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A dynamic modelling approach for estimating critical loads of nitrogen based on plant community changes under a changing climate

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Plant community composition can be used in dynamic modelling to estimate critical loads of nitrogen deposition, provided the appropriate reference deposition, future climate and target plant communities are defined.

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ABSTRACT

A dynamic model of forest ecosystems was used to investigate the effects of climate change, atmospheric deposition and harvest intensity on 48 forest sites in Sweden ($n = 16$) and Switzerland ($n = 32$). The model was used to investigate the feasibility of deriving critical loads for nitrogen (N) deposition based on changes in plant community composition. The simulations show that climate and atmospheric deposition have comparably important effects on N mobilization in the soil, as climate triggers the release of organically bound nitrogen stored in the soil during the elevated deposition period. Climate has the most important effect on plant community composition, underlining the fact that this cannot be ignored in future simulations of vegetation dynamics. Harvest intensity has comparatively little effect on the plant community in the long term, while it may be detrimental in the short term following cutting. This study shows: that critical loads of N deposition can be estimated using the plant community as an indicator; that future climatic changes must be taken into account; and that the definition of the reference deposition is critical for the outcome of this estimate.

1. Introduction

Within the Long Range Transboundary Air Pollution (LRTAP) convention, classical methods of defining critical loads of acidity have been successful in linking atmospheric deposition to ecosystem damage, and have contributed decisively to the setting of lower emission targets for acidity. For nitrogen (N) on the other hand, emissions continue to be elevated over many parts of Europe, exceeding the current critical loads for nutrient N in large areas (Hettelingh et al., 2008). There are two established ways to determine critical loads, i.e. empirical and modelling. Empirical critical loads are based on experimentally induced or observed damage to plants at given nitrogen inputs and, by definition, do not include other sources of reactive N such as net N mineralization or N input to the understory from canopy leaching. Neither do empirical critical loads take account of other drivers that may alter the response of plants to N input. Modelled critical loads for nutrient nitrogen have previously been based on concentrations of nitrogen in the soil solution, which have been used as an environmental quality criterion (De Vries et al., in press).

The assumption of a steady state, which is inherent in the classical critical loads methodology, supposes unchanging environmental conditions in the future. Current and continuing changes in climate and land use, mean that this is not a sound assumption, particularly given that the effects of climate and land use can confound the response of ecosystems to N deposition. This demonstrates the need for a complementary approach to estimate critical loads of N deposition based directly on changes in a biological criterion. The method presented in this study is intended to provide such a complement, offering a new tool to integrate different drivers simultaneously, and paving the way for the assessment of responses of terrestrial ecosystems to N deposition under changing climatic conditions and land use.

2. Aims of the study

The primary aim of this study is to investigate the feasibility of estimating critical loads of N deposition based on changes in the

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composition of plant communities. We investigate the relative importance of different drivers (climate, deposition and forest harvesting intensity) on soil chemistry and the composition of the ground vegetation community. We also describe the construction of a comprehensive, one-dimensional indicator to represent the composition of ground vegetation to allow its change over time to be followed. Finally, preliminary estimates of critical loads of nitrogen (CLN) based on changes in the plant community are presented. The method is illustrated by tentative results on the responses of vegetation communities to three nitrogen deposition scenarios, two climate change scenarios, and two land use change scenarios.

Our aim at this stage is not to define the actual critical load due to N deposition, the appropriate reference scenario of deposition and climate, against which change caused by further deposition is evaluated, or the most likely climate scenario, but rather to describe a method by which CLN can de estimated for any combination of the above-mentioned drivers.

3. Methods

3.1. The ForSAFE-Veg model

The ForSAFE-Veg model was used to test the methodology presented in this paper. ForSAFE-Veg is a composite model in which the ForSAFE model is the biogeochemical simulator platform providing data to drive the vegetation composition simulator Veg (Belyazid, 2006). ForSAFE simulates the cycles of carbon, nitrogen, base cations (Bc) and water in a forest ecosystem, simultaneously simulating soil chemistry, tree growth and soil organic matter accumulation or depletion. ForSAFE requires site-specific inputs of the physical properties of the soil (including mineralogy, hydrological parameters, density, depth and stratification), tree type, and time series of atmospheric deposition and climatic data (temperature, light, and precipitation) (Wallman et al., 2005). The model gives monthly estimates of weathering rates, soil moisture, soil solution concentrations, uptake fluxes of N and Bc, litterfall, decomposition and mineralization, as well as photosynthesis and growth rates. The Veg module reads a set of five drivers (soil solution pH, Bc concentration, N concentration, ground level light, soil moisture) from ForSAFE, in addition to air temperature, and uses them to estimate the relative abundance of a set of indicator plants at the site. The result is a model chain that can link changes in atmospheric deposition, climatic conditions and land use to responses in the biogeochemistry and plant community composition at site level, historically, as well as in the future (target years, t_i (i = 1…T)).

3.2. Modelling the ground vegetation community with the Veg model

The Veg model estimates the composition of the ground vegetation community by distributing the available ground area (a hypothetical, representative 1 m^2) between the plants that are able to grow, given the abiotic conditions at a particular site (Belyazid, 2006; Sverdrup et al., 2007). For each plant, the model evaluates whether the site conditions are suitable for the plant to become established at the site. The conditions that allow a plant to become established are referred to as a niche. The niche is thus the combination of the limits of N and Bc concentrations in the soil solution, soil solution pH, soil moisture, air temperature and light intensity reaching the ground vegetation (light below the tree canopy in cases where trees are present), within which a plant can become established. Usually, the conditions are favourable for the establishment of several plants at a site simultaneously. The model then calculates the relative ground area occupancy of each plant by distributing the area between the plants depending on their strength in response to the site conditions and their respective competitiveness. The plants compete by growing roots to different soil depths and by shading other plants aboveground. The root depth and shading height are given as inputs for each indicator plant.

The model requires a list of indicator plants, drawn up by biologists and ecologists familiar with the ecosystems to be modelled, as described by Sverdrup et al. (2007). In this study, Swedish and Swiss data were used (see Belyazid et al., 2010; Sverdrup et al., 2008 for details about the data). The list of indicator plants was drawn up in two steps. Firstly, a list was made of representative plants. For reasons of practicability, all plants were not included, but only those that are most representative of the ecosystem or of significant interest for conservation, ecosystem service, or other traits. Secondly, the responses of each plant were defined in relation to N and Bc concentrations, soil solution pH, air temperature, soil moisture, shade tolerance and palatability.

The plants' parametric responses to drivers are presented in Tables 1 and 2, and are defined in mathematical terms below. The nitrogen response combines promotion and retardation functions, as defined in Equation (1), where w_+ denotes the slope of the promotion function, k_+ determines the threshold of [N] where positive response starts, k_- the threshold of [N] where retardation starts, w_- the slope of the retardation function, and $a0$ is a normalizing factor used to set the maximum of the response curve to 1.

$$f(\mathrm{N}) = a0\frac{[\mathrm{N}]^{w_+}}{k_+ + [\mathrm{N}]^{w_+}}\frac{k_-}{k_- + [\mathrm{N}]^{w_-}} \quad (1)$$

The pH response is given in Equation (2), and is expressed as a function of hydrogen ion concentration $[H^+]$ in the soil solution.

$$f(\mathrm{pH}) = \frac{1}{1 + k_{\mathrm{pH}}\left[\mathrm{H}^+\right]} \quad (2)$$

The calcifuge response retardation function is defined for a limited number of plants which show signs of decline when their uptake function is impaired by elevated Ca^{2+} concentrations, given by Equation (3)

$$f(\mathrm{Bc}) = \frac{1}{1 + k_{\mathrm{Ca}}\left[\mathrm{Ca}^{2+}\right]^2} \quad (3)$$

The plants' responses to soil moisture, air temperature and ground level photosynthetically active radiation (PAR) are extrapolated between thresholds, as can be seen in Table 2. A minimum soil moisture threshold is defined for each plant, below which the plant cannot become established or subsist, as well as an optimal moisture level and an upper limit above which the soil is too moist for the plant to be present. Soil moisture is given as the fraction of saturated pores in the soil, meaning that a moisture value of 1 corresponds to completely water-saturated soil. Similarly, three values of air temperature are defined: a minimum value below which the plant cannot become established, an optimal value, and a maximum value above which the physiology of the plant fails due to excessive heat. Temperature is given as the average yearly air temperature. Only two values of the light response are needed, a lower limit below which it is too dark for the plant to become established, and an optimal level above which the plant receives sufficient light to grow. The light driver is given as the average yearly PAR in $\mu mol_{photon}\ m^{-2}\ s^{-1}$.

Apart from the parametric responses described above, each plant has two competitive strategies. The first is shading aboveground, and is expressed as the shading height of the plant, i.e. the elevation of the plant part that is able to shade out other plants. The second is the root distribution down the soil profile, which denotes the soil depth that the plants' roots can reach to gain access to water and nutrients.

3.3. Defining excessive change in a plant community composition

Three parameters are crucial to estimate whether a change in the composition of the ground vegetation due to N deposition is acceptable or not (based on tests by Belyazid and Moldan, 2009).

1 *The reference population* under a given reference deposition, against which possible changes in the composition of the vegetation are evaluated. For the method presented in this paper, N deposition according to the Maximum Feasible Reduction (MFR) of European emissions of nitrogen compounds was adopted as the reference N deposition, with the corresponding vegetation communities as the reference populations. However, the MFR is not a realistic choice for a reference deposition, and is used here only for illustrative purposes.
2 *The target population*, i.e. the segment of the ground vegetation community for which change is evaluated. The target population is defined as the entire plant community.
3 *The limit of acceptable change*, which is the magnitude of divergence of the plant community from the reference population, beyond which change in the target population is unacceptable. A critical limit of 5% difference was adopted, meaning that total differences in area cover of plants are acceptable up to a limit of 5% of the specific site area.

As stated above, the aim of this exercise was to test the method of estimating a critical load of nitrogen, not to determine actual values.

3.4. Defining a one-dimensional criterion for tracing changes in the composition of the ground vegetation

Unlike classical geochemical criteria, such as base saturation for acidity or N concentrations for eutrophication, which are one-dimensional, the use of plant community composition as a criterion requires tracking the composition of multiple species over time simultaneously. Multiple plant occurrences need to be simplified into a single variable that can be tracked over time, and on which a limit can be set to identify excessive change. Another difference when using the plant community as a criterion, compared with the classical critical load method, is that instead of defining a fixed, absolute critical value (e.g. Bc/Al = 1), the critical limit is set in relation to a steadily changing reference level, as plant populations are affected by other drivers than nitrogen deposition.