	4250 kg/ha	6870 kg/ha			

Table B14: Soil-sub (Subsidy to abandon fall tillage)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	127.3	40.0 [249] (26.0)	6.5 (9.3)	2.25	505 [1576]			
Δ Base	0.0	-0.4	0.0	-2.72	-676	-370	138	370
Grain	114.1	40.3 [249] (28.1)						
Δ Base	0.0	-0.4						
Meadow	189.0	41.4 [109] (19.2)						
Δ Base	0.0	0.0						
Other cr	89.7	17.8 [45] (6.8)						
Δ Base	0.0	-1.5						
Aull-B								
All crops	124.2	41.0 [249] (27.1)	7.8 (10.0)	2.93	635 [1916]			
Δ Base	0.0	-0.2	0.0	-1.71	-423	-310	117	710
Grain	115.5	42.1 [249] (30.0)						
Δ Base	0.0	-0.1						
Meadow	192.1	38.8 [109] (16.2)						
Δ Base	0.0	0.0						
Other cr	53.4	21.0 [45] (8.2)						
Δ Base	0.0	-1.4						
Mørdre								
All crops	119.2	29.5 [100] (15.7)	1.9 (2.8)	0.55	277 [782]			
Δ Base	0.0	0.1	0.0	-0.01	-4	-510	.	.
Grain	116.0	29.6 [89] (16.6)						
Δ Base	0.0	0.1						
Meadow	184.1	27.9 [100] (10.3)						
Δ Base	0.0	0.0						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	**Oats**	**S-wheat**	**W-wheat**	**Meadow**	**Other cr.**	**AP**	**SP**
Aull-A	30%	23%	21%	5%	18%	3%	29%	50%
	3610 kg/ha	3670 kg/ha	4070 kg/ha	4110 kg/ha	6230 kg/ha			
Aull-B	30%	24%	22%	8%	13%	3%	43%	43%
	3580 kg/ha	3790 kg/ha	4090 kg/ha	4280 kg/ha	6390 kg/ha			
Mørdre	34%	28%	19%	13%	5%	0%	41%	54%
	3940 kg/ha	3880 kg/ha	4450 kg/ha	4250 kg/ha	6690 kg/ha			

Table B15: Soil-50 (Mandatory requirement: < 50 % of the acreage with fall tillage)

	N-level kg/ha	N-leach [max] $(\hat{\sigma})$ kg/ha	N-air $(\hat{\sigma})$ kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	127.3	40.2 [249] (26.2)	6.5 (9.3)	3.18	736 [1757]			
Δ Base	0.0	-0.2	0.0	-1.79	-444	82	82	463
Grain	114.1	40.6 [249] (28.4)						
Δ Base	0.0	-0.2						
Meadow	189.0	41.4 [109] (19.2)						
Δ Base	0.0	0.0						
Other cr	89.7	18.7 [50] (7.1)						
Δ Base	0.0	-0.6						
Auli-B								
All crops	124.2	41.4 [249] (27.4)	7.8 (10.0)	3.08	671 [2090]			
Δ Base	0.0	0.1	0.0	-1.56	-387	90	90	
Grain	115.5	42.4 [249] (30.4)						
Δ Base	0.0	0.2						
Meadow	192.1	38.8 [109] (16.2)						
Δ Base	0.0	0.0						
Other cr	53.4	21.7 [50] (8.4)						
Δ Base	0.0	-0.7						
Mørdre								
All crops	119.2	29.0 [100] (15.3)	1.9 (2.8)	0.55	275 [822]			
Δ Base	0.0	-0.4	0.0	-0.01	-6	5	5	12
Grain	116.0	29.0 [83] (16.2)						
Δ Base	0.0	-0.5						
Meadow	184.1	27.9 [100] (10.3)						
Δ Base	0.0	0.0						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30%	23%	21%	5%	18%	3%	44%	36%
	3630 kg/ha	3700 kg/ha	4110 kg/ha	4110 kg/ha	6230 kg/ha			
Auli-B	30%	24%	22%	8%	13%	3%	46%	39%
	3590 kg/ha	3810 kg/ha	4110 kg/ha	4280 kg/ha	6390 kg/ha			
Mørdre	34%	28%	19%	13%	5%	0%	32%	64%
	3950 kg/ha	3900 kg/ha	4460 kg/ha	4250 kg/ha	6690 kg/ha			

Table B16: Soil-subTax100 (Soil-sub and Tax100 combined)

	N-level kg/ha	N-leach [max] $(\hat{\sigma})$ kg/ha	N-air $(\hat{\sigma})$ kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	111.0	34.3 [249] (25.0)	4.0 (7.7)	2.18	497 [1576]			
Δ Base	-16.3	-6.1	-2.5	-2.79	-683	190	218	36
Grain	103.4	35.8 [249] (27.7)						
Δ Base	-10.7	-5.0						
Meadow	146.3	30.2 [82] (15.5)						
Δ Base	-42.7	-11.3						
Other cr	89.0	16.8 [41] (6.5)						
Δ Base	-0.7	-2.5						
Auli-B								
All crops	109.2	35.9 [249] (26.6)	4.9 (8.7)	2.89	632 [1916]			
Δ Base	-14.9	-5.3	-2.9	-1.75	-426	200	182	34
Grain	104.2	37.7 [249] (29.8)						
Δ Base	-11.4	-4.6						
Meadow	152.2	28.0 [82] (12.6)						
Δ Base	-39.9	-10.8						
Other cr	53.0	19.8 [41] (7.7)						
Δ Base	-0.4	-2.6						
Mørdre								
All crops	105.8	25.1 [83] (13.4)	1.1 (2.3)	0.55	277 [782]			
Δ Base	-13.4	-4.3	-0.8	-0.01	-4	90	78	18
Grain	104.2	25.3 [83] (14.2)						
Δ Base	-11.9	-4.2						
Meadow	139.6	21.6 [81] (8.6)						
Δ Base	-44.6	-6.3						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3560 kg/ha	23% 3610 kg/ha	22% 4000 kg/ha	5% 4090 kg/ha	19% 6030 kg/ha	3%	27%	53%
Auli-B	30% 3550 kg/ha	24% 3760 kg/ha	22% 4020 kg/ha	8% 4220 kg/ha	14% 6210 kg/ha	3%	42%	44%
Mørdre	35% 3840 kg/ha	28% 3900 kg/ha	20% 4380 kg/ha	13% 4200 kg/ha	5% 6340 kg/ha	0%	41%	54%

Table B17: Soil-subStorage12 (Soil-sub and Storage12 combined)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max[loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	128.0	37.3 [249] (24.5)	6.6 (12.8)	1.51	357 [1426]			
Δ Base	0.7	-3.1	0.1	-3.46	-824	-390	269	87
Grain	115.0	38.5 [249] (26.9)						
Δ Base	0.9	-2.2						
Meadow	189.0	34.2 [93] (15.7)						
Δ Base	0.0	-7.2						
Other cr	89.7	17.7 [44] (6.8)						
Δ Base	0.0	-1.6						
Auli-B								
All crops	124.6	36.7 [249] (24.9)	7.6 (14.7)	1.57	364 [1007]			
Δ Base	0.4	-4.5	-0.2	-3.07	-695	-390	304	68
Grain	116.1	38.1 [249] (27.8)						
Δ Base	0.5	-4.1						
Meadow	192.1	31.3 [93] (12.9)						
Δ Base	0.0	-7.5						
Other cr	53.4	20.9 [44] (8.2)						
Δ Base	0.0	-1.5						
Mørdre								
All crops	119.5	27.4 [87] (14.3)	1.3 (3.6)	0.54	269 [748]			
Δ Base	0.4	-2.0	-0.6	-0.02	-12	-700	90	44
Grain	116.4	27.6 [83] (15.2)						
Δ Base	0.4	-1.9						
Meadow	184.1	23.5 [87] (8.8)						
Δ Base	0.0	-4.4						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3570 kg/ha	23% 3630 kg/ha	21% 4050 kg/ha	5% 4110 kg/ha	18% 6290 kg/ha	3%	14%	66%
Auli-B	30% 3520 kg/ha	24% 3740 kg/ha	22% 4050 kg/ha	8% 4280 kg/ha	13% 6420 kg/ha	3%	16%	69%
Mørdre	34% 3940 kg/ha	28% 3860 kg/ha	19% 4430 kg/ha	13% 4250 kg/ha	5% 6870 kg/ha	0%	16%	79%

Table B18: Soil-subTax100Storage12 (Soil-sub, Tax100 and Storage12 combined)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	111.8	31.8 [249] (23.9)	5.9 (11.8)	1.50	359 [1426]			
Δ Base	-15.5	-8.5	-0.6	-3.47	-821	170	339	40
Grain	104.4	34.1 [249] (26.7)						
Δ Base	-9.7	-6.7						
Meadow	146.3	24.3 [63] (11.8)						
Δ Base	-42.7	-17.1						
Other cr	89.0	16.8 [41] (6.5)						
Δ Base	-0.7	-2.5						
Aull-B								
All crops	110.0	31.8 [249] (24.5)	7.3 (14.2)	1.58	364 [1007]			
Δ Base	-14.1	-9.4	-0.5	-3.06	-694	100	359	38
Grain	105.1	33.8 [249] (27.6)						
Δ Base	-10.5	-8.4						
Meadow	152.2	21.8 [63] (9.3)						
Δ Base	-39.9	-17.0						
Other cr	53.0	19.8 [41] (7.7)						
Δ Base	-0.4	-2.6						
Mørdre								
All crops	106.1	23.1 [70] (12.1)	1.0 (1.7)	0.55	268 [750]			
Δ Base	-13.1	-6.3	-0.9	-0.01	-13	-110	148	23
Grain	104.5	23.4 [67] (12.8)						
Δ Base	-11.6	-6.1						
Meadow	139.6	17.5 [70] (7.4)						
Δ Base	-44.6	-10.4						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Aull-A	30% 3520 kg/ha	23% 3580 kg/ha	22% 3990 kg/ha	5% 4090 kg/ha	19% 5960 kg/ha	3%	14%	66%
Aull-B	30% 3490 kg/ha	24% 3720 kg/ha	22% 3990 kg/ha	8% 4220 kg/ha	14% 6130 kg/ha	3%	17%	69%
Mørdre	35% 3830 kg/ha	28% 3870 kg/ha	20% 4360 kg/ha	13% 4200 kg/ha	5% 6440 kg/ha	0%	16%	80%

Table B19: Feeding B (Changed feeding practices reducing excretion of N and P in manure)

	N-level kg/ha	N-leach [max] $(\hat{\sigma})$ kg/ha	N-air $(\hat{\sigma})$ kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Auli-A								
All crops	127.0	39.1 [201] (22.4)	5.9 (8.5)	4.90	1175 [3238]			
Δ Base	-0.3	-1.2	-0.6	-0.07	-5	7	7	5
Grain	113.7	39.3 [201] (23.7)						
Δ Base	-0.4	-1.4						
Meadow	189.0	40.9 [108] (18.8)						
Δ Base	0.0	-0.5						
Other cr	89.7	19.3 [47] (7.4)						
Δ Base	0.0	0.0						
Auli-B								
All crops	123.9	39.6 [201] (23.1)	6.8 (8.9)	4.46	1041 [3514]			
Δ Base	-0.3	-1.6	-1.0	-0.18	-18	14	14	9
Grain	115.2	40.4 [201] (25.3)						
Δ Base	-0.3	-1.8						
Meadow	192.1	38.3 [108] (15.9)						
Δ Base	0.0	-0.6						
Other cr	53.4	22.4 [47] (8.9)						
Δ Base	0.0	0.0						
Mørdre								
All crops	119.2	29.1 [99] (15.4)	1.8 (3.1)	0.56	280 [836]			
Δ Base	0.0	-0.3	-0.1	0.00	-1	8	8	26
Grain	116.0	29.2 [86] (16.3)						
Δ Base	0.0	-0.3						
Meadow	184.1	27.6 [99] (10.2)						
Δ Base	0.0	-0.3						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Auli-A	30% 3680 kg/ha	23% 3760 kg/ha	21% 4170 kg/ha	5% 4110 kg/ha	18% 6230 kg/ha	3%	79%	1%
Auli-B	30% 3630 kg/ha	24% 3870 kg/ha	22% 4170 kg/ha	8% 4280 kg/ha	13% 6390 kg/ha	3%	83%	2%
Mørdre	34% 3950 kg/ha	28% 3900 kg/ha	19% 4460 kg/ha	13% 4250 kg/ha	5% 6690 kg/ha	0%	48%	47%

Table B20 : Early-Plough (Ploughing shortly after grain harvest)

	N-level kg/ha	N-leach [max] ($\hat{\sigma}$) kg/ha	N-air ($\hat{\sigma}$) kg/ha	P-leach kg/ha	Soil [max] loss kg/ha	Farmer cost NOK/ha	Social cost NOK/ha	Social cost NOK/kg
Aull-A								
All crops	127.3	44.9 [264] (27.9)	6.5 (9.3)	5.57	1321 [3734]			
Δ Base	0.0	4.6	0.0	0.60	140	.	.	.
Grain	114.1	46.6 [264] (30.4)						
Δ Base	0.0	5.8						
Meadow	189.0	41.3 [109] (19.1)						
Δ Base	0.0	-0.1						
Other cr	89.7	19.2 [51] (7.5)						
Δ Base	0.0	-0.1						
Aull-B								
All crops	124.2	46.6 [264] (29.3)	7.8 (10.0)	5.28	1218 [4199]			
Δ Base	0.0	5.4	0.0	0.64	159	.	.	.
Grain	115.5	48.7 [264] (32.4)						
Δ Base	0.0	6.5						
Meadow	192.1	38.7 [109] (16.2)						
Δ Base	0.0	-0.1						
Other cr	53.4	22.6 [51] (8.9)						
Δ Base	0.0	0.1						
Mørdre								
All crops	119.2	32.3 [95] (17.9)	1.1 (2.3)	0.60	298 [909]			
Δ Base	0.0	0.9	-0.8	0.04	17	-380	34	35
Grain	116.0	32.6 [86] (19.1)						
Δ Base	0.0	3.1						
Meadow	184.1	27.8 [95] (9.8)						
Δ Base	0.0	-0.1						
Other cr								
Δ Base								

	Crops: distribution and yields						Soil preparation system	
	Barley	Oats	S-wheat	W-wheat	Meadow	Other cr.	AP	SP
Aull-A	30% 3600 kg/ha	23% 3660 kg/ha	21% 4060 kg/ha	5% 4100 kg/ha	18% 6110 kg/ha	3%	29%	50%
Aull-B	30% 3570 kg/ha	24% 3780 kg/ha	22% 4080 kg/ha	8% 4270 kg/ha	13% 6240 kg/ha	3%	43%	43%
Mørdre	34% 3900 kg/ha	28% 3910 kg/ha	19% 4460 kg/ha	14% 4230 kg/ha	5% 6630 kg/ha	0%	41%	54%

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