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# A methodology for integrated economic and environmental analysis of pollution from agriculture

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**Abstract**

This paper presents a methodology for analyzing the effect of policies focused at reducing pollution from agriculture. Such a methodology must take into account that agricultural pollution is an effect of a large set of interacting processes, covers many different substances, and may vary substantially due to shifts in natural and economic conditions. Thus, the methodology must both cover the specificities of the different processes/disciplines involved and foster integration across these in a consistent way. The basic challenge is to cover the non-linear fine-scale variations at different levels of land-based production systems. Our methodology is founded on the idea of partitioning. It implies structuring and simplifying existing variation

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in space and time into partitions that are considered homogeneous. These partitions are organized in a hierarchy, and the different processes involved are modeled at the relevant level. We have concluded that analyses with fairly high level of resolution are preferable. This way it is also possible to combine a systems perspective with disciplinary integrity. A modeling structure – ECECMOD (2.0) – based on the developed principles is documented. The paper also shows the ability of this structure to simulate choice of farming practices and emissions that are well in accordance with observations from four Norwegian regions with very different agricultural and natural conditions.


*Keywords:* Pollution from agriculture; Nutrient emissions; Erosion; Pesticide use; Policy analyses; Partitioning; Interdisciplinary analyses

## 1. Introduction

While modern agriculture is very productive, its negative effects on the environment have become increasingly visible. Many of these are the result of practices aimed at reducing per unit costs of production. This has resulted in increased intensity, more specialized production, and increased emissions of substances with negative effects on surrounding eco-systems.

In modern societies research is an important element in the process of shaping production systems. Such inquiries tend to be very specialized. Problems are often reduced to 'single factor issues'. This strategy has yielded tremendous immediate gains. However, in a complex system like the agronomic, there is great chance that 'single factor' manipulations – each being positive for the immediate productivity of the system – result in cumulative negative impacts both across processes and over time. The same observation goes for the study of counter-measures to those impacts. For example, what may be good policies for reducing soil erosion might enhance problems related to pesticide use. What may seem environmentally effective may not be agronomically viable or economically reasonable.

Solutions to the above problems are best found by looking at the whole system – including both the natural systems involved and the economic agents operating them. This shifts focus to the interactions and accumulation of effects – i.e., to the prediction of systems-wide consequences of possible measures to defined problems.

The aim of this paper is to present and discuss a methodology for the analysis of policies aimed at reducing pollution from agriculture. The methodology has been implemented through a structured model cluster, which in its current version – ECECMOD (2.0) – covers losses of nitrates, organically bound N, ammonia, soil, and phosphorous, as well as the amount of pesticides used and soil carbon developments. The quality of the ECECMOD system – i.e., its ability to predict farmers' behavior, and agronomic and environmental states – is also documented.

The first version of ECECMOD is documented in Vatn et al. (1996, 1999). The only part of that model which is fairly intact in the new version is the modeling of N-leaching. The modeling structure is first of all expanded to also include pesticide use. Crop growth and ammonia losses are now modeled on a process basis. A new erosion model is developed which is more robust and better at handling winter conditions. Finally, the economic model is expanded and reformulated due to the new demands.

## 2. Previous research

There are few existing tools that have been developed with the ambition of both spanning the natural science and economic aspects of the above problems and to cover the extent of emissions involved. The focus has primarily been on one type of emissions studied from a natural science perspective – e.g., separate studies of losses of nitrate/nitrogen, phosphorous/soil, or pesticides. Efforts to integrate natural science and economic analyses are, however, increasing. We can group these into three.

First, there are analyses that are dominantly economic, but where rather simple or indirect environmental indicators are attached to the economic analysis. The aim has been to estimate the effect of changed incentive structures on the level of these indicators. Typical examples are studies estimating the effect on N surplus at farm or sector level, e.g., Dietz and Hoogervorst (1991), Vermersch et al. (1993) and Oude Lansink and Peerlings (1997). van Calker et al. (2004) include seven different indicators for ecological sustainability, in addition to net farm income as an indicator for economic sustainability.

Second, there are analyses that are still dominantly economic, but where the estimation of environmental indicators is more sophisticated. This type covers studies that involve the assessment of emissions as a function of agronomic practice, soil conditions etc. In some cases these functions are estimated directly on the basis of field trial data – e.g., Leneman et al. (1993) and Vail et al. (1994). To an increasing degree these functions are based on data from natural science models that are run under different natural and agronomic conditions, making it possible to do studies under a variety of conditions. Examples here are Moxey and White (1994), Bouzaher et al. (1995), Gren et al. (1997), Brady (2003) and Gibbons et al. (2005). Some of these studies also include retention functions for the pollutant in recipient bodies.

Third, there are different types of modeling efforts where economic and natural science models are integrated in structures where interactions between farmers' actions and the dynamics of the natural systems involved are accounted for. NELUP (O'Callaghan, 1995) is one such tool focusing on land use and the dynamics of involved ecosystems. The FASSET model (Jacobsen et al., 1998; Berntsen et al., 2003) covers both nitrogen losses and pesticide use operating at the farm level. The INCA project (Wade et al., 2002) has recently developed another tool concentrating on N emissions in catchments. The sustainable agroecosystem model (SAM) (Belcher and Boehm, 2004), dynamically integrates an economic model that simulates land use decisions, and a soils and crop growth model that simulates crop yield, soil quality and soil function. Finally, we should mention the NitroGenius (Erisman et al., 2002). It is a decision support system focusing on nitrogen pollution, which includes economic evaluation of strategies to reduce pollution. Thus, agronomic practice is chosen by the user, not modeled.

Concerning the modeling strategies, the above tools vary substantially. This includes the natural science modeling, the economic parts and the way integration is done. While they are all great endeavors, we believe it would be beneficial to engage the community more in a discussion about principles for integration of the involved sciences. It is one of the aims of the present paper to do so.

## 3. Defining the system

Our focus is on the most serious pollution problems related to agriculture – namely the losses of various nitrogen compounds, soil and phosphorus, and pesticides to the external environment. To estimate the effect of various measures on these losses, we need a modeling system, which covers the interactions between the major sub-systems involved. Fig. 1 gives an overview of the elements and their main interactions.

First, we have the natural conditions on which the farming system is based (box 1). These include foremost the weather conditions (precipitation, wind, temperatures etc.), soil characteristics, and N-depositions. The other form of external constraint on the farming system is the political and economic conditions (2). These parameters influence farmers' choices of practices (3). These choices will then influence the agronomic system (4), and the various soil processes (5). Finally, we have the losses of the various polluting compounds (6). While farmers' choices influence the agronomic and soil systems, choices concerning management are themselves influenced by the expected and actual developments in these systems (e.g., crop growth and changes in soil N pools). These feedbacks are included and may be of great importance for the effect of certain measures, like growing catch crops.

We have restricted our analysis to the agronomic system (plant production and manure handling) and losses from this system to air and water bodies. We think that the fate of these losses can be modeled separately from the modeling of the agronomic system. The feedback from the environment to the agronomic system is considered to be negligible. There is one exception from this – atmospheric N deposition. This factor is therefore included.

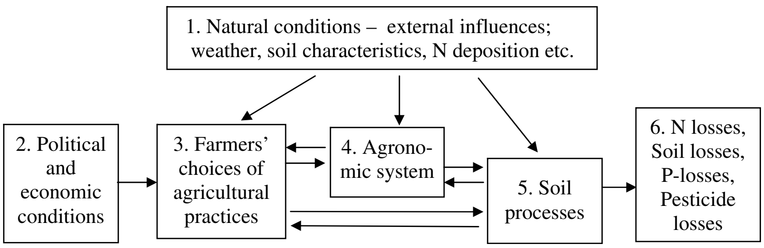


Fig. 1. The system and its main elements.

The chosen demarcation and structure is adapted to do *scenario analyses*. By changing political and economic conditions, it is possible to estimate the effects this will have on the losses under defined natural conditions. The chosen structure also makes it possible to model the effect of e.g., climate change.

## 4. The modeling system – ECECMOD (2.0)

### 4.1. The ECECMOD system

ECECMOD (2.0) is developed to cover the system as described in Fig. 1. According to Fig. 2 it consists of 8 process-based models and a specially designed aggregation routine. The modeling is divided in a set of pre runs and scenario analyses. Some of the models are involved in both the pre runs and the scenario analyses. All models with the suffix NOR are developed especially for ECECMOD to fit the principles we have defined not least concerning integration of processes.

The COUP model (Jansson and Karlberg, 2001) covers hydrology and temperature in the system. ENGNOR (Baadshaug and Lantinga, 2002) and KONOR (Bleken, 2001) are used to estimate plant dry matter production and N absorption. Concerning N turnover and N leaching the SOILN_NO model (a modified version of the Swedish SOILN model (Johnsson et al., 1987)) is used. PVNOR (Fykse and Tørresen, 2001) estimates weed development and pest management, while FIELDVOL (Hutchings, 1998) deals with ammonia losses to air and percolation into the soil. Loss of soil, P and particulate N is predicted by ERONOR (Lundekvam, 2002). Finally, FARMNOR (Rørstad et al., 2002) covers choices of agronomic practices/farmers' behavior. It also serves as an integration platform for the whole system.

When developing ECECMOD, we have actually been faced with several challenges concerning integration – i.e., *integration across scales* (both time and space), *integration across disciplines,* and *integration across processes* characterized by complex interactions and feedbacks. Substantial effort was put into clarifying how the various interactions should be treated to secure consistency across levels, disciplines and processes.

#### 4.1.1. Integration across scales

The choices and processes we study operate at different scales, which are linked in a spatial and temporal hierarchy. Basically, studying interactions between man and nature implies aggregation of non-linear fine-scale variations. Rastetter et al. (1992) describe various methods for doing this. Of these, *partitioning* is chosen as a basis for ECECMOD. It is considered preferable when studying land-based systems (see also Costanza et al., 1995). The basic principle is to lump fine-scale objects into a manageable set of homogeneous groups. The chosen hierarchical structure hence defines the levels at which the various analyses are undertaken, it formulates the basis for interactions across scales, and it forms the basis for the aggregation of the results.

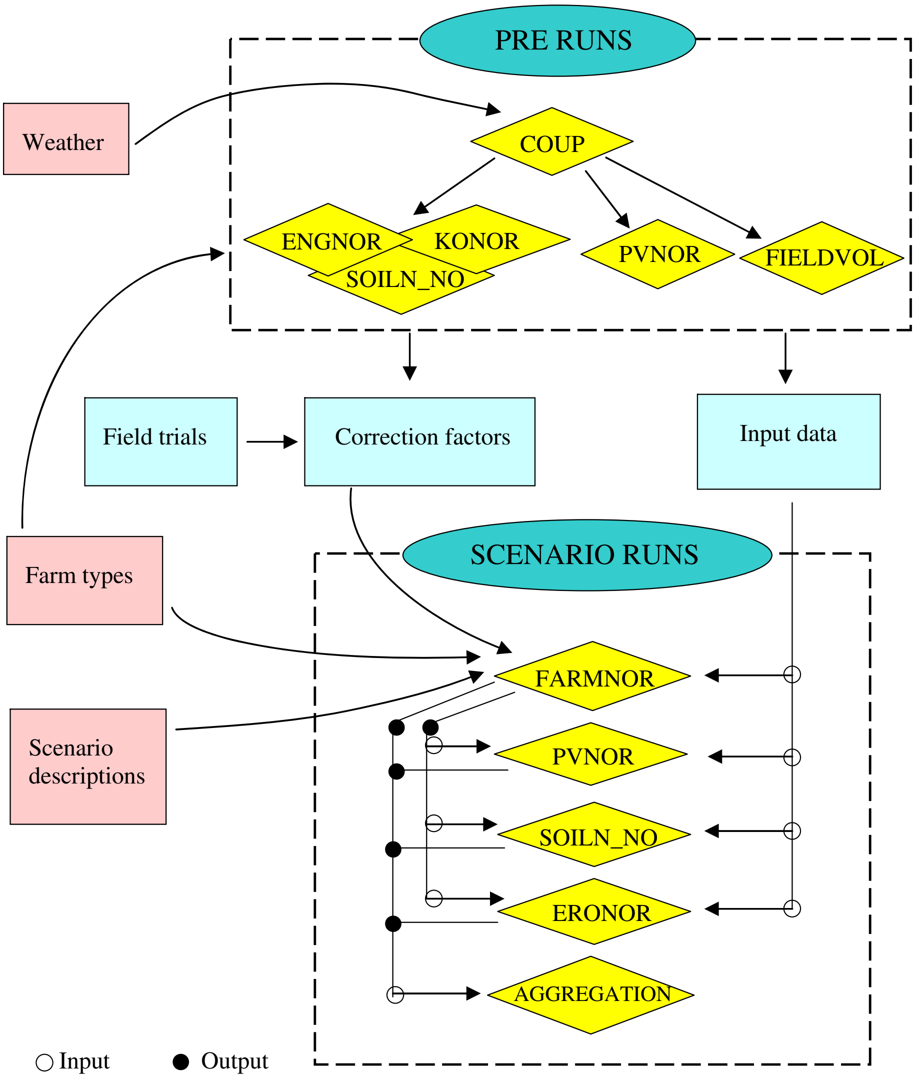


Fig. 2. The ECECMOD (2.0) modeling system.

The list below shows the criteria used for defining each partition and gives information about the level at which the various processes are modeled. A partition is considered homogeneous according to the following criteria:

- *Plot*. Partition criteria: slope (topography), soil properties (texture and organic matter content) and agronomic practice. Modeling: ERONOR (soil erosion, losses of P and particulate N).

- *Farm type field*. Partition criteria: soil properties (texture) and agronomic practice. Modeling: COUP (hydrology), SOILN_NO (nutrient turnover/nitrate leaching), FIELDVOL (ammonia losses), ENGNOR/KONOR (crop growth) and FARMNOR (field specific agronomic practices).
- *Farm type*. Partition criteria: farm size, type of production and animal density. Modeling: FARMNOR (farmers' choices of technology and farm specific agronomic practices).
- *Climatic zone*. Partition criteria: latitude and altitude. Driving data for the biophysical process modeling (COUP): global radiation, temperature, precipitation, relative humidity, wind speed, and day length.
- *Region*. Partition criteria: topographic characteristics and/or political borders. Modeling: Aggregation routine (total losses to water and air).

Considering the *time dimension*, the most important issue is weather variation. While natural processes are modeled on a daily basis, the economic analyses (FARMNOR) operate mainly on a seasonal or yearly basis. In situations where a high temporal resolution is crucial for the natural science modeling – i.e., sowing time (plant N absorption), tillage (erosion) and spreading/incorporation of manure – also the economic modeling operates at a daily level. The chosen length of the simulation period is 22 years, considered sufficient to cover weather variations across years.

*4.1.2. Integration across processes and disciplines*

Given the principle of partitioning, the natural processes involved can be modeled *deterministically*. Thus, soil characteristics, weather and agronomy are assumed to uniquely determine N turnover, crop and weed growth, ammonia losses, developments of diseases etc. Farmers' choices are on the other hand based mainly on *expectations*. Typically, year specific N mineralization and yields are unknown to farmers when decisions are made. These experience-based choices interact with actual weather, and determine actual yields, developments of weeds/diseases, soil losses and leaching. To handle this consistently, we have chosen a two-stage procedure.

The first step is to define expectations for important natural processes like yields, N mineralization, N absorption, weeds development and ammonia losses as an effect of various agronomic practices, soil, climate, etc. These expectations are estimated as the *average levels* for the relevant time periods (e.g., averages based on seasonal or yearly yields over the 22-year period) found by performing pre runs of the relevant natural science models under appropriate conditions (various combinations of soil properties, weather and agronomic practices) – see Fig. 2.[1] Data from the pre runs are used to estimate such expectations are called input data in the figure.

The second step is to estimate the agronomic practices, the 'actual yields', the 'actual' N absorption levels etc. By 'actual' we mean e.g., the yields estimated given

[1] Farmers also form expectations regarding price developments and other policy variables. Since our focus is on the effects of changes in prices, subsidies and taxes – i.e., the policy characterizing each scenario – we take prices as fixed and known for each scenario.

modeled agronomic practice and the actual weather for each year/season. This is necessary to be able to determine the various losses in the scenario analyses. The 'actual' yields are estimated on the basis of data from the mentioned pre runs (the input data) and a set of so-called *correction factors* capturing the effect of deviations from the standardized conditions set in the pre runs – see Fig. 2. On the basis of this information, relevant models are used to estimate the various losses.

The way expected and 'actual' yields are determined can serve as a good illustration of how various processes are integrated in ECECMOD. The crop growth models (ENGNOR/KONOR), together with SOILN_NO, produce estimates on yields for the different crops, soils, a series of fertilizer rates, and a standardized set of agronomic practices (e.g., earliest possible sowing date, fall tillage, no manure) and growth conditions (no weeds, pests or lodging). This is done for each soil type and climatic zone. The effect of practices and growth conditions differing from this standardized set is estimated separately, either on the basis of other pre runs of the models or by using data from field trials directly. These effects are integrated as correction factors. Dependent on which practices the model farmers (FARMNOR) find optimal, expected and year specific 'actual' yields can be calculated. Eq. (1) shows this for the year specific case:

$$Y_{tijc} = f_{tijac}(\mathrm{N}) * \Omega = f_{tijac}(\mathrm{N}_{1t}, \mathrm{N}_{2t}, \mathrm{N}_{3t}) * \Omega \quad t = 1, \ldots, T, \tag{1}$$

where $Y_{tijc}$ is the yield for period t (crop season), soil type *i*; crop type *j*; the standardized agronomic practice *a*; and climatic zone *c*. $f_{tijac}(\mathrm{N})$ is the standardized yield functions. The argument N is differentiated into three parts. $\mathrm{N}_{1t}$ denotes nitrogen from mineral fertilizers, which is the only external N source in *a*. $\mathrm{N}_{2t}$ denotes infiltrated mineral nitrogen from manure applied in period *t* (as estimated by FIELDVOL – input data). $\mathrm{N}_{3t}$ denotes changes in soil N mineralization in time period t due to the use of e.g., manure, catch crops (estimated by SOILN_NO – input data). The correction matrix operator $\Omega$ captures effects of deviations from the standardized practices defined for the basic estimation of dry matter yields $y_{tijac}$, e.g., soil tillage methods other than fall tillage, soil compaction following from manure spreading, delayed sowing time, competition effects (e.g., weeds, catch crops). Lodging effects are also captured.

By changing the levels of the various N fractions and using correction factors, the results from the pre runs are modified to fit other conditions. Ideally, one would have liked to model all processes explicitly and simultaneously. For relatively obvious reasons, this is not feasible. For some process interactions, mechanistic modeling is even impossible due to lacking understanding of the mechanisms. The effect of soil compaction on crop growth is one example. We have thus chosen to combine a mechanistic modeling of the core natural processes with the system of correction factors for effects of a more second order.

### *4.2. The components of ECECMOD (2.0)*

We shall now turn to a short description of the models. Vatn et al. (2002) offers a more extensive overview. In the presentation we also give information about how the data flow is organized. Due to its core integrative role in ECECMOD (2.0), we start by presenting FARMNOR.

### 4.2.1. Choices of agronomic practices – FARMNOR

FARMNOR (Rørstad et al., 2002) simulates choices of agronomic practices at farm (type) level. The model is mainly built on mixed integer and non-linear programming techniques. It consists of a set of integrated modules solving the following choice problems based on the assumption that farmers maximize expected profits: *crop selection*, *tillage practices*, *fertilization rates*, *manure handling*, *springtime management and harvesting*. Choices are made given the characteristics of the farm type (production, soils, manure volumes, etc.). The modules are run sequentially. To maintain consistent solutions, a module called *Integration* is run as a first step in each scenario setting the constraints necessary to avoid inconsistent combinations of practices. Input data for FARMNOR can be grouped into three:

- Farm characteristics (size, type of production, soils, manure, etc.).
- Scenario specific data concerning political and economic conditions. By changing these, we change the incentive structures for the 'model' farmers.
- Data concerning consequences of different agronomic practices:
  - data from pre-runs concerning; (a) year specific yields and N absorption for various crops (including catch crops), fertilizer rates and standardized practices (KONOR, ENGNOR) to produce standardized yield and N-absorption functions; (b) year specific days suitable for spring management (COUP); (c) expected needs for plant protection for various crops and soil tillage systems (PVNOR); (d) changes in N mineralization for different levels of manure application, use of catch crops and different times and types of soil tillage (SOILN_NO); and (e) expected infiltration and losses of ammonia given various spreading techniques and application periods (FIELDVOL).
  - correction factors, as previously defined – confer the correction matrix operator $\Omega$ of Eq. (1).

Outputs from FARMNOR are data on 'chosen' agronomic practices, season specific yields, N absorption in various plant fractions (including weeds and catch crops if relevant), ammonia losses and various data concerning costs and income. Output from FARMNOR is used as input in several of the natural science models (cf. Fig. 2). PVNOR (Section 4.2.5) uses data on type of crop, soil tillage methods and fertilizer level. SOILN_NO (Section 4.2.6) uses fertilization (rates and dates), tillage (method and dates), sowing and harvesting dates, crop type and 'actual' crop N absorption in various plant fractions. ERONOR (Section 4.2.7) uses data on crops (type, sowing and harvesting dates), manure spreading and tillage (method and dates). Finally, data on income and costs are used in the aggregation routine (Section 4.2.8).

*4.2.2. Hydrology and soil temperature – COUP*

COUP (Jansson and Karlberg, 2001) is a dynamic, one-dimensional hydrology and soil temperature model which predicts daily values of soil water content, evapotranspiration, water flows (surface, between layers and drainage to ground water), and temperature for different layers of the soil profile, based on weather input, plant cover, and soil characteristics. The water and heat model is based on two coupled differential equations describing one-dimensional heat and water transport in a soil profile. The model uses standard daily meteorological input data: global radiation, air temperature, relative humidity, wind speed, and precipitation. Soil properties are defined by the water retention curve and the hydraulic conductivity is a function of water content or tension. Plant characteristics (leaf area index, crop height, root depth) are estimated from air temperature sums.

As previously emphasized, the COUP model is run for the standard set of agronomic practices – i.e., it operates only at the pre run stage (see Section 4.1.2). Output from COUP is used as driving variables in the subsequent modeling of yields, N absorption, weeds and pest development and ammonia volatilization. Finally, the same data are used also in the modeling of N-losses and erosion.

*4.2.3. Yields and plant N absorption[2] – KONOR, ENGNOR and SOILN_NO*

In ECECMOD the KONOR, ENGNOR, and SOILN_NO models are joined in integrated soil-plant model runs to estimate plant dry matter production and N absorption for the set of standard agronomic practices. On a daily time step, the plant models (KONOR and ENGNOR) use the nitrate and ammonium in the soil-profile, simulated by SOILN_NO, to estimate the amount of nitrogen taken up by the crop from each soil layer. Nitrogenous ions are transported through the soil to the roots by both diffusion and mass flow, as in the model Daisy (Hansen et al., 1990). The demand for nitrogen has an upper limit set by a maximum concentration in the plant, which varies with standing biomass, and, in the case of leys, with number of cuts. The daily driving variables for the integrated soil-plant model are: radiation, air temperature, crop transpiration (ratio: actual/potential), soil moisture and temperature, and soil water flow.

*4.2.3.1. Cereal crop modeling – KONOR.* KONOR (Bleken, 2001) is a dynamic crop growth model for simulating dry matter production and nitrogen content in grains and other organs of spring cereals – barley, wheat and oats – with or without a catch crop of ryegrass. Canopy expansion (leaf area index) and radiation use efficiency (conversion from absorbed photosynthetic active radiation to dry matter increment) are estimated daily by means of empirical relationships based on field experiments in Norway. Canopy expansion is highly dependent on the amount of nitrogen in the plant. Lack of nitrogen and low actual/potential transpiration ratio reduce growth. The distribution of newly synthesized organic matter to either top or roots depends

[2] Potato growth is not modeled in ECECMOD (2.0). Yield and N absorption functions are estimated on the basis of trial data.

on the N-status of the plant. Reallocation of both dry matter and nitrogen from the stem and leaves to the grain is limited when temperature is low. Particular importance is given to a correct estimation of both total N assimilation (including straw and roots) and grain yield. The catch crop is modeled using the same functional relationships as for spring cereals, but with independent parameter values.

*4.2.3.2. Ley crop modeling – ENGNOR.* ENGNOR (Baadshaug and Lantinga, 2002) is a dynamic crop growth model for grass and clover grass leys. The photosynthetic module applied is adopted from the SUCROS model (van Laar et al., 1997). ENGNOR estimates the potential gross photosynthesis as a function of intercepted radiation and air temperature. Gross photosynthesis is limited by nitrogen stress, when plant N content is below a certain limit, and by lack of water, when the actual transpiration is lower than the potential. Subsequently, gross production is reduced by respiration losses to obtain net actual dry matter production. The partitioning to harvestable herbage, stubbles, and roots is related to the development stage, soil moisture, and herbage nitrogen status.

*4.2.3.3. Soil N dynamics modeling – SOILN_NO.* SOILN_NO (Vold, 1997) is a modification of the Swedish SOILN model (Johnsson et al., 1987). It simulates the C and N turnover in the soil/plant system and estimates soil N mineralization and leaching under different agronomic practices. It is a one-dimensional model, simulating the biological transformations within and nitrate transport between a number of horizontal soil layers. Driving variables needed by SOILN_NO are water transport (surface water infiltration, water flow between the soil layers and to drains), soil moisture (content of unfrozen water) and temperature in each layer as given by COUP.

#### *4.2.4. Ammonia volatilization – FIELDVOL*

FIELDVOL (Hutchings, 1998; Hutchings and Sommer, 1996) is a mechanistic model for estimating loss of ammonia. It is assumed that ammonia is either volatilized from the crop canopy or the soil surface, or it percolates into the soil. Ammonia is assumed to be protected against further volatilization after entering the soil. The volatilization rate is determined by the concentration of ammonia at the surface of the pools and the resistance to ammonia transport between the surface and air advecting from outside the spread area. Important input data include weather conditions, soil characteristics, manure type, crop, timing, application rates and technology. The technology variables cover a set of application technologies and different types of soil tillage (if relevant). Timing of soil tillage is also included.

#### *4.2.5. Crop protection – PVNOR*

PVNOR is a dynamic system model, constructed to simulate the development of weeds and diseases in cereals, the need for plant protection measures and the resulting yield responses. The weed population is divided into three groups: *perennial monocots, perennial dicots* and *seed propagated weeds*, while the diseases are grouped as: p*owdery mildew, leaf spots on barley* and *septoria*. The model is based on biological data, e.g. yearly variation of weed emergence, response of the crop to weed density/disease infestation, and response of weeds and diseases to chemical treatments and tillage treatments. The majority of these data are collected by The Plant Protection Centre of The Norwegian Crop Research Institute over a number of years, but some data are extracted from the literature. As the climate is of great importance for the development of pests, PVNOR is designed to use real data from local weather stations. The programming language of PVNOR is Powersim 2.51. Input to the model such as weather information and data concerning agronomic practices (crops, time of seeding and harvest, soil tillage methods, fertilizer levels) are given by FARMNOR. Thus, in the scenarios PVNOR is run after the FARMNOR modules covering crop selection, tillage practices and fertilizer levels. For a detailed description of PVNOR, see Fykse and Tørresen (2001). Concerning leys and potatoes, crop protection is not modeled explicitly. Practice here is set according to present Norwegian standards.

#### 4.2.6. Nitrogen leaching – SOILN_NO

The SOILN_NO model is also used in the scenario analyses – here to simulate nitrate leaching based on the levels of N absorption in crops and weeds as determined by FARMNOR according to chosen agronomic practices in the various scenarios. Input data delivered from FARMNOR concern agronomic practice (e.g., fertilizer rates and dates, tillage method and dates, and sowing and harvesting dates) and 'actual' crop N absorption in various crop fractions, catch crops and weeds. SOILN_NO has an internal routine that distributes N absorption through the growing season using a modified logistic function (Vold, 1997). If the N supply from the soil is insufficient to satisfy the demand, the final plant N absorption is reduced. The simulation of nitrate leaching is done for each farm type field.

#### 4.2.7. Soil erosion and P losses – ERONOR

ERONOR (Lundekvam, 2002) is used in the scenario analyses. It is an empirically based erosion model. ERONOR is dynamic, operates on a daily basis and calculates soil loss as the product of runoff (surface and drain)[3] and particle concentrations. It is constructed to produce long term estimates of soil erosion from surface and through tile drains for the climates, soil types, topography and cultivation systems, which are most common in Norway. Well-acknowledged erosion models like USLE, CREAMS/GLEAMS, EUROSEM, and WEPP do not perform satisfactorily under Norwegian conditions because winter erosion and erosion from moderate rainfall and saturated conditions are not well handled. ERONOR operates at the level of plots. The model needs data concerning soil characteristics. Data concerning weather, soil water content, drainage, temperatures and snow coverage are given by COUP on a daily basis. Input data concerning crops (type, sowing and harvesting dates), manure spreading and tillage (method and dates) are given by FARMNOR. The model does not simulate deposition, main rill or gully erosion.

[3] Surface and drain runoff may in ERONOR be simulated in two ways: 1) By use of the COUP model which calculates surface runoff and drain runoff directly before ERONOR is run or 2) by the use of an empirical method internally in ERONOR.

*4.2.8. Aggregation/upscaling and final output*

Output data on costs (FARMNOR), pesticide use (PVNOR), N leaching (SOILN_NO), ammonia losses (FIELDVOL/FARMNOR), soil and P losses (ERONOR) are aggregated on the basis of the distribution of types of production, soils etc. in the regions or catchments of a study. As emphasized in Section 4.1.1, all agricultural land in a region is represented by a set of farm types and farm type fields. Thus, total production, losses, costs etc. can be estimated by multiplying data from each farm type field with a coefficient that is relative to the total acreage each field represents. These data are used to produce output concerning costs and effects on losses per crop type, type farm and regions/catchments of scenario specific incentives (political and economic conditions). This way it is possible also to study variations between and within regions. Temporal variations are furthermore captured – primarily by identifying extreme years. Results can also be presented in the form of cost-efficiency measures both at farm type and regional level.

## 5. Testing ECECMOD in four Norwegian regions

ECECMOD (2.0) has been used to study the effects of different environmental policy instruments in four regions in Norway. In the following we will present results concerning how well ECECMOD (2.0) predicts farmers' choice of agronomic practices, and emissions. Some of our results concerning effects of different policy measures are found in Lundekvam et al. (2002) and Vatn et al. (2002).

The analyses presented are based on weather data for the period 1976–1997. The year 1995 is taken as the base year, implying that the reference scenario is based on the political and economic conditions of that year. Concerning the general modeling principles presented in Section 4.1, we have made two simplifications in these runs. The regions are demarcated such that they cover only one climatic zone each. The number of farm type fields is quite substantial in each region – about 60 – thus we have also simplified by assuming that each farm type field has one slope – i.e., the hierarchical levels of plots and fields have been merged.

### *5.1. Region descriptions*

The chosen regions cover a wide variety of agronomic and climatic conditions offering good possibilities to test the capacities of the modeling system. The regions are:

- *South-eastern region* (parts of the Counties of Akershus and Østfold: the municipalities Ski, Ås, Vestby, Hobøl, Spydeberg, Askim, Våler and Skiptvedt)
- *Hedmark* (parts of Hedmark County: Ringsaker, Vang, Løten and Stange municipalities)
- *Trøndelag* (parts of Nord-Trøndelag County: the municipalities Stjørdal, Levanger and Verdal)

- *Jæren* (parts of Rogaland County: the municipalities Sola, Sandes, Time and Klepp)

As is illustrated by Fig. 3, all areas are situated in Southern Norway.

The total area modeled is about 10% of the entire agricultural land in Norway. While the South-eastern region is dominated by grain production, Jæren is dominated by animal husbandry. The two other regions are intermediate. Table 1 offers details for the situation in the 'base year' 1995.

Concerning soils, the South-eastern region and the region of Trøndelag are dominated by clay, while the two other regions are dominated by lighter – i.e., more sandy soils. The climate is wettest in Jæren and driest in the region of Hedmark. Jæren is characterized by a coastal climate and mild winters. Hedmark is a typical inland region with cold winters.

The classification of soils in Table 2 represents a simplification – i.e., it shows the classification we have used in the simulations of crop growth. The soil structure used in the erosion modeling is much more detailed, since each soil is divided into subgroups according to erosion risk (the content of organic material, some soil structural variables and slopes). The South-eastern region and Trøndelag are the hilliest.

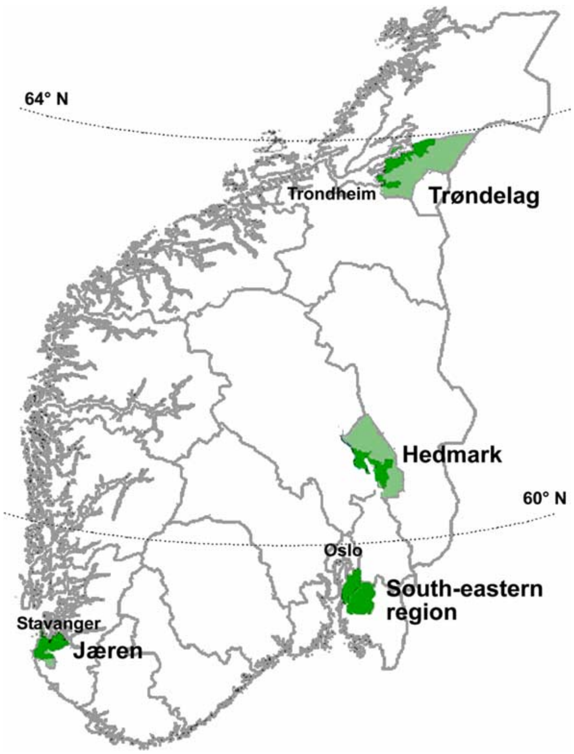


Fig. 3. The location of the study areas.

Table 1
Total agricultural area and the distribution of main crops in the four regions in 1995 (base year)

| | South-eastern region | Hedmark | Trøndelag | Jæren |
|---|---|---|---|---|
| Total agricultural area in ha | 27,412 | 28,586 | 21,096 | 21,803 |
| Number of farms | 1189 | 1049 | 1149 | 1415 |
| Average farm size (ha) | 23.0 | 27.3 | 18.4 | 15.4 |
| Crops in % of total area | | | | |
| Grain | 89.5 | 74.5 | 57.0 | 8.5 |
| Leys | 8.5 | 17.5 | 38.5 | 86.5 |
| Potatoes/vegetables | 2.0 | 8.0 | 4.5 | 5.0 |

*Source*: Analyses based on Statistics Norway (1995).

Table 2
Soils and climatic conditions in the four regions

| | South-eastern region | Hedmark | Trøndelag | Jæren |
|---|---|---|---|---|
| Soils in percentage | Silty clay loam: 61<br>Silt loam: 39 | Sandy loam: 67<br>Loam: 33 | Silt loam: 39<br>Silty clay loam: 36<br>Sandy loam: 25 | Sandy loam: 84<br>Sand: 16 |
| Climate[a] | | | | |
| Precipitation, mm[b] | 785 | 585 | 892 | 1180 |
| Average temperature, °C[b] | 5.3 | 3.6 | 5.3 | 7.4 |
| Temperature in July, °C | 16.1 | 15.2 | 13.9 | 14.2 |

*Sources*: Based on NIJOS (Unpubl.), DNMI (Unpubl.), Norwegian Crop Research Institute (Unpubl.) and Department of Agricultural Engineering (Unpubl.).

[a] Average figures for the period 1976–1997. The weather stations are: Ås (South-eastern region), Kise (Hedmark), Værnes (Trøndelag), and Sola (Jæren).

[b] Yearly average.

The density of animals expressed by available amount of manure per ha varied eightfold among the regions (Table 3).

The largest concentration of manure was in Jæren. In this region the data furthermore showed a fairly even distribution over all levels in terms of intensity, ranging from the farm type with the highest N level – 425 kg per ha, which represented 5.2% of the total area – to the type farm that did not have any animals – representing

Table 3
Amounts of animal manure in the four regions in 1995 (base year) and fraction of total arable land situated at farms with large amounts of animal manure

| | South-eastern region | Hedmark | Trøndelag | Jæren |
|---|---|---|---|---|
| Average amount of manure, kg N per ha | 22 | 44 | 71 | 161 |
| Percentage of the area belonging to farms where kg manure N per ha is | | | | |
| >150 | 1.5 | 2.6 | 4.1 | 49.1 |
| >200 | 1.5 | 2.6 | 3.0 | 17.6 |

*Source*: Analyses based on data from the register of production support (Statistics Norway, 1995).

3.3% of the area. In other regions – especially the South-eastern region and Hedmark – the distribution was bimodal. Here we found a few farms that were very manure intensive. These regions were still dominated by farms without or with very little manure – i.e., 79% of the South-eastern region and 42% in the region of Hedmark. In Trøndelag no farm type had more than 300 kg manure-N per ha. However, farm types with manure covered 77% of the total area of this region.

### 5.2. Observed and simulated agronomic practices

All farms in each region were divided into 10–12 groups, which formed the basis for the construction of farms types (Section 4.1.1). Each farm type consisted of approximate 6–7 farm type fields. Since each farm type represents a certain number of farms – a certain acreage – in each region, aggregate losses can be obtained (Section 4.2.8).

Validation of ECECMOD has several components. First, the simulation of farmers' choices under existing economic constraints should match actual choices. Second, the calculations of various 'downstream' variables like actual yields, N leaching, and erosion should be realistic and in accordance with observations. Data concerning actual practice in the regions were delivered by Statistics Norway (census data and data from production support register). Table 4 shows the choices of crops as observed and simulated for the base year 1995.

The simulated distribution of the main groups of crops was very similar to the observed practice. There were some deviations for the different types of grains, but even in this case the strong contrasts between the regions were rather well captured by the simulation.

The observations of actual fertilization rates (chemical fertilizer plus manure) were far more uncertain than those for the distribution of crops. A particular problem was the uncertain estimation of ammonia losses from manure, which implies

Table 4
Observed and simulated choices of crop type in the four regions in 1995 (base year), in percent of total area covered by each crop type

| | South-eastern region | | Hedmark | | Trøndelag | | Jæren | |
|---|---|---|---|---|---|---|---|---|
| | Obs. | *Sim.* | Obs. | *Sim.* | Obs. | *Sim.* | Obs. | *Sim.* |
| All grains[a] | 89.6 | *90.6* | 74.8 | *72.3* | 56.8 | *55.9* | 8.7 | *8.0* |
| Barley | 26.2 | 33.7 | 46.6 | *42.5* | 52.7 | *38.5* | 7.2 | *8.0* |
| Oats | 32.7 | *26.5* | 7.1 | *11.3* | 3.2 | *17.4* | 1.3 | *0.0* |
| Spring wheat | 11.2 | *15.0* | 17.0 | *9.8* | 0.5 | *0.0* | 0.1 | *0.0* |
| Winter wheat | 19.4 | *15.4* | 4.1 | *8.7* | 0.3 | *0.0* | 0.1 | *0.0* |
| Leys | 8.4 | *8.7* | 17.3 | *20.9* | 38.5 | *40.7* | 86.4 | *88.9* |
| Potatoes[b] | 2.0 | *0.7* | 7.9 | *6.8* | 4.7 | *3.4* | 5.0 | *3.1* |

*Source*: Observed data are from analyses based on the register of production support (Statistics Norway, 1995).

[a] Rye and oil seeds are not modeled and thus excluded from the statistics.

[b] Potatoes and vegetables. ECECMOD (2.0) is only modeling potatoes as a representative crop.

great uncertainty concerning total mineral N application to the soil. We did, furthermore, have only limited data on the allotting of manure to various crops.

The data concerning observed fertilizer rates in Table 5 are from two sources. The data in the first column for each region are from the yearly agricultural census (Statistics Norway) and cover a representative sample in the four regions. If a farm has animals, it was assumed that the manure was allocated evenly to all crops. It was furthermore assumed that 60% of the ammonia was lost. The second column gives data from some more detailed studies of the agronomic practice on a small sub-sample of farms in each region. They come from the so-called JOVÅ-areas (the 'Agricultural Environmental Monitoring Programme' run by the Centre for Soil and Environmental Research (Jordforsk)). These data are of better quality since they are based on a detailed documentation system. They are on the other hand less representative, and even here we lack data on the actual ammonia losses. Thus, the same assumptions were made as for the census data (60% loss of ammonia and even allocation of manure to all crops). In the case of the JOVÅ data, the number of farms, and thus the areas of some crops, were very low. Therefore we have used data for a series of years – mainly around the mid 1990s.

The predictions showed good fit to observed fertilizer use, in particular considering the mentioned uncertainties concerning fertilizer use. The simulated figures are possibly a bit high for barley, oats and leys (especially in the South-eastern region), while they may be somewhat low at least for winter wheat. The model responds fairly well to the variations across regions where the South-Eastern region is observed to have the most intense grain production and Jæren has similarly high intensity in grass production.

Table 6 gives yield data for the different crops in chosen periods. Concerning observed yields, the first column gives average figures for the entire counties in which our regions are situated. These data are supplemented by data for the region itself. They cover, however, only grains and give data just for the period 1990–1999.

Generally, we consider the observed grain yields to be much more reliable than those of leys. The simulations match the observed values quite well. It should be mentioned that in the Hedmark region, grain was sprinkle irrigated once a year in the simulations. This may actually be too low, since sprinkle irrigation is frequently used in that district.

In 1992 subsidies were introduced to stimulate farmers to reduce use of fall tillage. It was thus of special interest to see how well the simulated tillage practices fitted with the observed data. The available data are based on registered areas for which the owner had been granted a subsidy for using reduced tillage/spring tillage. Most probably some farmers using such practices have not applied for the subsidy, thus the observed acreage is perhaps a bit low. Still, we do not consider this to be an important error since subsidies were quite high. Table 7 gives the results for grain areas, which are the relevant ones in this case.

Here we observe considerable deviations between observed and simulated data. Farmers simply did not respond to the subsidies for reduced tillage to the extent the model simulations indicate is profitable. The results were obtained despite our effort to capture all important effects and mechanisms that may be involved. We have

Table 5
Observed and simulated fertilization rates in four regions

| | South-eastern region | | | Hedmark | | | Trøndelag | | | Jæren | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Obs[a] | | *Sim.*[b] | Obs[a] | | *Sim.*[b] | Obs[a] | | *Sim.*[b] | Obs[a] | | *Sim.*[b] |
| | Census | JOVÅ | | Census | JOVÅ | | Census | JOVÅ | | Census | JOVÅ | |
| Grain (average) | 125 | | *124* | 111 | | *123* | 105 | 89 | *91* | 101 | | *112* |
| Barley | 116 | 125 | *121* | 105 | 121 | *119* | 103 | [e] | *90* | 103 | 108 | *112* |
| Oats | 103 | 137 | *117* | 95 | 93 | *118* | 92 | [e] | *93* | 92 | [d] | [d] |
| Spring wheat | 136 | 169 | *139* | 135 | 135 | *137* | 122 | [e] | [d] | [d] | [d] | [d] |
| Winter wheat | 144 | 181 | *125* | 135 | 151 | *135* | [d] | [e] | [d] | [d] | [d] | [d] |
| Leys | 181 | 183 | *235* | 172 | 230 | *239* | 191 | 162 | *199* | 234 | 274 | *278* |
| Potatoes[c] | [d] | 155 | *117* | [d] | 89 | *115* | [d] | [d] | *115* | [d] | 105 | *120* |

Observed data consist of two sets – census and JOVÅ data, kg N per ha per season.
*Sources*: Observed data is from an analysis based on yearly census data (Statistics Norway, 1995) and Jordforsk (unpubl.).
[a] Census data are from 1995 (reference year). JOVÅ data are from a series of years in the middle of the 1990s with some variation between the areas.
[b] Simulations are done on the basis of 1995 prices.
[c] ECECMOD (2.0) models potatoes as a representative crop for potatoes and vegetables.
[d] Data are lacking or no simulations. In Trøndelag and Jæren very little wheat is grown.
[e] Not distributed on the different types of grain.

Table 6
Observed and simulated yields in the regions, kg per ha and year

| | South-eastern region | | | Hedmark | | | Trøndelag | | | Jæren | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Obs.[a] | | *Sim.*[b] | Obs.[a] | | *Sim.*[b] | Obs.[a] | | *Sim.*[b] | Obs.[a] | | *Sim.*[b] |
| | County | Region | | County | Region | | County | Region | | County | Region | |
| Barley[c] | 3660 | 3810 | *3930* | 3710 | 4210 | *4210* | 2930 | 3060 | *3180* | 3770 | 4130 | *4050* |
| Oats[c] | 3700 | 3970 | *4170* | 3590 | 4670 | *4450* | 2910 | 2950 | *3000* | 3600 | 3690 | [e] |
| Spring wheat[c] | 4050 | 4290 | *3760* | 4530 | 4640 | *4050* | 3210 | 3410 | [e] | 3350 | 3920 | [e] |
| Winter wheat[c] | 4050 | 4800 | *4350* | 4530 | 5280 | *4160* | 3210 | 3990 | [e] | 3350 | 4220 | [e] |
| Leys[d] | 6540 | [e] | *6450* | 5380 | [e] | *6400* | 6400 | [e] | *6900* | 8330 | [e] | *8160* |
| Potatoes[f] | | [e] | *19590* | | [e] | *20950* | | [e] | *21500* | | [e] | *20820* |

*Source*: Observed data based on data from Statistics Norway (1978–1999).
[a] Observed data are (a) average for the counties for the entire simulation period 1976–1997 and (b) for the regions themselves for the 1990s.
[b] Simulated yields are averages for the whole simulation period 1976–1997.
[c] 15% moisture content.
[d] kg dry matter.
[e] No data (obs.) or not simulated (sim.).
[f] Sold crop (kg fresh tubers).

Table 7
Grain area with no tillage in the fall

| | South-eastern region | | Hedmark | | Trøndelag | | Jæren | |
|---|---|---|---|---|---|---|---|---|
| | Obs.[a] | *Sim.* | Obs.[a] | *Sim.* | Obs.[a] | *Sim.* | Obs.[a] | *Sim.* |
| No tillage in the fall in grain fields | 28 | *75* | 17 | *81* | 9 | *84* | 0 | *8* |

Observed and simulated areas in percent of total grain acreages of the regions. Data for 1995 (base year).
*Source*: Observed data are based on analyses of the yearly census data (Statistics Norway, 1995).
[a] Only areas for which subsidies for reduced tillage are paid are included.

thus taken into account the fact that farmers have experienced more severe yield depressions in reduced tillage regimes than the moderate (if any) yield reductions obtained in experimental field trials (cf Ekeberg and Riley (1989); Etana et al. (2000); Molteberg (2000) and Børresen and Riley (2003)). Furthermore, the quality of the harvested grain may be lower due to different mechanisms following from a shift in tillage practices. Finally, the labor costs are different (higher) in spring than in fall (reduced tillage shifts more labor to the spring). All these factors were taken into account. One may, therefore, wonder whether farmers in 1995 had not yet realized how profitable reduced tillage had become by the substantial subsidies introduced in 1992. This view is supported by the observation (not shown) that 8 years later more farmers had switched to reduced tillage, despite the fact that by that time, the subsidies had been reduced.

### 5.3. Comparisons between observed and simulated losses

Field and laboratory experiments were utilized both to estimate various parameters and to validate different parts of the entire modeling system. At the system level we had only one set of data, that from the JOVÅ areas where run-offs from a number of (rather small) watersheds have been measured. The measurements were started in the late 1980s in Hedmark, and during the first half of the 1990s in the other regions. The estimated losses made via ECECMOD (2.0) are losses from the agricultural fields, whereas the measurements were done in the creek draining the area. Thus there are two potential differences between estimated and measured losses. First, the agronomy in the JOVÅ catchments may deviate from that of the whole region. Second, there are retention effects. The possible N-retention between fields and the creek outlet implies that the predicted N-leaching values should be higher than the measured ones. Still, this effect should not be substantial since most agricultural land is artificially drained and the average retention time is rather short. In the case of soil particles and P, the situation is more complex. The retention works in the same direction as for N, but it is likely to be larger and more variable. Soil particles and P may also be released due to gully erosion on the field (not modeled) and erosion of the riverbanks, both resulting in higher measurements in the creek than simulated. There may also be errors in the observed data since run-offs from other areas than the agricultural land must be accounted for.

Table 8
Observed and simulated run-off of nitrate N, soil and P loss in four regions, kg per ha and year

| | South-eastern region 1993–1997 | | Hedmark 1986–1997 | | Trøndelag 1992–1997 | | Jæren 1995–1997 | |
|---|---|---|---|---|---|---|---|---|
| | Obs.[a] | *Sim.*[b] | Obs.[a] | *Sim.*[b] | Obs.[a] | *Sim.*[b] | Obs.[a] | *Sim.*[b] |
| N leached | 36 | *43* | 48 | *59* | 44 | *51* | 54 | *93* |
| Soil loss | 1070 | *940* | 100 | *190* | 2340 | *540* | 120 | *110* |
| P loss | 1.5 | *1.4* | 0.4 | *0.6* | 3.1 | *1.0* | 1.5 | *1.4* |

[a] Observed data concern measurements in the creek as it leaves the areas (JOVÅ areas).
[b] Simulated data concern losses to drainage pipes and ground water (N) and losses from fields (soil particles and P) for whole regions.

The simulated values for N losses correspond well to the observations for all regions except for Jæren where the estimates seem to be much too high (Table 8). The amount of mineral fertilizers used in this region is very high, and so are the amounts of manure N applied. Given the high precipitation, mild winters and light soils, we actually find it surprising that the observed $NO_3$ transport in the watershed is almost at the same level as in the other areas.

There have been some specific measurement problems in the JOVÅ monitoring area in Jæren. The area is flat, and it is somewhat unclear in which direction parts of the groundwater are draining. It is still possible, of course, that ECECMOD (2.0) underestimates the plant N absorption especially in the period outside the growing season. We have put much effort into this part, incorporating results from a study by Korsæth et al. (2003) whose data suggest very high N assimilation in late fall and winter in the Jæren area. Our model may also have underestimated the level of denitrification.

The losses of soil and P in Hedmark and Jæren were low and fit well to the observations. The low figures are explained by topography, soil types and agronomy. The relatively high level of P losses in Jæren is explained by the high concentration of manure. The fit is also very good for the South-eastern region.

In Trøndelag the observed figures were substantially higher than those obtained by the simulations. The overestimated frequency of spring tillage in the simulations (cf. Table 7) explains parts of the deviations. Running ECECMOD (2.0) with the observed level of spring tillage did, however, still not fill the gap between model and observation. Another reason for the observed high values for soil transport could be river-bank erosion; substantial supply of matter from the banks of the river has been observed in this region (Bechmann, Pers. com.).

## 6. Conclusion

Tools for analyzing the economic and environmental performance of agriculture should reflect the complexity of interactions and the multitude of environmental effects. This paper has been devoted to presenting ways in which these multifaceted needs can be handled, taking the various unique characteristics of the agricultural system into account. We have also documented how the principles can be operationalized into a functioning modeling system – ECECMOD (2.0).

We have shown that it is possible to develop an analysis tool, which is capable of both handling all the complex interactions and producing results that are mostly in line with what is observed under a range of conditions. Obtaining this has been a great challenge, since the number of potential errors that might appear in such a modeling structure is vast. On the other hand, once the system is established and validated, it offers a unique possibility to study the impacts of a broad set of policy measures with high precision. We have furthermore experienced that the basic partitioning structure – securing that the various models are set to operate at the most pertinent level of resolution – has offered a very flexible basis for the analysis. It has made it rather easy to integrate new processes when needed and to study policy measures with a great variety of characteristics.

Certainly, we have observed deviations between modeling results and observations. This was especially the case concerning soil tillage practices and the adjoined soil losses. Here one should note that the model operates on the basis of the most up to data information. It thus assumes farmers to be equally updated. It is also based on assuming farmers maximizing profits. Especially in areas where the economic conditions are changing fast, these assumptions are probably unrealistic. We believe that the model is thus better at predicting long term adaptations than immediate effects of policy changes – the reason being a substantial lag in farmers' response to the changes.

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