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Abstract: Damage to semi-natural habitats due to air pollution has hitherto been quantified using biogeochemical indicators, but predictions of species change are necessary to relate impacts on ecosystems to the habitat quality metrics used in conservation and policy communities. Ongoing pollution by reactive nitrogen (N) is delaying the recovery of acid-sensitive ecosystems from sulphur (S) pollution, and causing additional damage through eutrophication. Dynamic soil chemistry models are currently used to set national emissions thresholds for acid pollutants in a UNECE process, using simple targets based on soil pH or acid-base balance. These indicators are however poorly related to conservation targets based on habitat quality, which are defined in terms of the presence and abundance of indicator species. We demonstrate an approach to predicting habitat quality change under different N and S pollution scenarios, which brings together biogeochemists, biodiversity specialists and policymakers in an open modelling framework.

Keywords: Acidification; Eutrophication; Indicator; Open modelling; Niche.

1. INTRODUCTION

The Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the UNECE is an effective international policy instrument which uses evidence of actual or potential damage from pollutants to set emissions limits. The CLRTAP has been particularly successful in regulating emissions of the acidifying pollutants nitrogen (N) and sulphur (S). Damage indicators and thresholds are currently defined in terms of soil chemical criteria such as pH or Ca/Al ratio. This approach is being reconsidered due to two pressures. Firstly, a large reduction in S emissions has shifted the emphasis from acidification damage towards eutrophication, i.e. a damaging increase in ecosystem productivity driven by N pollution. Secondly, EU conservation legislation uses habitat quality indicators that are largely based on species occurrence, not soil properties (Figure 1). Hence, we have developed a model chain which predicts the effects of pollution emissions scenarios on species-based habitat quality indicators, by linking models of pollutant deposition, soil chemistry, species occurrence and habitat quality. This requires much transdisciplinary communication, so there is a clear requirement for transparency in model description, in particular the definition of model inputs and outputs.
2. SIMULATING SPECIES OCCURRENCE

2.1 Introduction

A two-stage process was used to simulate the effects of different N and S deposition scenarios on plant species. Firstly, a dynamic model which is currently used by the UNECE Coordination Centre for Effects to simulate effects of pollution on soil [de Vries et al., 2007] was used to predict changes in soil pH and carbon (C) to N ratio. These variables were used as inputs into a set of static regression models [Smart et al., 2005] which predict species’ probabilities of occurrence under a given set of environmental conditions.

2.2 Soil chemistry

The MAGIC model focuses on acid-base dynamics, solving at each timestep a system of linear equations which describe ionic competition for exchange sites. This model also simulates N dynamics using a simple saturation function. Nitrogen pollution affects habitats mainly through effects on competition. With a decrease in N limitation, low-growing, light-demanding species are shaded out by increased growth of faster-growing and taller species. However, the soil microflora competes strongly with plants for N additions, and initial inputs of N into a pristine ecosystem are mainly immobilised by interaction with the soil carbon (C) pool, resulting in a decrease in soil C/N ratio [Gundersen et al., 1998]. Because of the large organic matter pool in most soils, C/N ratio changes only slowly with typical levels of atmospheric inputs. In the absence of historic soil measurements, N addition experiments allow predictions of soil C/N change to be assessed (Figure 2).
2.3 Plant niches

Plant species occur within specific ranges of environmental conditions, determined by their autecology, competition with other plants, and susceptibility to pests and diseases. This ‘realised niche’ is a hypervolume within the space defined by a set of environmental factors. Maximum probabilities of occurrence exist for many species in relation to these factors, although some species have broad tolerance or bimodal distributions when plotted against individual factors. Ellenberg [1992] and subsequent authors defined optima scores for European plant species on arbitrary scales related to the availability of nutrients, water and light, and acid reactivity. We modelled the occurrence of plant species in two stages, to make use of datasets where environmental factors were measured alongside occurrence as well as the far larger datasets where only species were recorded. For the former dataset, multiple regression was used to calibrate mean scores for present species against five soil variables: total C and N content, pH, % soil moisture, and bicarbonate-extractable phosphorus. Minimum adequate models were determined by first rejecting factors with no significant effect on mean Ellenberg score and then using deviance reduction tests to accept or reject interactions and quadratic terms for the remaining factors. Next, multiple logistic regression was used to relate probability of occurrence within the larger dataset to the mean Ellenberg score, by stepwise elimination from the set of significant effects, interactions and quadratic effects. This results in a set of per-species models (Figure 3), collectively known as GBMOVE, which can predict the probability of a species occurring under a given set of environmental conditions [Smart et al., 2005].
2.4 Species dynamics

Coupling the MAGIC dynamic soil chemistry model with the GBMOVE static species niche model allows the dynamics of plant species occurrence to be simulated. Testing this model chain is difficult due to the scarcity of long-term datasets covering both soil chemistry and plant species occurrence. However, the model chain proved fairly successful in simulating the rates of change in probability of occurrence in a floristic dataset extending from 1973 to 2001 (Figure 4).

Figure 3 GBMOVE niche models for *Drosera rotundifolia* and *Urtica dioica* (plants typical of infertile and fertile habitats, respectively) in relation to soil pH and soil carbon/nitrogen ratio, at fixed levels of canopy height (0.8 m), soil moisture content (35%) and soil carbon content (5%).

![GBMOVE niche models for Drosera rotundifolia and Urtica dioica](image)

**Figure 3** GBMOVE niche models for *Drosera rotundifolia* and *Urtica dioica* (plants typical of infertile and fertile habitats, respectively) in relation to soil pH and soil carbon/nitrogen ratio, at fixed levels of canopy height (0.8 m), soil moisture content (35%) and soil carbon content (5%).

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![Predicted versus observed change](image)

**Figure 4.** Predicted versus observed change for individual species in blanket bog (Moor House long-term monitoring site, Cumbria, UK). Predicted change is the slope coefficient of a linear regression on occurrence probabilities predicted by the MAGIC-GBMOVE model chain for each year between 1973 and 2001. Observed change is the slope coefficient of a linear regression on % frequency in sample plots in each survey year. Pearson correlation coefficient = 0.568, p=0.002 [Smart et al., 2005].
3. FROM SPECIES OCCURRENCE TO BIODIVERSITY INDICATORS

Predictions of changes in probability of occurrence for a large number of individual species are of limited value in themselves for assessing habitat quality, which is assessed according to criteria such as rarity, typicality and fragility [Ratcliffe, 1977]. The Habitats Directive of the European Union [EEC, 1992] has lead in the UK to the development of Common Standards Monitoring (CSM) protocols [JNCC, 2006] which list species for each habitat, grouped into positive and negative indicators. We have used this categorisation to interpret predictions of species change, by calculating an overall habitat-specific quality score $Q$ as

$$Q = \sum_{j=1}^{p} \left( \frac{P_j}{P_{\text{max},j}} \right) - \sum_{j=1}^{n} \left( \frac{P_j}{P_{\text{max},j}} \right)$$

where $P_j$ and $P_{\text{max},j}$ are the probabilities of occurrence of the $p$ positive indicators and $n$ negative indicators for a habitat, respectively, and $P_{\text{max}}$ is the maximum probability of occurrence for the species within the parameter space. Re-scaling to $P_{\text{max}}$ is necessary because the large variation in abundance of individual species within large survey datasets and in maximum occupancy of suitable sites means that absolute probabilities of occurrence vary widely. Rescaling to $P$ and $n$ allows for the variable numbers of positive and negative indicator species listed for different habitats. Species not included in the CSM indicator lists are not used in this calculation.

The approach is illustrated using simulations of C/N and pH change due to atmospheric S and N deposition (Figure 5). Whilst with more N pollution the probability of occurrence increases for some positive indicators, and decreases for some negative indicators, the overall pattern of response is for N pollution to favour negative over positive indicators and so there is a clear decline in the overall quality score.
Figure 5. Simulated changes in blanket bog at Moor House long-term monitoring site, Cumbria, UK, under a) Gothenberg emission scenario, and b) an extreme N addition scenario with an additional 50 kg N ha$^{-1}$ yr$^{-1}$ from 1960. (I) Soil pH and C/N ratio simulated using the MAGIC soil chemistry model. Soil water content and canopy height were assumed to be constant. (II) Probabilities of occurrence of positive Common Standards Monitoring indicator species for blanket bog, rescaled to Pmax. (III) Probabilities of occurrence of negative CSM indicator species for blanket bog, rescaled to Pmax. (IV) Overall habitat quality Q (see equation 1).
4. MODEL IMPROVEMENT

4.1 Uncertainty
Linking models increases uncertainty related to both parameterisation and model structure. A major source of uncertainty in the MAGIC-GBMOVE model chain relates to the prediction of mean Ellenberg fertility score from soil biophysical measurements. Between-habitat variation in the inert proportion of soil organic matter [Rowe et al., 2006] results in a poor correlation between total soil C and N pools and mean Ellenberg fertility score. We are currently measuring a set of soil properties including mineralisable N alongside floristic data in a large national survey, to identify more accurate predictors. This reduction in parameter-uncertainty will however lead to a requirement for more structural complexity in the soil organic matter model.

4.2 Additional drivers
The inclusion of multiple environmental gradients in the GBMOVE niche models offers the potential to link to other dynamic biophysical models. Canopy height is used in the niche models as a surrogate for ground-level light availability, which has a profound effect on environmental suitability for plant species. We are currently using this mechanism to link GBMOVE to the SUMO vegetation model [Wamelink, 2007] to simulate the effects of vegetation succession on plant species occurrence. The effects of changes to rainfall pattern could be represented via effects on mean soil moisture content. We have also developed an extended version of GBMOVE that includes other climatic variables, allowing simulations of climate change. Since the niche models are based on empirical data that includes the effects of multiple drivers, we have some confidence that this approach can be applied to simulations of several interacting biophysical drivers.

4.3 Open model development
The model development process has historically been monopolised by the subset of scientists who are also programmers. We are using several methods to open this process to wider scrutiny and discussion. Static niche models related to measurable factors are easily understood and checked by plant ecologists, compared with dynamic models of species populations or of cover proportion. Dynamic soil chemistry models written in FORTRAN are being re-implemented in SIMILE graphical modelling software [Muetzelfeldt and Massheder, 2003], which can be understood and assessed by non-programming modellers. This also makes it easy to see submodel boundaries, eliminating the danger of double representation of processes when combining models. Lastly, the use of CSM indicators to assess habitat quality allows discussion with habitat specialists in the UK nature conservation agencies using familiar terms.

5. CONCLUSIONS
By linking a dynamic soil chemistry model to static plant niche models, we have obtained positive correlations between predicted and measured change in the abundance of individual plant species. This approach could be applied to a variety of other problems in nature conservation, which urgently requires methods for predicting the effects of a changing environment on species abundance. The proposed one-dimensional habitat quality summary statistic is based on indicators used by conservationists and policymakers, yet allows definition of a simple damage threshold that could be used to define acceptable pollutant loads.
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