METHODS

ECECMOD: an interdisciplinary modelling system for analyzing nutrient and soil losses from agriculture

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Abstract

   This article discusses a set of principles for policy analysis of environmental problems. The main focus is on integrating economic and ecological analyses through a mathematical modelling framework. The paper starts by developing a general model for the study of environmental issues. Principles for operationalizing the model are discussed, and ECECMOD (a new modelling system constructed to analyze pollution from agricultural systems on the basis of these principles) is introduced. Some of the results obtained by ECECMOD are presented to facilitate a discussion about the gains to be obtained by this kind of analysis. The study shows that it is of great importance to combine economic and ecological analyses at a fairly high level of resolution when studying environmental effects of complex systems. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

   Environmental problems are characterized by interactions among societal institutions, resource use choices made by economic agents within these institutions, and the different natural processes these choices influence and are influenced by. In this light it is disturbing that most studies (even those addressing environmental policy issues) have been undertaken within single disciplines. Given the character of the problem, such a strategy runs the risk of producing research with low cross-disciplinary coherence and little policy relevance (Vatn et al., 1997).

   The background of the study presented here is the North Sea Treaty mandating that the countries of the area reduce nutrient emissions to the sea by 50%. Given the problem, we were 'forced' to find practical and productive ways of integrat-

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ing relevant sciences. It turned out to be a challenge both to integrate and to maintain the quality standards of the involved disciplines. We experienced (in a very concrete way) why interdisciplinary research is so rare.

To be able to communicate coherently across the fields of study, we had to find a common language and scientific structure. We found that mathematical modelling could facilitate that. Our first step was to develop a general model for studying policy choices concerning pollution and degradation of natural resources such as water, air and soils. Next, we had to find ways of making the model operative and of developing an analysis tool by which empirical studies in the field of nutrient losses from agriculture could be undertaken.

In this paper we present the most important steps of the process of model construction, illuminating the various conflicts that arise when integrating across disciplines. Further, we introduce the interdisciplinary modelling system that was finally developed (ECECMOD) and present some of the results obtained using this system. Since our focus is methodological, we will concentrate on results illustrating the potential of integration and the gains that can be obtained by using rather detailed analysis with high levels of resolution. For those interested in a more comprehensive overview of the results, we refer to Vatn et al. (1996, 1997).

2. A general and idealized model

From an economics point of view, pollution problems are considered to be incentive problems. Economic agents do not face all costs associated with their activities. For natural scientists, pollution is primarily about changes in matter cycles, cumulative or disruptive changes in various ecosystems where the 'actors' are ions, bacteria, fish, etc., operating at very different scales compared to the economic 'actors'. In order for the potential consequences of certain policies to be foreseen, the different levels/subsystems involved need to be well linked and the right levels of resolution chosen. The problem, as we see it, is that economists

in their analysis primarily utilize very simplified assumptions about the natural world, and the natural scientists hardly take into account the fact that in formulating policies one has to consider motives, constraints, and institutions determining human choices.

From an economic perspective, a pollution problem is of interest if there exists a potential for welfare improvement by institutional changes resulting in less pollution. Coached in a principal-agent framework and assuming the agents to be expected profit maximizers, the policy problem may be formulated in the following general way: Principal:

$$\underset{\{u\}}{\text{MAX}} \quad W = W\left\{ \sum_{t=1}^{T} \beta^t \left[\sum_{i=1}^{n} E_{it}(\pi_{it}), r_t \left(\sum_{i=1}^{n} d_{it}, u_{it} \right) \right] \right\} \tag{1a}$$

where

$$u_{it} = \frac{\partial h\left(\sum_{i=1}^{n} r_{it} \right)}{\partial d_{it}} \tag{1b}$$

subject to: Agent:

$$\underset{\{\phi_{t\tau}\}}{\text{MAX}} \quad E_i(\pi_i) = \sum_{t=1}^{T_i} \left\{ \beta_i^t E_{it}[f_{it}(p, v, z_{it}, \phi_{it}, u_{it})] \right\} \tag{1c}$$

and where: u denotes a vector of environmental taxes; W denotes social welfare; t denotes a time index, $t \in \{1,2,...,T\}$; i denotes an index over location specific firms, $i \in \{1, 2,...,n\}$; E denotes an expectations operator set prior to each production decision made by the firm; π denotes profits; r denotes a vector characterizing the state of the recipient; d denotes a vector of emissions influencing other economic agents through changes in the characteristics of the recipient; h denotes a function describing the value of the recipient given its state; o denotes a vector of the agent's choice variables; β denotes the discount factor; f denotes a multi production function; p denotes a vector of product prices; v denotes a vector of variable input factor prices; and z denotes a vector describing the natural assets used in production.

To simplify the exposition, all agents (i) are considered to be firms, and each firm owns a homogenous element (i) of the natural assets z. The arguments in the social welfare function W consist only of the present value of agents' incomes (profits π) and the states of the recipient r. The emissions are here considered to be global (e.g. the location of the emission does not influence its effect). Following the standard Pigovian policy solution, the principal's choice variable is a set of firm-specific taxes on emissions equal to their marginal environmental costs. The tax changes the incentive structure the agents are facing, as the costs they impose on others become part of their optimization calculus.

Eq. (1c) contains little information about the structure of the agent's decision problem and the dynamics of the environment. A more complete formulation is given in Eqs. (2a), (2b), (2c) and (2d):

$$\begin{array}{c} MAX \\ \{x_{it} b_{it} q_{it}\} \end{array} E(\pi_i)$$

$$= \sum_{t=1}^{T_i} \{\beta_i^t [p'_t E_t[f_{it}(x_{it}, b_{it}, q_{it}, g_{it}(z_{it}))] - u_t^{*'} d_{it}$$
$$- v_t' x_{it} - b_{it}]\} + \beta_i^{T_i} k_t(b_{iT_i}, z_{iT_i}) \qquad (2a)$$

where:

$$d_{it} = m_{it}(x_{1,t-1}, b_{i,t-1}, q_{i,t-1}, z_{i,t-1}) \qquad (2b)$$

subject to:

$$z_{it} = l_{it}(x_{i,t-1}, b_{i,t-1}, q_{i,t-1}, z_{i,t-1}, r_{t-1}) \qquad (2c)$$

where:

$$r_{t-1} = s_t(\sum_{i=1}^{n} d_{i,t-2}, r_{t-2}) \qquad (2d)$$

and where: x denotes a vector of variable inputs used; b denotes a vector of fixed inputs in the form of man-made capital; q denotes a parameter for the quality of the chosen technology; g denotes a function for the productivity of the natural assets z; u^* denotes a vector of optimal environmental taxes obtained through solving Eqs. (1a), (1b) and (1c); k denotes a function for the terminal value of assets b and z; l denotes a function for the effects of agents' choices and

previous states of z and r on the state of the natural assets r; m denotes a function for the effects of agents' choices and previous state of z on emissions; and s denotes a function for the relation between emissions and the state of the recipient.

Eq. (2a) is formulated as a standard profit maximization problem for agent (i) given that it faces a set of environmental taxes (u^*) and has access to natural resources z_i. The input vectors x and b and technology (q) are specifications of the vector o of choice variables as depicted in Eq. (1c).

The dynamics of the natural system which the agent influences through choices about inputs (x, b) and technology use (q), are described by Eqs. (2b), (2c) and (2d). As to assets, a distinction is made between man-made capital b and natural assets z and r. Elements of z are used as inputs in production, while r describes the state of the recipient. The distinctions are purely analytical, and what is a recipient (r) for one agent may be the resource (z) for another. Thus, the dynamics of emissions, the state of the recipients, and the quality of the resources are influencing each other in complex and time dependent ways. This is taken care of by Eq. (2c) where the elements of z at time t depend upon previous capital investments (in b and z) and the changes in the recipient r (Eq. (2d)).

Through the specification of z and t, the model incorporates variation both in space and time. In the case of biologically based production systems, the productivity of the resources may vary substantially due to variations in the quality of soil and water and the variability in weather. The weather will only be known with certainty ex post. The agent must therefore make decisions on expected profits, justifying the use of the expectation operator E in Eq. (2a).

3. Principles for operationalizing the general model

One is faced with a long list of difficult choices when trying to operationalize the general model covered by the equation systems (Eqs. (1a) to (1c),

and (2a) to (2d)). In general there are important trade-offs to be made between preserving some complexities while reducing others.

First of all, agents are not necessarily profit maximizers, even though most production analyses assume this. They may both have a more complex preference structure (utility maximization, risk aversion (Nakajima, 1986; Singh et al., 1986)), and they may not (always) maximize. They may use satisficing rules or follow specific behavioral norms developed among practitioners in the field (Simon, 1979; Hodgson, 1988; Vedeld, 1998). Profit maximization still has high merit, as it is chosen also because it is easier to handle analytically, avoiding further complications in an already very complex model structure.

Environmental taxes in Eqs. (1a) to (1c), and (2a) to (2d), assumed to be assigned to emissions, as in the standard point-source pollution case. This is not an obvious solution, since emissions often are non-point and variable. In most cases where renewable natural resource use is involved, the non-point character of emissions renders the costs of gathering necessary information to undertake emission based regulations prohibitively high. This introduces an extra complication for the principal, since measures may either have to be assigned to input factors (x or b), or to the way these factors are combined internally and with z through defined technologies (q). In our case we found it necessary to address these complications.

The complexity of the problem will often make it difficult to determine optimal levels of the policy control variables in u. It is sufficient to mention the problems of valuing environmental functions (Hausman, 1993; Vatn and Bromley, 1994). Thus a full cost-benefit analysis may be very difficult and, even obscure the problem. An alternative then is to use a cost-effectiveness criterion, measuring costs for obtaining certain levels of emission reductions. Technically speaking this implies omitting the optimization problem defined in Eqs. (1a) to (1c) and instead produce information for the principal through a scenario type modelling. Here the effect of various levels of the policy vector u on π, z, d and r is explored utilizing the equations in Eqs. (2a) to (2d) only.

We chose to use this type of sequential search procedure. This does not necessarily reduce information quality. Rather, it may make the results more transparent, as it also makes it easier to preserve higher resolution especially in the natural science part.

Given the above simplifications, one is still faced with the problem of describing and linking processes (and thus disciplines) demanding analyses at widely different scales. Moreover, one has to find tractable ways of solving an optimization problem with the complicated dynamics and feedbacks described in Eqs. (2a) to (2d). Let us address these issues.

3.1. Integration across scales

While economists do their analyses at the level of the firm, a sector or the society, natural scientists normally undertake their analyses within geographically localized, often rather small-scale-specified, physical and/or biological conditions. These differences are caused both by variations in scope and by the type of processes studied (Antle and Capalbo, 1993).

A way to overcome the problem of varying scales and foci is to utilize the fact that natural systems tend to be organized in hierarchies (O'Neill et al., 1986). Processes are nested, with those at one level becoming elements of those at higher. The problem becomes one of maintaining the necessary non-linear fine-scale variation as one moves upwards into more coarse-scale aggregations. Rastetter et al. (1992) discuss three methods by which to accomplish this:

a. partial transformation using an expectation operator to incorporate fine-scale variability;
b. partitioning—separating the coarse-scale objects (aggregates) into a manageable set of relatively homogeneous subgroups; and
c. calibration—recalibrating fine-scale data to coarse-scale information.

Incorporating fine-scale variability by a statistical expectations operator (method (a)) may yield good results, but is often difficult to utilize in systems with many elements and dimensions of variation. The covariation structure often must be assumed, and hence becomes ad hoc. The useful-

ness of method (c) rests on the availability of data both at the fine and coarser scales, and is difficult to use if the aim is to study effects of changes in a system.

As Costanza et al. (1995), we find partitioning to be a good solution for analyses of land-based systems. Here the various resources or decision units are classified into homogenous groups at relevant levels and integrated in a hierarchical structure. This way partitioning offers a surveyable platform for linking analyses that must be undertaken at different levels and studied with various resolutions.

Linking across levels means to a large degree linking across disciplines. While natural hierarchies exist, it may still be difficult to identify aggregates that serve both the 'aggregate' and the 'disaggregate' sciences well. Partly, this reflects disciplinary traditions, but it may also reveal real discontinuities. These kinds of problems are especially prone to occur as one crosses over from the natural to the social sciences. We will return to this issue later.

3.2. Solving the optimization problem

The optimization problem in Eqs. (2a) to (2d) is formulated as an optimal control problem in discrete time. The complexities, especially in the underlying structure of the natural processes, will however often prohibit solving Eqs. (2a) to (2d) simultaneously. Reducing complexity may not be justifiable. Two partial solution concepts that stand out are:

1. Iteratively solving each equation in Eqs. (2a) to (2d) for relevant sequences of time, updating the equations with necessary information from each other.
2. Modelling for the whole time period in two sequences—first agents' choices, then the effect of these choices on the natural processes. To cover important feed-backs, the natural science information necessary to solve agents' optimization problems are produced initially under simplified assumptions about agents' choices/practices.

The merits of these two methods depend on the problem, the type of dynamics and the role of

time. Method 1 takes best care of the interactions between the different levels of the system — the dynamics between the economic and ecological parts. For large systems, iteration will tend to be very resource demanding, and it will by definition not be possible to solve the economic optimization problems simultaneously for the defined period of analysis.

According to procedure 2, the agents' optimization problem will be solved given rather coarse pre-estimated information about developments in the natural processes. Thereafter, the equations describing the natural asset dynamics are solved at the most desirable level of resolution and on the basis of information about the model agents' choices of production practices. Agents' information about the development of the natural resources are often coarse and uncertain at the time of decision. Procedure 2 actually mimics that feature, as it also is the easiest to implement if high resolution in the natural science part is necessary. We have chosen method 2 in our analysis.

4. ECECMOD—The economics and ecology modelling system

To demonstrate how the above principles may be utilized, we will turn to a presentation of ECECMOD—a modelling system established to study the effect of different policy measures on mineral emissions from agriculture. The system is fully documented in Vatn et al. (1996) and consists of a set of process-based, interlinked models. Some are constructed specifically for the project, while it has been possible, in other cases, to build on existing models.

Reviewing the literature on agricultural pollution, we found few studies focusing on the dynamics between the relevant economic and ecological processes. As an example, a dominant trend in policy oriented studies of nitrogen emissions is to look at the effect of various instruments on a calculated nitrogen surplus (Vatn et al., 1997). In our opinion a more sophisticated treatment of natural processes with a higher level of resolution is warranted.

4.1. The agronomic system and nutrient losses

Nitrogen and phosphorus are essential elements of mineral fertilizers added to enhance plant production in agriculture. If lost to the environment, the same elements represent a potential pollution problem. They may cause eutrophication in fresh and/or coastal waters. Nitrates may reduce groundwater quality, induce acidification and, in the form of N_2O, affect the ozone layer and global warming.

Phosphorus displays more local effects, while nitrogen in different compounds influences the environment both at the local level and on a global scale. Nitrogen is a dynamic and elusive element in nature. Therefore, both the form and magnitude of losses depend on a series of conditions such as weather, fertilizer levels, plant uptake, incorporation of organic matter into soils, utilization of manure N, etc. Supplies of mineral N during the growing season is a prerequisite for successful plant production. Nitrate (NO_3^-) is a very mobile ion, making it a preferred N-source in plant production, but also prone to leaching. Losses may be decreased by reducing the input of mineral N. However, both plant uptake and soil processes affect losses greatly. This implies that to control losses, one must look at the agronomic practice as a whole.

Plant roots are by far the strongest mineral N sink in the soil. The response of plants to N fertilization is crucial in predicting the relationship between fertilizer levels and nitrate leaching (Vold et al., 1994). Crop failure due to drought periods in rainfed agriculture results in large N losses through leached residual nitrate out off season (Uhlen, 1989).

The soil and the heterotrophic soil microflora (+ fauna) are other potential sinks. N incorporated in organic soil compounds represents a large pool of nitrogen in the system—20–100 times the annual doses of mineral fertilizers. Depending upon the supply of energy through plant residues and/or the type of tillage system used, the microflora functions either as a net sink or net source of mineral N. Due to the stability of the organic components involved, a net increase or decline in the soil organic N pool may continue for decades, depending on the agronomic practice (Christensen and Johnston, 1997).

The annual changes in soil organic N may be moderate compared to the total amount in the soil, but large in relation to the nitrogen inputs (fertilizers) and outputs (crops) from the system. Soil texture has a profound influence on the level and changes in soil organic nitrogen (ibid). This role of soil organic N invalidates N budgets as a criterion for the environmental performance of an agronomic system with normal N inputs. At the same time it constitutes an important rationale for choosing a process-oriented N modelling approach with a high resolution both in time and space when analyzing the effects of policy measures for reducing nitrate leaching.

Phosphorus is much less elusive than N, as it is strongly bounded to soil mineral fractions. Since losses are to a large degree the result of erosion, the input of mineral phosphorus through fertilizers has little impact on losses, at least for short and intermediate time spans. Plant cover, tillage practices, etc. are far more important for erosion and resulting P-losses than input/output relations. Thus even this case shows how important it is to understand the dynamics of the agronomic practice as a whole. Further, the impacts vary substantially with differences in soil characteristics and topographical conditions. In the case of soil erosion, losses are highly episodic, due to the importance of precipitation.

4.2. System, levels and processes

As previously emphasized, studying dynamics of the kind described above requires careful consideration of system boundaries, choice of resolution, and how to link various processes. In constructing ECECMOD we decided to use watersheds or catchments as the largest unit of analysis. Weather developments and water movements are the most significant natural process of importance for system demarcation. Certainly catchment areas can be substantial. There is in principal no technical obstacles other than capacity and data requirements related to covering substantial areas. As we have formulated the modelling system, though, weather conditions are

considered homogeneous within each catchment, in practice often implying necessary division into subcatchments. While few economic units are defined by watershed borders, they are capable of subsuming a number of production units fairly well.

Using partitioning as the basic method for preserving the necessary variation and for nesting levels, we observe that farms, soil types, and topography are important spatial elements of variation. Farm size, type of production, and stocking rates are notable sources of diversity at the farm level. Nitrogen turnover, plant growth and P losses vary with climate, soil types and topography, the latter influencing water erosion. Based on this, we chose the following levels and partitioning criteria:

1. Watersheds/catchments. Partitioning criteria: Weather conditions, topography and production. Modelling: Aggregated emissions to air and water.
2. Farm. Partitioning criteria: Farm 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; hydrology, nutrient (N) turnover and leaching.
4. Plot/grid cell. Partitioning criteria: Topography, soil properties, slopes, and agronomic practice. Modelling: Erosion and P-losses.

With regard to the time dimension, it was necessary to combine high resolution (episodic nature) with long simulation periods (variation). The total length of the analysis period is set at 20 years. Farmers' decisions are dominantly modelled at the level of years or seasons (choice of crops, tillage practice etc.), but in some cases at the level of days (sowing dates, etc.). Each of these decisions is modelled consistently with the information resolution of the corresponding decision problem. The natural science modelling is mainly undertaken at the level of days. In the erosion analysis, the basis is rainfall events that may have durations from minutes up till several hours.

4.3. The structure of the modelling system

ECECMOD consists of a set of linked submodels covering the different parts of the system as described in the above hierarchy. As the modelling system now works, the optimization problem in Eq. (2a) is solved on a year by year basis. This is due to capacity constraints. It does, however, represent a minor problem in our case, since the terminal value of the relevant assets (e.g. soil and soil N volume) is not considered to influence the choices studied.[1] Fig. 1 gives an overview of the main structure of ECECMOD.

The figure differentiates between external inputs, (process based) models, and model outputs (intermediate and final states). The level of resolution (scales) for the space and time dimensions is also given. The analyses are driven by a set of input data defined by farm structures and soil and weather conditions in the actual catchment. By changing the institutional setting within which farmers' decisions are to be made, it is possible to analyze the effects on emissions and the costs implied. Thus far the effects of the emissions on down-stream water-courses is not integrated into the model.

As to the different parts of the system, we would emphasize the following:

ECMOD is an optimizing model operating at the farm level. The optimizing problem to be solved follows in principle the formulation in Eq. (2a) with constraints related to acreage and labor. The policy variable is (as already emphasized) formulated differently though, as taxes or other types of regulations are attached to inputs (x or b) like fertilizers, or to the management practices (q) like plowing time, catch crop use[2], storing facilities for manure, etc. and not to emissions.

ECMOD consists of a set of modules solving the choice problems that are assumed to be the

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[1] For example, farmers are, under Norwegian conditions, not considered undertaking soil mining — a point where the model formulation actually deviates from a strict net profit maximizing rule.

[2] Catch crops are in this case undersown rye grass in grain.

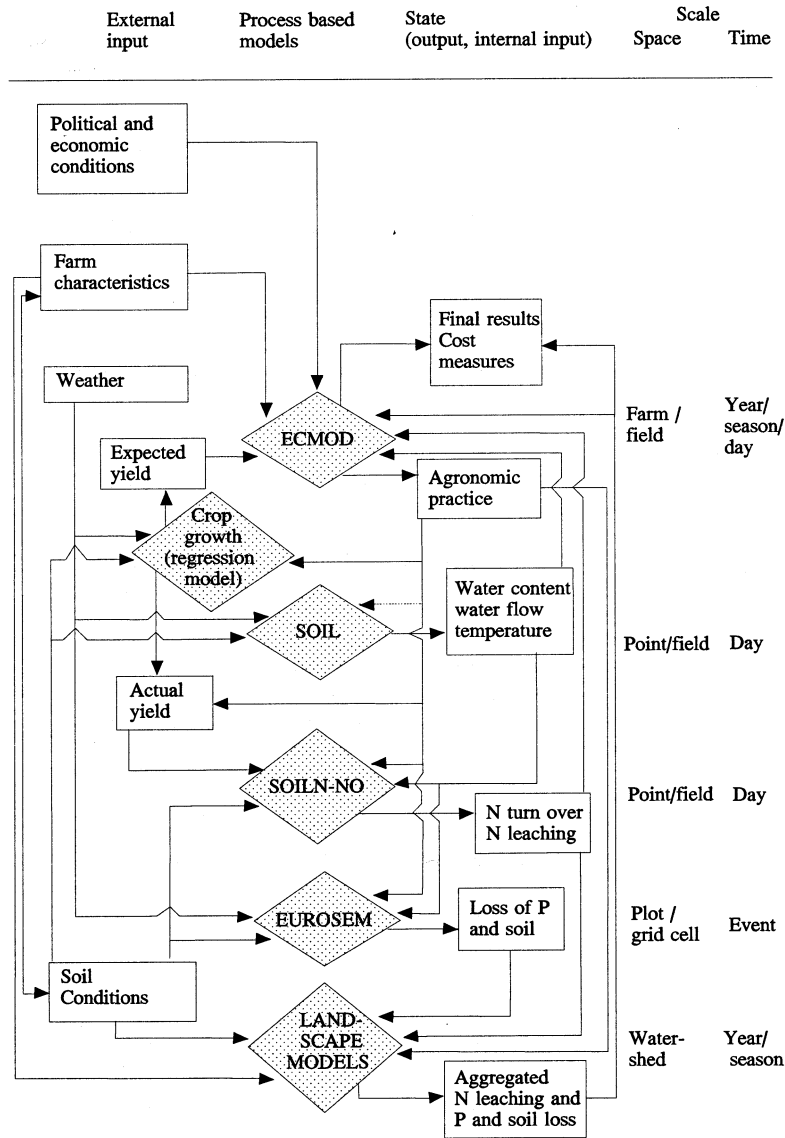| External input	Process based models	State (output, internal input)	Scale	
			Space	Time

Fig. 1. The structure of ECECMOD.

ones influencing emissions the most. These are the setup of machinery, choice of crops and crop rotation, fertilizing levels, manure practices (both storing and spreading), soil tillage, and sowing dates. The optimizing procedures are mainly non-linear and based on expectations where relevant. The model also calculates economic parameters to be used when estimating the cost-efficiency of different strategies.

SOIL is a deterministic, one dimensional, layered hydrology model simulating water content, water movements and temperature driven by weather input and soil characteristics (Jansson, 1991; Botterweg, 1992). The information produced here is used both as driving data for modelling nutrient turnover (N) and erosion and for determining sowing date (simplified pre-runs made for use in ECMOD).

SOILN–NO is also a one-dimensional, layered deterministic model describing nitrogen turnover (Johnsson et al., 1987; Vold, 1997). It produces information about loss of N as a function of agronomic practice, plant growth, weather, and soil characteristics (soil type and agronomic history) expanded from point to field level assuming homogenous fields. The modelling of the microbial N-transformations has been found to respond adequately to various physical and chemical factors, and to various litter types (Vold et al., 1994; Vold, 1997). Parameterization of the plant N uptake function is based on regional agronomic experiments (yield and N uptake) and regional annual yield statistics. It is estimated as a set of non-linear functions with yield and available N as arguments with good fit (R^2 for single crops varied from 0.82 to 0.92; Vold et al., 1999). Pre-runs are undertaken to estimate the effect on N-mineralization of changed manure practices, catch crop use, etc. for use in ECMOD.

EUROSEM describes erosion as a function of agronomic practice, weather, soil characteristics and local topography. It is an episode-oriented, process-based model substantially diverging from the more dominant tradition of regression-based analyses (Botterweg, 1998; Morgan et al., 1998). It is used to produce estimates for soil losses as a function of soil characteristics, topography, agronomic practice, and weather conditions.

Landscape models. Finally, two systems or models for aggregating data from plot and/or field level to the level of watersheds are developed. The aggregation of costs and N leaching estimates is a fairly simple weighing based on the relative distribution of productions, soils, etc. in landscapes. For erosion, GRIDSEM (Leek, 1993) is used to estimate mass transport in landscapes, aggregating losses over whole watersheds as a function of estimated losses at each plot/grid cell (from EUROSEM), the distance from plot to surface waters, and topographic characteristics over this distance (Botterweg et al., 1988).

ECMOD is run for a set of representative model farms covering the variation in each catchment. The actual farms in the area are partitioned into groups defined by what is considered the most important variables in our case—e.g. type of production, farm size and amount of manure (total and per ha). For each of these groups a model farm is defined, generally based on the mean values for various parameters for the underlying real farms. Each model farm is divided into fields with representative soil characteristics. The landscape is divided into series of plots/grid cells homogeneous in soil type and slope. To be able to transfer information about agronomic practices from the analyses at the model farm level back to the landscape level, each plot is attached to a model farm field on the basis of soil properties and which partition of real farms it belongs to. The methodology chosen thus demands data about the location of each farm and extensive landscape information.

4.4. Partitioning and interaction — crop growth as an example

The way crop growth is modelled illustrates the manner in which different levels of ECECMOD interact. The function f in Eq. (2a) is developed in the following way:

$$Y = f_{ijkt}(N_{1t}, N_{2t}, N_{3t})*\Omega_{at}|P \tag{3}$$

where: Y denotes yield as dry matter; i denotes model farm field/type of soil; j denotes type of crop; k denotes climate zone; t denotes time (year or season); N_{1t} denotes nitrogen in mineral fertilizers applied at time t; N_{2t} denotes nitrogen from manure in mineral form (ammonia) applied at time t; N_{3t} denotes mineralized N from the organic components of the soil at time t; Ω_{at} denotes an operator covering the effects of different elements of agronomic practice except fertilizing; and P denotes phosphorus in fertilizers.

The production function is partitioned by soil, crop, climate zone and year, the latter to capture weather dependent variation between years. Further, it is structured so that mineral N is the only argument in the production function, while the influence of other elements on $f(\cdot)$, is taken care of by the operator Ω_{at}. The N component is divided into three parts, whereby mineral N from fertilizers and manure are elements of the x-vector in Eq. (2a) and mineralized N from the soil is an element of $g_{it}(z_{it})$. Other elements of the produc-

tion function of Eq. (2a) are either kept constant (e.g. incorporated into f) or they are taken into account by Ω_{at}.

The function f_{ijkt} is estimated on the basis of trial data for an agronomic practice using fall tillage and mineral fertilizers only. Changes in tillage practice, sowing date, use of cover crops, etc. are taken into account by Ω_{at} inducing changes in the parameters of f_{ijkt} relative to their estimated effects in trials. This illustrates that the structure is chosen also to facilitate the use of data from factorial trials in a more dynamic type of modelling.[3] As Eq. (3) is structured, changes in mineralization (N_3) due to the use of animal manure, catch crops etc. is captured in a way that also influences the optimal use of fertilizers in the form of N_1 or N_2. The level of N_3 is established on a more coarse scale than in the final N modelling—e.g. the average values for the whole 20-year period is used. The data is produced through pre-estimations by running SOILN–NO under different standardized catch crop regimes.

The crop growth module illustrates a major difference in needs between economics and the natural sciences. While the plant growing processes must be modelled following the actual weather, the farmer makes decisions mainly on expectations about the weather and subsequent crop growth. This distinction is taken care of by estimating annual production functions to be used in the natural science part of the modelling (f_{ijkt}) and an average function used to represent the expectations of the farmer (f_{ijk}). This demonstrates that modelling economic choices at a coarser scale than the N dynamics may often be the appropriate choice, representing no information loss compared to the real world situation. In some cases (as in the study of a split fertilizing regime) we allow the farmer to update f_{ijk} with information about weather development between the different applications to secure consistency.

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[3] It must also be emphasized that most of the data available was of this kind.

5. The gains of high resolution eco-eco modelling

To illustrate some of the gains of the type of analysis advocated here, we will turn to a selected group of results from a study undertaken for two catchments in southeastern Norway. A series of research objectives has been formulated focusing on the cost-effectiveness of input regulations versus regulating the agronomic practices. Since natural conditions and types of production vary substantially among farms and regions, it is of special interest to analyze gains and losses related to uniform versus differentiated policy measures.

5.1. The study sites

The analysis covers the Mørdre catchment and a subsection of the Auli catchment in the counties of Akershus and Vestfold, respectively. The amount of arable land in the Mørdre catchment is approximately 450 ha and in Auli 2.600 ha. Both areas are dominated by grain production, while there is some animal production especially in the Auli area. The distribution of soil types is very different in the two catchments (Figs. 2 and 3).

While clayey and sandy soils dominate in Auli, silty soils dominate in Mørdre. Auli has a higher mean annual temperature (6.3°C compared to 4.2°C) and precipitation (1009 mm compared to 809 mm). In both areas, grain is the most important crop. However, Auli has a much larger proportion of animal husbandry. The amount of manure N per ha is on average ca. 75 kg in Auli and 18 kg in Mørdre.

5.2. Strategies for reducing nitrogen emissions.

Various types of regulations directed either towards inputs (x, b) or the farming practice (q) are available to the authorities. Analyzing this we distinguish between 'physical' measures which are the changes farmers undertake in the way they farm, and 'policy' measures which are the instruments the authorities use to motivate or compel farmers to change practices. According to the dynamics of the plant-soil system (z) in grain producing areas like ours, we grouped physical measures into four categories:

- reduced total nutrient input (lower 'intensity', better manure practices, etc.);
- improved adjustment of nutrient input (especially of N) to yearly growth condition (split fertilizing, etc.);
- changed tillage practices and/or continuous plant cover (catch crops) etc. to reduce erosion and enlarge the plant N uptake period; and
- increased rates of N immobilization in the soil in periods where crops are not grown (incorporation of catch crops, straw, etc.).

Policy measures to accomplish the above changes may be a tax on mineral N fertilizers (fertilizer intensity/manure handling), seasonal quota system (split fertilizing), mandatory or subsidized practices (changed tillage practices and catch crops). The interactions covered by ECEC-MOD make it possible to account for a wide range of both direct and indirect effects in the system, related to changes in agronomic practices and losses of nutrients. Many of these effects could hardly have been studied through a more aggregate procedure, and in some instances the effect of preserving high resolution turns out to be profound. Through the following presentation of results, we will try to illuminate the role of production type, choice of crops, choice of technology, soil characteristics, soil dynamics and topography.

5.3. Comparing different policy measures

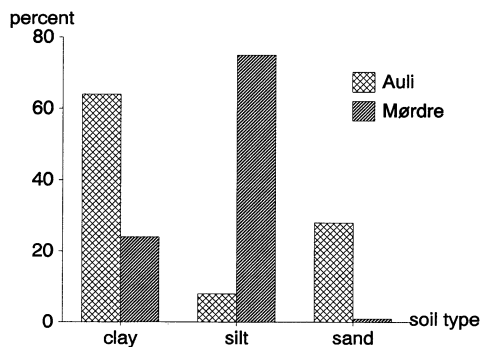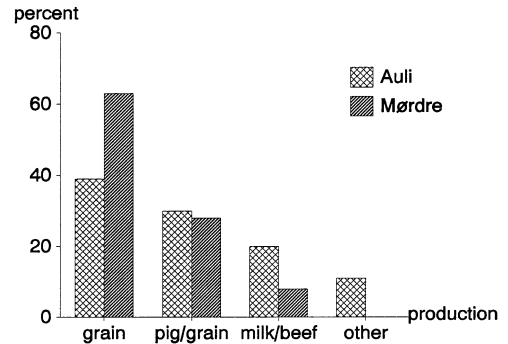To compare policies, a set of scenarios was constructed. To validate the modelling system, a

Fig. 3. Distribution of production types in Auli and Mørdre, farms classified by dominant production.

scenario covering the actual policy conditions in 1992 was run. Compared with available data, the results were very encouraging both concerning chosen agronomic practices and leaching levels. The fit for yearly and average yields, fertilizer levels and choice of crops was very good, with deviations of only a few percent. The level of spring tillage was somewhat over-estimated, whereas the opposite was the case regarding manure storing capacities (for more specific documentation see Vatn et al., 1996). As to leaching and erosion, we encountered some problems with acquiring spatially comparable observational data. Data both from smaller parts of the catchments and lysimeter experiments have been utilized. Except for the lysimeter trials, direct comparisons are difficult to do. For these trials model fit was in general found to be very good, except for abnormally high fertilizer level treatments (Vold, 1997). Concerning erosion and P losses comparisons with field observations was utilized, showing deviations normally within a range less than ± 20–30%.[4] Estimated level of P losses in Auli were the ones deviating the most. For more specific documentation see Botterweg (1998) and Vatn et al. (1996).

Next, a Base scenario was run. Again the reference was the policy conditions in 1992, but existing environmental regulations were ignored to formulate the best basis for comparing various

Fig. 2. Distribution of soil types in Auli and Mørdre.

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[4] When evaluating this, one should remember the difficulties in finding strictly comparable results and the high variability in erosion processes.

Table 1
The effect of various policy measures to reduce emissions[a]

Scenario	N leaching mean kg/ha (%)[b]	ΔN air[c] mean kg/ha (%)[b]	ΔP loss mean kg/ha (%)[b]	ΔS loss[d] mean kg/ha (%)[b]	Costs farmer NOK[e]/ha	Soc.abatem. costs A NOK[e]/ha	Soc.abatem. costs B NOK[e]/kg N[f]
Base							
Auli	40.4	6.5	4.97	1180			
Mørdre	29.4	1.9	0.56	281			
Tax100							
Auli	34.5 (15)	4.0 (38)	4.88 (2)	1171 (1)	570	77	13
Mørdre	25.0 (15)	1.1 (42)	0.56 (0)	281 (0)	610	51	12
Catch50							
Auli	29.6 (27)	6.5 (0)	2.81 (43)	660 (44)	199	199	18
Mørdre	21.5 (27)	1.9 (0)	0.56 (0)	283 (−1)	294	294	37
Soil-sub							
Auli	40.0 (1)	6.5 (0)	2.25 (55)	505 (57)	−370	138	370
Mørdre	29.5 (0)	1.9 (0)	0.55 (2)	2.77 (1)	−510	30	[g]

[a] Estimated costs and changes in emissions as compared with the Base scenario.
[b] Percent reduction from Base.
[c] Loss of ammonia-N in connection with manure spreading.
[d] Soil loss.
[e] NOK = Norwegian kroner.
[f] Costs per Kg reduced N leaching.
[g] Irrelevant since N leaching is increasing

policy options. We will start by comparing the results from the following scenarios:

- Tax100: 100% tax on N-fertilizers;
- Catch50: 50% arable land requirement on catch crops or grass cover; and
- Soil-sub: A per hectare subsidy for spring/no tillage (1992 level: 1000 NOK per hectare).

While the tax has to be uniform for the entire economic–political area (in our case the whole of Norway) the other measures can be differentiated between regions if desirable.

The results (including the Base scenario) are given in Table 1. The estimates are produced on the basis of weather data for each area for the period 1973–1992. The table shows a fairly broad array of environmental indicators, making it possible to analyze trade-offs involved. Estimates are given for N leaching, NH₃ losses to air, P losses and losses of soil. A set of cost-efficiency measures is also presented. 'Farmers' costs' shows average reductions in profits per ha as measured against the Base scenario. Two average social cost-efficiency measures (defined as 'Farmers' costs' exclusive environmental taxes/subsidies) are

presented. Since there are several types of emissions with no obvious common yardstick, a per ha measure is given ('social abatement costs A'). In the case of 'social abatement costs B', all costs are carried by the N-leaching—the dominant form of N emission. Costs related to policy administration are not included. This will be addressed later.

Starting with the Base scenario, we see that the estimated agronomic practices and losses differ between the areas. The higher level of leaching in Auli is mainly due to the level of animal manure and the rather large proportion of sandy soils, which are most prone to leaching. The low soil loss in Mørdre is explained by differences in slope characteristics, as well as the dominance of silty soils. These soils are generally tilled in spring since that produces the highest yields. Spring tillage reduces erosion.

Turning to the other scenarios, we observe a rather complex picture of changes. As one would assume, Tax100 mainly influences N leaching and ammonia losses while Soil-sub influences P and soil losses mostly. The effects vary substantially between the catchments, though. The low effects

of Soil-sub in Mørdre is mainly explained by the mechanisms keeping losses in the Base scenario down.

Catch50 reduces both N-leaching, P and soil loss. It could thus seem to be a good alternative in areas where all the measured types of losses are of importance. The effect of Catch50 on N-leaching is quite substantial, illustrating that losses can be reduced considerably if one is able to continue plant uptake for a longer period of the year. Reductions in inputs are thus not the only interesting options for reducing N losses. For the most part, nitrogen taken up by catch crops enters a pool of stable organic compounds after ploughing. This pool has a decay rate (first order decay) of about 0.01 per year (Vatn et al., 1996, pp. 55–67). This implies that the system is able to accumulate N in this pool for several decades before returns (as humus-derived mineral N) becomes a significant contributor to the mineral N supply. A separate model study showed that the catch cropping will reduce the mineral N supply to the cash crop for a period of some 30–40 years. This actually results in increased optimal N fertilizer $(N_1 + N_2)$ levels. After this period the soil starts 'paying back' and the level of fertilizers can then be reduced (Vold et al., 1995).

Looking at the costs, the tax entails the lowest social abatement costs if we only consider N-leaching. The reductions in P and soil losses following the two other measures, may still be considered large enough to outweigh the higher per hectare costs, especially in the case of catch crops. We observe that farmers' costs and social costs are identical in the case of Catch50, while in the tax scenario, the tax counts for about 90% of farmers' costs. The observed income gain (negative costs) for the farmer in the case of Soil-sub, indicates that the subsidy was set higher than necessary to motivate farmers to reduce fall tillage. The table illustrates that the distributional effects can be substantial depending on the type of policy measures used (taxes, requirements or subsidies).

Catch crops are less effective in Mørdre than in Auli. The social abatement costs are 50–100% higher than those of the latter. Several factors cause this. The lower initial level of leaching plays a role. The most significant mechanisms, however, is lower catch crop yields in Mørdre due to climatic factors, and the changes in tillage practices following the use of such crops. The silty soils of Mørdre will, in the absence of catch crops, be tilled in spring. Using catch crops implies a switch towards fall tillage, causing decreased yields counteracting the positive effect of catch crops on leaching. The yield loss also influences the income from production, resulting in higher per ha costs, as shown in Table 1.

Table 1 covers only average costs. Calculations show that while the marginal costs are fairly constant for catch crops over large intervals, they increase almost linearly with increased tax levels. At the margin, catch crops seem to compete with an N-tax under Auli conditions at tax levels around 75%, even if we only consider N leaching. In the case of a tax, marginal costs increase primarily because the plant production functions are concave. For catch crops, the marginal costs shift only dependent on which soil types are involved.

As mentioned earlier, administration costs are not included in Table 1. The costs of administering the tax system is considered negligible. Presently, a low tax exists. Since there are few wholesalers in Norway, the administration costs amount to just a few man months per year. The costs of a catch crop requirement will be higher. Estimates made (Vatn et al., 1996) show that administration costs will increase social costs by approximately 5%.

5.4. Variation between productions

Production type is an important source of variability that Table 1 does not inform us about. Table 2 shows the effects of a tax and a catch crop requirement for a selected group of model farms in Auli. Here we only focus on N-leaching.

MF1 is one of three model farms representing milk production in Auli. MF4 represents producers of pork/grain with fairly low manure levels, while MF7 covers the smallest grain farms.

In the Base scenario these farms have an average leaching varying between 37 and 42 kg N/ha. MF1 has the lowest and MF4 the highest losses. While the tax has the largest effect on the milk producing model farm, the effect of a 50% catch crops/grass land requirement is negligible here, since it already has nearly 50% of its acreage in grass production. In the case of farms with grain as the dominant crop, the situation is the opposite.

We observe a much larger reduction in the use of fertilizer N in grass than in grain production— both absolutely and relatively. While the average effect of a 100% N tax is approximately 27% (40 kg/ha) for grass, the figures for grain are 10% (11 kg/ha). The difference is primarily due to substitution between fertilizer N and clover in production of roughage. We observe positive effects following changes in the manuring practices, too. In the case of MF1, Tax100 induces increased storage capacity up till a full year's storage. This eliminates losses related to fall spreading. The greatest effect of this change, however, is due to less compaction damages, hence improved conditions for plant growth.

Finally, we observe that social abatement costs vary rather substantially across the model farms in the case of a 100% tax, while they are much more uniform for the catch crop regime. The private costs are hardest to bear for the specialized grain farm since per ha incomes are lowest in this case.

5.5. High sensitivity for changes in the plant–soil system

5.5.1. The effect of different tillage practices

The results are, as already observed, heavily dependent upon a series of interacting agronomic factors. One aspect of plant–soil interaction, the effect of tillage practice on N dynamics, caught our interest. Analyzing this more in detail we observed:

- Postponing fall tillage by about 5 weeks from the end of August to early October gives, according to ECECMOD, a reduction in leaching approximately at the level of a 100% N tax in grain dominated areas like Auli and Mørdre. This is entirely an effect of N-uptake by weeds and germinating shed grains and its subsequent influence on the soil micro flora/fauna. The estimates show higher effects in Auli than in Mørdre. This difference relates mostly to the fact that 50% of the area in Mørdre is tilled in spring also in the Base scenario and is thus not influenced by this change. One should take into account that delayed fall tillage induces no extra costs, except the risk that some areas will not be tilled in time in years with rainy autumns and/or early frost.

- Increased spring tillage (mandatory or following from a subsidy scheme) turned out, as we have already seen, to give very small effects on N leaching. This was a surprise. Even though the mass of weeds/shed grain is increased by

Table 2
Changes in N-leaching (Δ N) and costs as compared with the Base scenario[a]

Model farm[b]	Tax100				Catch50			
	Δ N kg/ha	Costs farmer		Soc. abatem. costs NOK/kg ΔN	Δ N kg/ha	Costs farmer		Soc. abatem. costs NOK/kg ΔN
		NOK/ha	NOK/kg ΔN			NOK/ha	NOK/kg ΔN	
MF1	−10.5	610	59	18	−1.3	20	16	16
MF4	−3.7	510	139	46	−18.3	300	16	16
MF7	−5.1	650	129	10	−15.9	300	19	19

[a] Some model farm estimates, Auli.
[b] MF1, milk/beef; MF4, pork/grain; MF7, grain.

expanding the growth period for some extra weeks compared to late fall tillage, we observe that the effect of extra plant uptake is counteracted by a decline in the subsequent main crop yield on sandy and clayey soils the following season.

To comprehend the sensitivity of the system, recognize that the average leaching in the Base scenario is about 20–25% of a total plant uptake of about 150 kg N per ha and year. A change in this uptake of about 3% will, other things being equal, create a potential change in leaching at the level induced by a 100% N tax. On clayey soils like the ones in Auli, yield losses following a transition from fall to spring tillage are at the average level of about 4%, explaining much of the above results.

As mentioned, the modelled effect of delayed autumn tillage on nitrate leaching is attributable to N-assimilation by weeds and germinating shed grains throughout the autumn. This has not been confirmed by direct observations of nitrate leaching in field experiments, however. The model assumes no extra mineralization of soil organic N by tillage, despite the widespread notion that plowing has such effects. However, this is an assertion for which there is very little evidence. Our modelling has pinpointed that nitrate leaching is sensitive to such possible direct effects of plowing and to N-assimilation by weeds and germinating shed grains. This puts new questions on the agenda for natural scientists about the specific mechanisms invoked by ploughing, and on the N-assimilation by weeds.

5.5.2. Split fertilization

The assumed positive effect of split fertilization is related to better adjustment of the fertilizer level to the actual growing conditions each year. A more complete analysis of the issue is given in Romstad and Rørstad (1995). Here we will emphasize the following:

- An effect of split fertilizing is lower fertilizer levels in 'bad' years, but also increased levels in 'good' years. To create an environmentally interesting scheme, the total level of N must be reduced even for split fertilizing.

- A system combining reduced and split fertilization can be obtained by a scheme of season-specific tradeable N quotas. Except for sandy soils, the results obtained from such a scheme are not very different from those obtained using a uniform N-tax giving the same reductions in the overall fertilizer levels. The costs for farmers are considerably lower (no taxes), while the administration costs are expected to be higher.

The difference between sandy soils and other soils was as expected. The results for clay and silt were still surprising to us since yields also vary substantially between years in these cases. Interactions between hydrology and the biological sink mechanisms explain much of the observed effects. Further, the results depend strongly on the precision of the crop growth modelling. To exemplify: in our analyses, average yield is reduced by approximately 2% due to the extra trafficking following a second round N application. As we have already seen, this is of a magnitude influencing leaching rather substantially. The positive effect of increased fertilizing precision obtained by split fertilizing is thus more or less nullified by this seemingly minor effect on the yield for both clayey and silty soils.

6. Conclusion

The results obtained demonstrate the necessity of interdisciplinary cooperation and a formalized integration between economic and natural scientific models when designing policy measures to reduce agricultural pollution. The fact that pollution consists of several components and is controlled by a plethora of mechanisms, warrants a complex dynamic modelling thus ensuring that the mechanisms and pollutants involved are adequately represented. The inclusion of the most relevant pollution components also ensures an explicit treatment of the potential conflicts between aims. This is of importance when studying pollution from agriculture, as the principles discussed here are equally relevant for studies in other fields with high levels of complexity.

Adequate understanding of the basis for farmers' choices, both from an agronomic and social science point of view, is important. We have used a profit maximization rule in our analysis, believing that it is an adequate basis for 'comparing changes' in adaptation under different policy scenarios. We admit that it does not offer a complete description of agents' behavior. Still, progress is obtained by undertaking a detailed description of the setting and constraints under which choices are made. Farmers respond differently to political measures, depending on their production system, warranting a careful economic analysis of such choices at a reasonably high resolution.

The interdisciplinary discourse is necessary to identify and nurture new/more relevant research within each discipline. The division of science into rather narrow subfields has been necessary to increase the depth of the analysis. As the only strategy, however, it prevents the understanding of inter-linkages and dynamics at higher system levels. Practical relevance may be lost. Interdisciplinary research may serve us greatly by just making the disciplines relate better to higher respective lower level entities.

ECECMOD is a structure that can be developed in different directions. First of all other pollution problems like pesticide use can be integrated, a process we have started on. Such an enlargement has proven to be relatively easy to undertake without having to make major changes in the system. This is both an effect of the way ECECMOD is structured, its process orientation, and the level of resolution chosen.

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