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Ecosystem functions as indicators for heathland responses to nitrogen fertilisation

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ABSTRACT

Anthropogenic deposition of reactive nitrogen (N) has increased during the 20th century, and is considered an important driver of shifts in ecosystem functions and biodiversity loss. The objective of the present study was to identify those ecosystem functions that best evidence a target ecosystem's sensitivity to N deposition, taking coastal heathlands as an example. We conducted a three-year field experiment in heathlands of the island Fehmarn (Baltic Sea, North Germany), which currently are subject to a background deposition of 9 kg N ha^{-1} yr^{-1}. We experimentally applied six levels of N fertilisation (application of 0, 2.5, 5, 10, 20, and 50 kg N ha^{-1} yr^{-1}), and quantified the growth responses of different plant species of different life forms (dwarf shrubs, graminoids, bryophytes, lichens) as well as shifts in the C:N ratios of plant tissue and humus horizons. For an applicability of the experimental findings (in terms of heathland management and critical load assessment) fertilisation effects on response variables were visualised by calculating the treatment 'effect sizes'. The current year's shoot increment of the dominant dwarf shrub *Calluna vulgaris* proved to be the most sensitive indicator to N fertilisation. Shoot increment significantly responded to additions of $\geq$ 5 kg N ha^{-1} yr^{-1} already in the first year, whereas flower formation of *Calluna vulgaris* increased only in the high-N treatments. Similarly, tissue C:N ratios of vascular plants (*Calluna vulgaris* and the graminoids *Carex arenaria* and *Festuca ovina* agg.) only decreased in the highest N treatments (50 and 20 kg N ha^{-1} yr^{-1}, respectively). In contrast, tissue C:N ratios of cryptogams responded more quickly and sensitively than vascular plants. For example, *Cladonia* spp. tissue C:N ratios responded to N additions $\geq$ 5 kg N ha^{-1} yr^{-1} in the second study year. After three years we observed an increase in cover of graminoids and a corresponding decrease of cryptogams at N fertilisation rates of $\geq$ 10 kg N ha^{-1} yr^{-1}. Soil C:N ratios proved to be an inappropriate indicator for N fertilisation at least within our three-year study period. Although current critical N loads for heathlands (10–20 kg N ha^{-1} yr^{-1}) were confirmed in our experiment, the immediate and highly sensitive response of the current year's shoots of *Calluna vulgaris* suggests that at least some ecosystem functions (e.g. dwarf shrub growth) also might respond to low (i.e. < 10 kg N ha^{-1} yr^{-1}) but chronic inputs of N.

1. Introduction

Anthropogenic emission of reactive nitrogen (N) compounds has increased steadily in the wake of industrialisation during the last century, and is expected to further increase in the course of this century (Galloway et al., 2004; Dentener et al., 2006). Oxidized N forms (NO_x) mainly arise from fossil fuel combustion, whereas reduced N compounds (NH_y) originate predominantly from industrial agriculture (Bobbink et al., 2010). Enhanced N deposition has led to species loss in ecosystems that are known to be N-limited. N limitation is often associated with low buffering and cation exchange capacity of the soils that are typical of these ecosystems (Clark et al., 2007).

Increased N deposition can cause a loss of biodiversity in different ways. Enhanced N availability through accumulation can induce an alteration of interspecific competition, and thus may result in shifts in species composition (Bobbink et al., 2010, 1998;

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McClean et al., 2011). The susceptibility of plants to both abiotic and biotic stressors such as drought, frost, pests or herbivory may also increase with enhanced plant tissue N contents (Power et al., 1998; Throop and Lerdau, 2004). Besides eutrophication, increased N deposition may cause soil acidification in nutrient-deficient ecosystems with low buffering capacity. Thus, plant growth and interaction could be affected by both increased availability of toxic metal ions (Al^{3+} and Fe^{2+}) and the leaching of macro nutrients (mainly Ca^{2+} and Mg^{2+}), particularly in acidic soils with pH values below 4.5 (Aerts and Bobbink, 1999).

More than 11 % of natural ecosystems of the world are currently exposed to N deposition beyond a threshold of 10 kg N ha^{-1} yr^{-1}, which is considered the ‘critical load’ for most natural and semi-natural ecosystems (Dentener et al., 2006). Hence, Sala et al. (2000) identified airborne N deposition as one of the most important drivers of global biodiversity loss. In this context, scientific working groups under the UNECE Convention on ‘Long-range Transboundary Air Pollution’ (CLRTAP) elaborated the ‘critical load concept’ as an instrument to assess the risk by air pollution in vulnerable ecosystems and to predict accompanying degradation processes. Critical loads are defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (CLRTAP, 2004).

In recent years, different approaches have been applied to assess critical N loads for natural and semi-natural ecosystems, e.g. steady-state models, dynamic models, and empirical studies on critical N inputs. The latter is mainly based on field observations and experiments (Bobbink et al., 2010). Empirical critical loads of natural and semi-natural ecosystems were compiled and updated by experts under the auspices of the CLRTAP since 1992 (Bobbink and Hettelingh, 2010). The deduction of concrete values for critical N loads is mainly based on observational changes in the structure and functioning of ecosystems (Bobbink et al., 2010). Exceeding these thresholds can thus influence species composition and ecosystem functioning, e.g. when species with higher competitive vigour establish as a result of altered nutrient cycles (Bobbink, 2004).

Many recent analyses have contributed valuable databases on empirical critical loads to reliably assess an ecosystems’ susceptibility to airborne N. However, for many habitat types available knowledge is still limited, and the determination of critical N loads for these habitats still relies on expert judgement (Bobbink and Hettelingh, 2010). Problems for the applicability of findings may also arise from the short duration of many experiments (Silvertown et al., 2010) and the lack of long-term analyses with low N additions, which would allow for a more precise assessment of cumulative effects of low N inputs (Bobbink et al., 2010; De Schrijver et al., 2011). In some areas, high and long-lasting background N deposition may also hamper our ability to disentangle past and current effects of N deposition (Bobbink et al., 2010). In addition, the N deposition measurements and mapping, including wet, dry, and occult deposition, is laborious and expensive. Since these data are often modelled on the basis of few measuring stations (Builtjes et al., 2011), exact values at an ecosystem scale are scarce. The structure and height of the vegetation of an ecosystem, but also the landscape topography, wind direction, and distance to emission sources are variables influencing local (small-scale) variation of N deposition and making predictions of ecosystem responses to N depositions difficult (Schaap et al., 2015). A convenient and cost-efficient approach to assess the effects of N deposition is the usage of indicators (Pitcairn et al., 2003) that directly respond to shifts in N availability and thus may reveal both an ecosystem’s susceptibility to N fertilisation and consequences of an exceedance of critical N loads for ecosystem functions and related services.

The objective of our study was to identify ‘indicators’ (in terms of plant species responses and shifts in ecosystem properties) that best evidence a target ecosystem’s susceptibility to N deposition. To this end, we performed a three-year field experiment in which we quantified and compared growth responses of different plant species of different life forms (dwarf shrubs, graminoids, bryophytes, lichens) and shifts in ecosystem’s properties (plant tissue and soil C:N ratios) to six levels of experimentally simulated N deposition rates (0, 2.5, 5, 10, 20, and 50 kg N ha^{-1} yr^{-1}). Specifically, we aimed to identify those response variables with the shortest reaction time and the highest sensitivity to experimental N inputs. We selected coastal heathlands as a model ecosystem, because coastal heathlands are considered low-N environments with high sensitivity to N deposition, but current knowledge on the impact of N deposition on species composition and ecosystem functions in these systems is very limited (Bobbink and Hettelingh, 2010). Heathlands (i.e. communities of the *Calluno-Ulicetea*) occur in West and Northwest Europe in regions with high summer precipitation (oceanic to sub-oceanic climate) and under acidic soil conditions (Loidi et al., 2010). Coastal heathlands and heathlands in general form important ancient cultural landscapes within Europe that are currently highly endangered across Europe (e.g. due to airborne N deposition, encroachment of trees and invasive species, and habitat loss by land-use change and building development; Vikane et al., 2013; Saure et al., 2014; Bundesamt für Seeschifffahrt und Hydrographie, 2010; Bundesamt für Naturschutz, 2013). They are classified as a priority habitat type within the NATURA 2000 conservation network (code 2150: Atlantic calcified fixed dunes – *Calluno-Ulicetea*, Council Directive 92/43/EEC, Annex I). In this respect, our study also aims to contribute to a better understanding of the effects of N fertilisation on the species composition and ecosystem properties of a Europe-wide endangered habitat type. Our findings on coastal heathland responses to N fertilisation also may provide more information for evidence based assessments of critical loads in general, both within and beyond heathlands.

2. Materials and methods

2.1. Study site

The field experiment was conducted in coastal heathlands of the island of Fehmarn (Baltic Sea, North Germany; 54°28 N, 11°7 E, 0 m a.s.l.). This area was chosen due to low background deposition rates of N, which amounted to 9 kg ha^{-1} yr^{-1} (based on modelled data of Schaap et al., 2015). The study area is characterised by an oceanic climate with a mean annual precipitation of 544 mm and mean annual temperature of 9.5 °C within the years 1997–2014 (German Weather Service, downloaded on 2015-03-16). Coastal heathlands of the study area are associated with nutrient-poor, acidic and sandy Regosols (Food and Agriculture Organisation of the United Nations, 2015). Mean pH-values (in $H_2O_{dest.}$) ranged between 4.1 (O-horizon), 4.4 (A-horizon), and 4.7 (C-horizon). The average soil N content amounted to 0.84 % (O-horizon), 0.07 % (A-horizon), and 0.01 % (C-horizon), and the average cation exchange capacities were low as expected for such sandy acidic soils: 26.5 $mmol_c$ kg^{-1} (O-horizon), 3.6 $mmol_c$ kg^{-1} (A-horizon), and 2.6 $mmol_c$ kg^{-1} (C-horizon). The study sites were dominated by the dwarf shrub species *Calluna vulgaris* (L.) Hull. (henceforth referred to as *Calluna;* with an average cover of this species of 67 % in 2012), followed by graminoid species (16 %). Moreover, the cryptogam flora covered more than 20 % with lichens of the genus *Cladonia* Hill ex Browne and different bryophyte species (11 and 10 %, respectively).