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The DYNAMO Project: An Introduction

Dynamic Models to Predict and Scale Up the Impact of Environmental Change on Biogeochemical Cycling

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Abstract

European concerns about the consequences of anthropogenic impacts on environmental quality have led to the establishment of numerous ecosystem-scale manipulation experiments. This site-specific experimentation has also led to the development of various dynamic modelling approaches through which the consequence of impacts over time can be assessed. Similarly, throughout Europe, there has been extensive collection of regional data on "environmental capital" resulting in the production of wide area mapping of environmental quality (soils, land use etc). The aim of the DYNAMO was to integrate data and models, specifically; (1) to enhance the existing process based models to evaluate the impacts of multiple drivers of environmental change; (2) the evaluate these models at intensively studied (and manipulated) catchments and stands; (3) to scale up in time from observations collected over several years to predict the long term impacts over decades, and (4) to scale up in space from the individual site level to regional, National, and European scale. The project aims to develop and enhance regional modelling approaches so that European scale impacts of acidic deposition, land use (forestry practices) and global change can be determined without compromising process level understanding of ecosystem function. The DYNAMO project contributes to the EU TERI (Terrestrial Ecosystems Research Initiative) framework of the Environment and Climate Programme of the European Commission.

Introduction

The development of predictive mathematical models is fundamental to understanding of how systems function. They provide necessary feedback into the planning of future research. They also allow for the testing of scientific hypotheses, and have a pivotal role in the synthesis of the requirements of policy makers and resource managers with those of the research community.

Many International and National agencies have collected regional data in response to statutory monitoring requirements, driven primarily by European legislation (Stanners and Bourdeau, 1995). Although environmental pressures are global in context, even at an European scale much of the information that is available is often inadequate to provide the basis for rigorous assessment and accurate analysis of the state of the environment and how it has responded to anthropogenic influences. Dynamic ecosystem models can assist in the prioritisation and development of monitoring networks by identifying key parameter interactions, and highlighting areas of uncertainty. Their dominant role, however, is in the analysis of the impact of different scenarios of anthropogenically driven environmental change.

There is a requirement for such predictive models to be amenable to implementation at multiple sites or at a regional basis to address the impacts of global change responses, and for the development of a robust and sustainable International Environment Policy. In such situations, model complexity must be maintained at a level consistent with process knowledge while recognising simultaneously, that management needs often require model applications in situations where data are sparse or incomplete. The use of spatial mapping technologies and data-manipulation frameworks such as Geographic Information Systems (GIS) combined with advances in computer technology allow for the development of both temporal and spatial representations of impacts to be mapped at the European scale. Such spatial representations form a strong basis for policy assessment and development, such as the determination of critical loads (Posch *et al.*,1997).

The focus of the DYNAMO programme of research is on biogeochemical cycling in terrestrial ecosystems, and the effects on soil, surface and ground water quality in catchments. Integrated European process-based research programmes, have created substantial databases and the utilisation of such data in modelling studies maximises the potential value of this research. DYNAMO aims to integrate these data with dynamic models within a spatial framework, extrapolating understanding of systems at the individual stand and site level to the larger units of ecotype, landscape, region and continent.

OBJECTIVES OF DYNAMO PROJECT:

- Enhance current model structures to evaluate the synergistic effects of global environmental change, and develop appropriate modelling approaches for regionalisation;
- Apply and evaluate these dynamic biogeochemical models at intensively-studied (and manipulated) catchments/large forest stands;
- Use these models to scale up in space from the catchment/stand to the regional and continental scale;
- Use these models to scale up in time from observations over several years to predict future impacts over decades under scenarios of global change, acid deposition and land-use (Fig. 1).

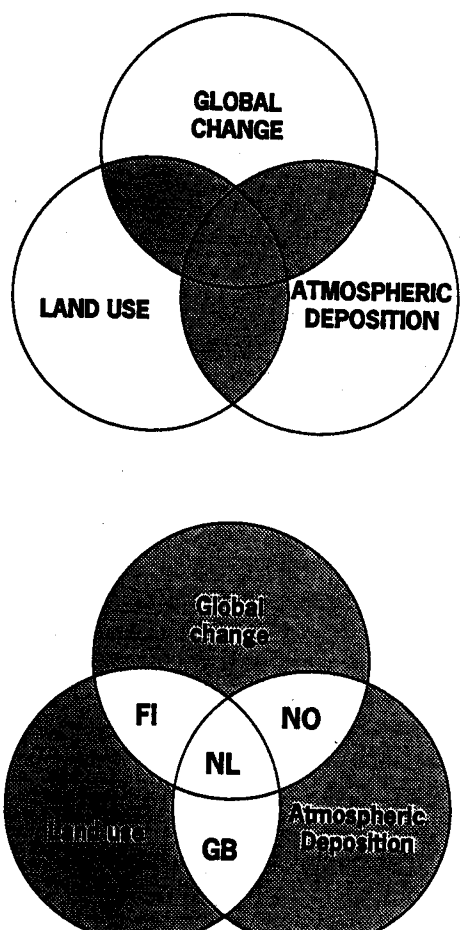

Figure 1: *Environmental driving variables and principal research groups involved in the DYNAMO project. GB – Macaulay Land Use Research Institute and the Institute of Hydrology; NO – Norwegian Institute for Water Research; NL – SC-DLO Winand Staring Center; FI – Finnish Environment Institute.*

The DYNAMO project contributes the EU TERI (Terrestrial Ecosystems Research Initiative) framework (Menaut and Struwe, 1995) which is part of the Environment and Climate Programme of the European Commission, in the Fourth Framework Programme. Its aims are to improve the ability of ecosystem science to predict the consequences and interactive effects of changes in land use, climate and atmospheric composition and physics on three main areas of primary concern for European terrestrial ecosystems:

- carbon, nutrients and water pools and fluxes, and related trace gas emissions;
- biodiversity in terms of its significance for ecosystem functioning;
- future landscape patterning constrained by changes in the above;

(Lawton *et al.*, 1998).

Methodology

MODEL DEVELOPMENT

Three main objectives were defined for the modelling activity undertaken in the DYNAMO project. These were linked to the development of a range of approaches capable of simulating ecosystem/catchment scale responses to environmental drivers at a range of spatial scales. These were:

1. The development of models capable of extrapolating ecosystem/catchment responses to enhanced nitrogen deposition against a background of declining sulphur deposition (RECOVERY models);
2. The development of models capable of predicting ecosystem responses to interactions of climate change and enhanced nitrogen deposition (C/N models);
3. Extrapolate site/stand models to the regional, national, and European scales (REGIONAL models).

The first two objectives for enhancing model structures are compatible with the development of approaches to elucidate potential synergistic effects of the main environmental drivers of change; however the main scientific challenge within the DYNAMO project was to extrapolate from the site to European scale.

Regionalisation techniques are necessary to provide meaningful information for evaluating environmental consequences of alternative control strategies of emissions of acidifying air pollutants and greenhouse gases. These methods are based on new kinds of mathematical constructs that are no longer calibrated just for individual sites, field plots, stands or catchments, but can make use of spatial information.

Model complexity is strongly determined by the degree of spatial and temporal resolution in available data, and appropriate process representation. Simple empirical models need relatively few input data and they generally do not allow quantification of impacts, since the empirical relationships are derived from present-day conditions. Predicting responses by site specific application of complex process-oriented models to detailed records (in particular, those responses determined from large scale ecosystem manipulation experimentation) represent the best formulations of the functioning of systems. Indeed, in an ideal world where data availability and quality were not limiting, the application of highly mechanistic modelling approaches in a regional context would be the ultimate goal. However, there must be a trade off made between model complexity and data resolution, such that scientifically robust determinations of regional responses can be determined.

As a compromise, simple process-oriented models are presently the best available starting point for assessing the impacts of a changing atmospheric composition on soils and surface waters. There are numerous process-based hydrochemical models such as MAGIC (Model of Acidification of Groundwaters in Catchments) (Cosby *et al.*, 1985a, 1985b), MAGIC-WAND (MAGIC-With Aggregated Nitrogen Dynamics) (Ferrier *et al.*, 1995; Jenkins *et al.*, 1996), MERLIN (Model of Ecosystem Retention and Loss of Inorganic Nitrogen) (Cosby *et al.*, 1997), SMART/SMART 2 (Simulation Model for Acidification's Regional Trends) (de Vries *et al.*, 1989, Posch *et al.*, 1993; Kros *et al.*, 1995), RESAM (Regional Soil Acidification Model) (de Vries 1995), NUCSAM (Nutrient Cycling and Soil Acidification Model) (Groenenberg *et al.*, 1995). To achieve regionalisation, either site level deterministic models must be simplified according to sensitivity analysis or different models should be developed to operate at different scales. Indeed, comparison between models of different complexities at the same site allows for the adaptation of the simpler modelling approaches which enhances the mechanistic and quantitative nature of the model output (Mol-Dykstra *et al.*, 1998). It is important that the selection of the approach employed is linked to the intended use of the model outputs (e.g. scientific hypothesis generation, or policy evaluation).

Acidification models represent a logical starting point also for the analysis of the combined effects of changes in climatic conditions, land use and atmospheric deposition. These models already include descriptions of many of the key processes affected by changes in temperature and hydrological characteristics (e.g. weathering, cation exchange, nutrient uptake by different ecotypes). However, further extensions of the models require the improvement of the physical description of the water balance, and descriptions of organic matter dynamics as a function of temperature, CO_2 and soil water content (Groenenburg *et al.*, 1998, van der Salm *et al.*, 1998).

An example of the process of regional model development (objective (3)) which is also compatible with objectives (1) and (2) can be highlighted by considering the evolution of the MAGIC suite of modelling approaches (Fig. 2).

MAGIC is a process-oriented, intermediate-complexity dynamic model for the long-term reconstruction and future prediction of soil and surface-water acidification at the catchment scale (Cosby *et al.*, 1985 a,b). MAGIC uses a lumped parameter approach to (1) aggregate the complex chemical and biological processes active at the catchment scale into a few readily described processes and (2) represent the spatial heterogeneity of soil properties throughout the catchment. The model comprised a simplified version of nitrogen responses involving a net catchment retention to calibrate simulated nitrogen against observed nitrogen in streamwater. This net retention is the integrated result of all the fluxes and processes of the terrestrial nitrogen cycle.

The MAGIC model has been applied to catchments in the USA (Cosby *et al.*, 1985b), Scandinavia (Wright and Hauhs, 1991) and the UK (Jenkins *et al.*, 1997) and has proved to be a powerful tool for assessing the likely future consequences of changing acidic deposition (in particular sulphur deposition) and land use on soil and surface-water acidification status. The generic nature of this lumped approach combined with intermediate complexity, alows for a high degree of transferability to different catchments, and hence represents a useful tool for regional assessments (objective 3) (Helliwell *et al.*, 1998 a,b; Evans *et al.*, 1998; Sefton and Jenkins, 1998; Collins and Jenkins; Cosby and Wright, 1998)

MAGIC-WAND represents an extension to the MAGIC model to incorporate the major fluxes and changes in fluxes of nitrogen through time. The key element of the model is that the nitrogen dynamics are fully coupled to the existing sulphur driven model (objective 1) (Ferrier *et al.*, 1995; Jenkins *et al.*, 1996). The model structure is designed to enable assessment of future soil and water response to a specified future scenario of nitrogen deposition. Assumptions relating to the uptake capabilities of the vegetation and future land use change can be assessed, and regional responses evaluated through multiple site calibration (objective 3).

The model MERLIN considers linked biotic and abiotic processes affecting the cycling and storage of nitrogen in terrestrial ecosystems and losses to the aquatic environment (Cosby *et al.*, 1997; Emmett *et al.*, 1997). The model is aggregated in space and time and contains compartments intended to be observable and/or interpretable at the plot or catchment scale. Nitrogen fluxes are controlled by carbon productivity, the C:N ratios of the organic compartments and inorganic nitrogen in the soil solution. The model is, therefore, a more complex mechanistic representation of the dynamic of nitrogen and carbon in terrestrial ecosystems, and provides an excellent evaluation tool for the interaction of atmospheric nitrogen deposition with climate change (objective 2) (Wright *et al.*, 1998a). The main obstacle is that such detailed mechanistic representation is inconsistent with data availability at the larger regional scale.

The development of a further model (MAGIC 7) aims to provide the balance between complexity and data resolution (Wright *et al.*, 1998b). All major nitrogen fluxes are incorporated, with a control on soil immobilization being based on the rate of change of C:N ratios within the soil. A threshold value, currently derived from regional and European scale observations (Gundersen, 1998), controls the rate and timing of potential losses of nitrogen from the terrestrial compartment. As the model is fully coupled to the existing sulphur dynamics and acid-base chemistry of the original MAGIC model, this offers an exciting possibility of enhancing process-based representation, whilst maintaining the potential for regionalisation (objectives 1,2 and 3) (Wright *et al.*, 1998b).

As with the MAGIC model framework, different levels of detail can be distinguished in the soil acidification models that have been developed at the SC-DLO Winand Staring Centre, i.e. SMART/SMART 2 (de Vries *et al.*, 1989; Kros *et al.*, 1995), RESAM (de Vries *et al.*, 1994), and NUCSAM (Groenenberg *et al.*, 1995; Kros *et al.*, 1996) (Fig. 2). NUCSAM has been coupled with FORGRO (Forest Growth Model; Mohren *et al.*, 1991) to simulate the response to acidic deposition of both the soil and the tree, in terms of growth and nutrient dynamics. Indeed, current model development has focused on the dynamics of soil organic matter turnover and the prediction of the long-term impacts of changes in N deposition on N accumulation and N leaching from forest soils (Groenenberg *et al.*, 1998). The aim of the models and the scale of application are crucial factors in selecting the level of detail in both the model formulation and associated input data. A less detailed objective, and decreasing data availability at a larger spatial scale, justify the development of a simpler modelling approach (Tables 1 and 2).

APPLICATION AND VALIDATION OF MODEL BEHAVIOUR

For calibration and enhancement of models at different scales, sites with the best, most extensive European data on effects at the stand/catchment level, and at which environmental-driving factors (acid deposition, global change, land-use) have changed either 'naturally' or by large-scale manipulation experiments, and at which the ecosystem response has been measured as the change has occurred have been selected (Table 3). Furthermore, these sites are located in areas for which there are extensive regional data such that the site response can be scaled up to the regional/landscape/National level (Fig. 2). These data include regional or national surveys of driving variables (e.g. acid deposition, land-use change, climatic variables (Evans *et al.*, 1998) and of response variables e.g. stream and lake chemistry (Skjelkvale, 1998) forest growth (Gundersen *et al.*, 1998), and soil (Helliwell *et al.*, 1998 b).

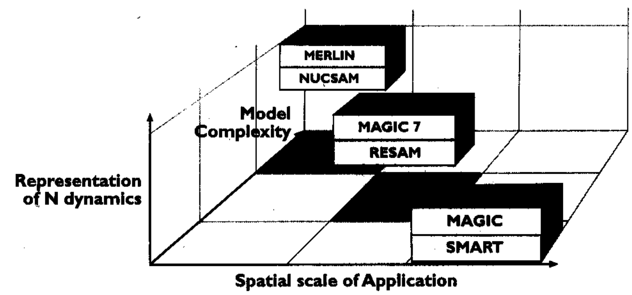

Fig. 2. *Examples of the different dynamic models used within the DYNAMO project in terms of their complexity, representation of N dynamics, and their spatial scales of application.*

Research networks of large-scale manipulation experiments were initiated in the 1980s under the auspices of the Commission of European Communities. The NITREX (Nitrogen Saturation Experiments) experimental network comprised 10 experiments at 8 sites in 7 countries, with research focussing on the factors and processes affecting nitrogen 'saturation' ie. the situation in which the supply of inorganic nitrogen exceeds the nutritional demand of plants and microbes, which is defined, operationally, at the ecosystem level by increased leaching of inorganic nitrogen below the rooting zone (Aber *et al.*, 1989). Such manipulation experiments provide an ideal opportunity for evaluating model formulation and performance in response to enhanced atmospheric deposition of nitrogen (Wright *et al.*, 1998 a,b; Mol-Dykstra *et al.*, 1998; van der Salm *et al.*, 1998; Kjonaas and Wright, 1998; Tietema *et al.*, 1998). Similarly, the CLIMEX project (Climate Change Experiment), provides a unique data set to evaluate the interactive effects of enhanced CO_2 and temperature (Wright *et al.*, 1998b) (Fig. 3; Table 3). Other National networks are targeted towards specific goals, ie the UK Acid Waters Monitoring Network (Helliwell *et al.*, 1998a),

Table 1. Characteristics of dynamic soil acidification models

Name	Complexity	Soil Layering	Time Step	Application Scale
SMART	Simple	One-layer	One year	European
RESAM	Intermediate	Multi-layer	One year	National
NUCSAM	Complex	Multi-layer	One day	Site specific

Table 2: Process descriptions of the soil acidification models

PROCESS	SMART	RESAM	NUCSAM
Water flow	Annual precipitation excess	Annual flow varying with depth	Hydrological sub-model
Nutrient cycling	Not included	Annual basis	Daily basis
N transformation	Simple linear	First order kinetics	First order kinetics (temp. dependent)
Weathering and exchange	Equilibrium reactions	First order equilibrium	First order equilibrium (temp. dependent)
Complexation reactions	Not included	Not included	Equilibrium reactions
Heat flow	Not included	Not included	Heat transport sub-model

Table 3. The sites and regional data used in the DYNAMO project

	Site	Experiment / focus	Regional data
Finland	Kangasvaara	Forest management	–national lake surveys 1987, 1995
Norway	Risdalsheia (RAIN, CLIMEX)	Roofed catchment with clean rain and climate change (CO_2 and temp.)	–national lake surveys 1974, 1986, 1995 –soil and forest inventories
Netherlands	Speuld (NITREX)	Roofed stand with clean rain	–national survey of forest stands, 1990, 1995 –Veluwe regional water quality database 1995
UK	Aber (NITREX);	N additions, afforestation, Anthropogenic deposition	–survey of forests, Wales –survey of lakes and streams, Wales 1984, 1995 –survey of lakes in SW Scotland 1979, 1988, 1993, 1994, 1996, 1997, 1998 Critical load for freshwater sites (>1,200) –Acid Water Monitoring Network sites (22)

or the impact of forest management practices on soil and water quality (Kamari *et al.,* 1998).

MODELLING REGIONAL RESPONSES

Two major approaches have been adopted in regional modelling studies, namely; Monte-Carlo analysis and multiple site application; the former involves the stochastic modelling of observed distributions of measurements, whilst the latter involves the modelling of numerous soil or catchment systems as individual entities. Monte-Carlo analysis is able to simulate the response of systems over time, however, it cannot distribute any predicted changes in space.

Cosby *et al.* (1989) and Hornberger *et al.* (1989) applied Monte Carlo simulation techniques to select joint distributions of input parameters for MAGIC for an application to Southern Norway. Such an approach enables the incorporation of variability into the model to account for the inherent heterogeneity in the physical and chemical characteristics across a region and uncertainty in the measurement of physical and chemical parameters. This provides an excellent assessment tool in situations where regional data availability or quality are lacking, but where mapped

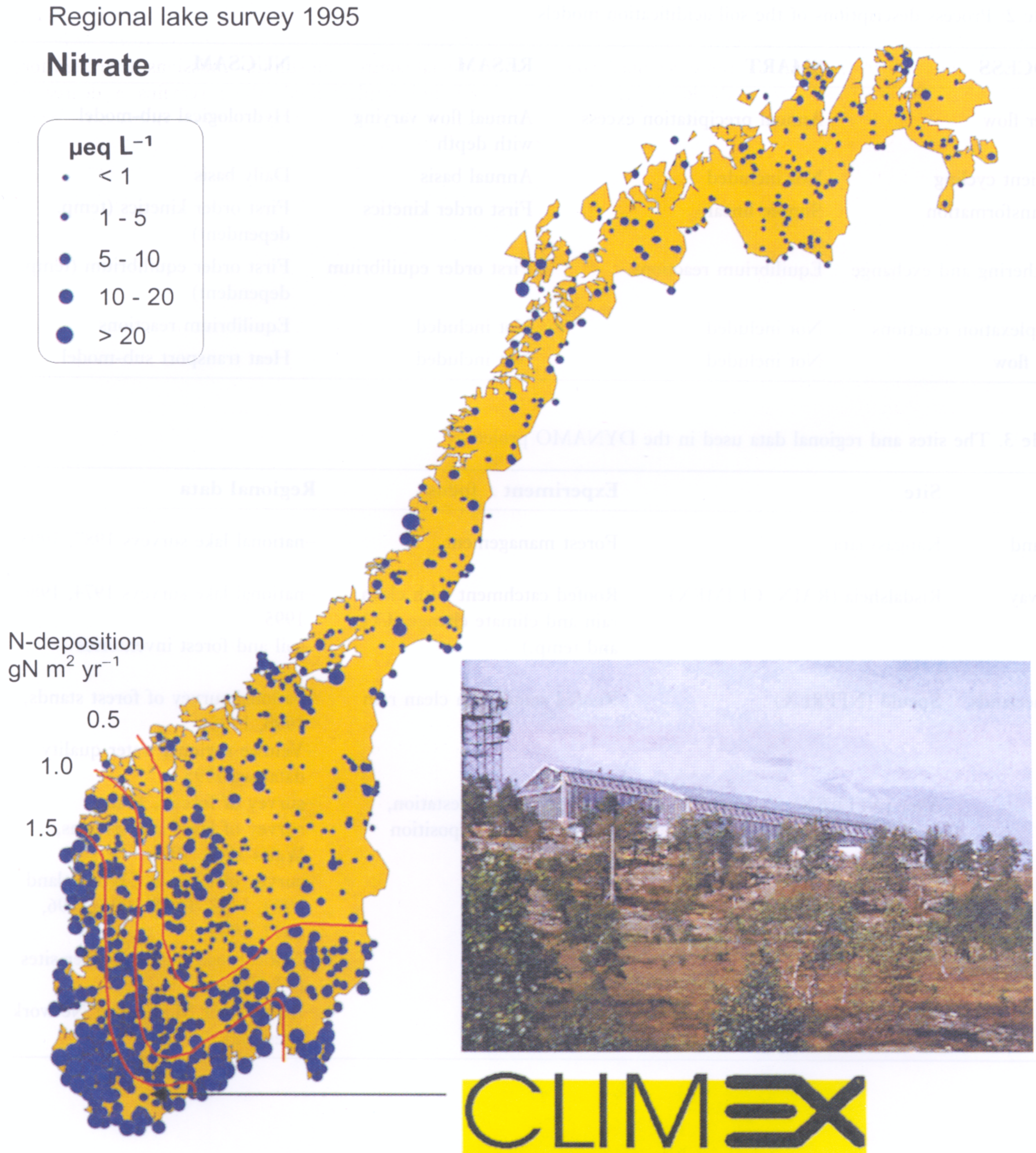

Fig. 3. *Example of the site specific and regional scale data used in the DYNAMO project. The location of the CLIMEX ecosystem manipulation study, and regional lake survey data for nitrate (1995).*

characteristics of, for example, soils data exist. A similar approach has been used successfully for a regional scenario assessment in Wales by Sefton and Jenkins (1998), however, the modelling incorporated no explicit representation of land use impacts. The authors highlight the importance of the interactive effects of afforestation and atmospheric deposition and suggest two possible approaches for the inclusion of land use effects at a regional scale. The simplest approach is to incorporate land use as a further Monte Carlo parameter and make some generalisations about forest age and function; the more satisfactory approach is to undertake a multiple site calibration incorporating known land use histories for each of the study catchments. This latter approach has been undertaken by Collins and Jenkins (1998), using the same regional data (Wales), and following a similar methodology to that undertaken for a regional analysis of land use and deposition interactions in SW Scotland (Wright *et al.*, 1994). This technique uses the best available information for the chemical and physical characteristics of soil and water at many sites, and is capable of predicting in both time and space. Cosby and Wright (1998) compared both the Monte Carlo and multiple site regionalisation techniques on lake survey data collected in southernmost Norway in 1974, 1986, and 1995. They concluded that estimates of trends that can be derived from the Monte Carlo are limited to changes in population parameters (e.g. changes in means rather than mean changes as derived from the site-specific approach).

The maintenance of one to one correspondences between simulated and observed systems means that simulation results can be mapped for a geographically explicit presentation of results. The ability to examine geographical patterns of response is becoming increasingly important in regional assessments, both as an analysis and as a policy tool.

SCENARIOS

Three dominant drivers of environmental change are the focus of DYNAMO, namely climate change, atmospheric deposition, and land use. Global and currently available regional climate models are uncertain with respect to predictions of the magnitude, seasonality, and latitudinal variation of future temperature and moisture regimes. In contrast, atmospheric carbon dioxide concentrations are predicted to increase with a doubling of the pre-industrial level of CO_2 anticipated over the next 50 years. Although international controls on sulphur emissions have been formulated and implemented, there remains a degree of uncertainty about future trends of atmospheric nitrogen. Land use change in Europe presently occurs rapidly and is expected to continue at the same or increased rate in the coming decades. Conversion of land cover type (natural to 'managed'), changes in management practices (extensification/intensification), and changes at the landscape scale are all perceived to be the most important aspects of land use change (Menaut and Struwe, 1995). DYNAMO had addressed the impact of land use changes through altered forest practice and management.

Scenarios of future change in environmental driving variables singly and in combination that are realistic for the next 50 years and appropriate for each of the regions studied within the DYNAMO project, and for Europe as a whole, are listed in Table 4. These represent the best estimates of the relative changes in atmospheric deposition, land use, and climate change.

European Environmental Policy

The increasing awareness of the concept of achieving 'sustainable development' requires information on the consequences of anthropogenic activity on ecosystem functioning ('pressure-state-response'). The DYNAMO project has focused on the development of technologies to address this issue. Up-scaling procedures for dynamic biogeochemical models have emphasised the uncertainty of the impacts of current EU policy on emissions reductions and highlighted the potential long-term consequences of eutrophication and acidification as a result of land use and

Table 4. Examples of scenarios to be used in evaluation of the future impact of environmental change at the site and regional scale

	Reduce	Constant (business-as-usual)	Increase
acid deposition			
S	80% reduction (1994 Oslo protocol)	Constant	—
NOx	50% reduction	Constant	linear at current rate of increase
NHx	50% reduction	Constant	linear at current rate of increase
Land-use			
Forestry	cut, no replant	Cut, replant	new planting, intensive forestry
climate change			
CO_2		Constant CO_2	doubling by 2030
Temperature		Constant	+3–5°C by 2030
Precipitation	—10%	Constant	+ 10%

climate change. The project has extrapolated models initially formulated to understand process controls in complex systems to provide the scientific underpinning for the policy-making process. This has been highlighted with the production of geographically explicit presentation of results.

The DYNAMO project homepage is located at: www.mluri.sari.ac.uk/dynamo.htm

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References

Aber, J.D., Nadelhoffer, K.J., Steudler, P. and Melilo, J.M., 1989. Nitrogen saturation in northern forest ecosystems. *Bioscience*, **39**, 379–386.

Collins, R.P. and Jenkins, A., 1998. Regional modelling of acidification in Wales; calibraiton of a spatially distributed model incorporating land use change. *Hydrol. Earth System Sci.* **2**, 533–541.

Cosby, B.J., Wright, R.F., Hornberger, G.M. and Galloway, J.N., 1985a. Modelling the effects of acid deposition: Assessment of a lumped parameter model of soil water and streamwater chemisty. *Wat. Resour. Res.*, **21**, 51–63.

Cosby, B.J., Wright, R.F., Hornberger, G.M. and Galloway, J.N., 1985b. Modelling the effects of acid deposition: Estimation of long-term water quality responses in a small forested catchment. *Wat. Resour. Res.*, **21**, 1591–1601.

Cosby, B.J., Hornberger, G.M. and Wright, R.F., 1989. Estimating time-delays and extent of regional acidification in southern Norway in response to several deposition scenarios. In: Kamari, J., Jenkins, A., Norton, S.A., and Wright, R.F. (Eds.) *Regional Acidification Models*, Springer-Verlag, Berlin, pp 151–166.

Cosby, B.J., Ferrier, R.C., Jenkins, A., Emmett, B.A., Wright, R.F. and Tietema, A., 1997. Modelling the ecosystem effects of nitrogen deposition at the catchment scale: Model of Ecosystem Retention and Loss of Inorganic Nitrogen (MERLIN). *Hydrol. Earth Systems Sci.*, **1**, 137–158.

Cosby, B.J. and Wright, R.F., 1998. Modelling regional response of lakewater chemistry to changes in acid deposition: the MAGIC model applied to lake surveys in southernmost Norway 1974-1986-1995. *Hydrol. Earth System Sci.*, **2**, 563–576.

de Vries, W., Posch, M. and Kamari, J., 1989. Simulation of the long-term soil response to acid deposition in various buffer ranges. *Wat. Air Soil Pollut.*, **48**, 349–390.

de Vries, W., Kros, J. and van de Salm, C., 1994. The long term impact of three emission deposition scenarios on a Dutch forest soil. *Wat., Soil Air Pollut.*, **75**, 1–35.

de Vries, W., Kros, J., and van de Salm, C., 1995. Modelling the impact of acid deposition and nutrient cycling in forest soils. *Ecol. Model.*, **79**, 231–254.

Emmett, B.A., Cosby, B.J., Ferrier, R.C., Jenkins, A., Tietema, A. and Wright, R.F., 1997. Modelling the ecosystem effects of nitrogen at the catchment scale: Simulation of nitrogen saturation in a Sitka spruce forest, Aber, Wales, UK. *Biogeochemistry*, **38**, 129-148.

Evans, C.D., Jenkins, A., Helliwell, R.C. and Ferrier, R.C., 1998. Predicting regional recovery from acidification: the MAGIC model applied to Scotland, England and Wales. *Hydrol. Earth System Sci.*, **2**, 543–554.

Ferrier, R.C., Jenkins, A., Cosby, B.J., Helliwell, R.C., Wright, R.F. and Bulger, A.J., 1995. Affects of future N deposition scenarios on the Galloway region of Scotland using a coupled sulphur and nitrogen model (MAGIC-WAND). *Wat., Air, Soil, Pollut.*, **85**, 707–712.

Groenenberg, J.E., Kros, J., van der Salm, C. and de Vries, W., 1995. Application of the model NUCSAM to the Solling spruce site. *Ecol. Model.*, **83**, 97–108.

Groenenberg, B.-J., de Vries, W. and Kros, J., 1998. Simulation of the long-term carbon and nitrogen dynamics in Dutch forest soils under Scots pine. *Hydrol. Earth System Sci.*, **2**, 439–449.

Gundersen, P., Emmett, B.A., Kjonaas, O.J., Koopmans, C.J. and Tietems, A., 1998. Impact of nitrogen deposition on nitrogen cycling in forests: A synthesis of NITREX data. *For. Ecol. Manage.*, **101**, 37–55.

Helliwell, R.C., Ferrier, R.C. and Jenkins, A., 1998. A two-layer application of the MAGIC model to predict the effects of land use scenarios and reductions in deposition on acid sensitive soils in the UK. *Hydrol. Earth System Sci.*, **2**, 497–507.

Helliwell, R.C., Ferrier, R.C., Evans, C.D. and Jenkins, A., 1998. A comparison of methods for estimating soil characteristics in regional acidification models: an application of the MAGIC model to Scotland. *Hydrol. Earth System Sci.*, **2**, 509–520.

Hornberger, G.M., Cosby, B.J. and Wright, R.F., 1989. Estimating uncertainty in long-term reconstructions. In: Kamari, J., Jenkins, A., Norton, S.A. and Wright, R.F. (Eds.) *Regional Acidification Models*, Springer-Verlag, Berlin, pp 279–290.

Jenkins, A., Ferrier, R.C. and Cosby, B.J., 1996. A dynamic model for assessing the impact of coupled sulphur and nitrogen deposition scenarios on surface water acidification. *J. Hydrol.*, **197**, 111–127.

Jenkins, A., Renshaw, M., Helliwell, R.C., Sefton, C.M., Ferrier, R.C. and Swingewood, P 1997. Modelling surfacewater acidification in the UK: Application of the MAGIC model to the Acid Waters Monitoring Network. IH/MLURI Report No. 131, Wallingford, UK. 54 pp.

Kamari, J., Rankinen, K., Finer, L., Piiraninen, S. and Posch, M., 1998. Modelling the response of soil and runoff chemistry to forest harvesting in a low deposition area (Kangasvaara, Eastern Finland). *Hydrol. Earth System Sci.*, **2**, 485–495.

Kros, J., Groenenberg, J.E., de Vries, W. and van der Salm, C., 1995. Uncertainties in long-term predictions of forest soil acidification due to neglecting seasonal variability. *Wat., Air, Soil, Pollut.*, **79**, 353–375.

Lawton, J.H., Moreno, J.M. and Struwe, S., 1998. *Ecosystem Research and European Union Environment Policy Needs.* Report of the Terrestrial Ecosystems Research Initiative Concerted Action Workshop. Toledo, Spain, 28April – 1 May 1998.

Menaut, J-C. and Struwe, S., 1995. *Terrestrial Ecosystems Research Initiative: Science Plan.* EC Ecosystems Research Report No. 17. Brussels.

Mohren, G.M.J., Jorritsma, I.I.M., Florax, J.P.G.G.M., Bartelink, H.H. and van den Veen, J.R., 1991. *FORGRO 3.0 A basic forest growth model: model documentation and listing.* Research Institute for Forest and Urban Ecology Report No. 524, Wageningen, The Netherlands, 137pp.

Mol-Dykstra, J.P., Kros, H. and van der Salm, C., 1998. Comparison of the simulated forest soil response to deposition reduction with two models of differing complexity. *Hydrol. Earth System Sci.*, **2**, 473–483.

Posch, M., Reinds, G.J. and de Vries, W., 1993. *SMART- A simulation model for acidification's regional trends: Model description and user manual.* Mimeograph Series of the National Board of Waters and the Environment No. 47, Helsinki, Finland, 43 pp.

Posch, M., Hettelingh, J-P., de Smet, P.A.M. and Downing, R.J., 1997. Calculation and mapping of critical thresholds in Europe. Status Report 1997. Coordination Center for Effects. RIVM Report 259101007.

Sefton, C.E.M. and Jenkins, A., 1998. A regional application of the MAGIC model in Wales: calibration and assessment of future recovery using a Monte-Carlo approach. *Hydrol. Earth System Sci.*, **2**, 521–531.

Skjelkvale, B.L., Wright, R.F. and Henriksen, A., 1998. Norwegian lakes show widespread recovery from acidification; results from national surveys of lakewater chemistry 1986-1997. *Hydrol. Earth System Sci.*, **2**, 555–562.

Stanners, D. and Bordeau, P., 1995. *Europe's Environment: The Dobris Assessment.* European Environment Agency, Copenhagen.

Van der Salm, C., Groenenberg, B.-J. E. and Boxman, A.W., 1998. Modelling the response of soil and soil solution chemistry upon roofing a forest in an area with high nitrogen deposition. *Hydrol. Earth System Sci.*, **2**, 451–471.

Wright, R.F. and Hauhs, M., 1991. Reversibility of acidification: soils and waters. *Proc. Roy Soc. Edin.* B, **97**, 169–193.

Wright, R.F., Cosby, B.J., Ferrier, R.C., Jenkins, A., Bulger, A.J. and Harriman, R., 1994. Changes in the acidification of lochs in the Galloway region, S.W. Scotland, 1979–1988: The MAGIC model used to evaluate the role of afforestation, calculate critial loads, and predict fish status. *J. Hydrol.*, **161**, 257–285.

Wright, R.F., Beier, C. and Cosby, B.J., 1998a Effects of nitrogen deposition and climate change on nitrogen runoff at Norwegian boreal forest catchments: the MERLIN model appoied to Risdalsheia (RAIN and CLIMEX projects). *Hydrol. Earth System Sci.*, **2**, 399–414.

Wright, R.F., Emmett, B.A. and Jenkins, A., 1998b. Acid deposition, land-use change and global change: MAGIC 7 model applied to Aber, UK (NITREX project) and Risdalsheia, Norway (RAIN and CLIMEX projects). *Hydrol. Earth System Sci.*, **2**, 385–397.