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Editorial

Nitrogen deposition impacts on biodiversity in terrestrial ecosystems: Mechanisms and perspectives for restoration

1. Nitrogen deposition and biodiversity

Human influences on environmental conditions have grown to such a large, planetary scale that scientists have coined a new geological era, the Anthropocene, to mark anthropogenic change as a geological force (Corlett, 2015). One of the major geological impacts of humanity concerns the nitrogen (N) cycle. Overall, human activities have been estimated to increase the global production of reactive N to more than three times the natural production (Fowler et al., 2013). The invention of chemical fertilisers, based on the conversion of inert N_2 into reactive forms of N, has enabled the human population to grow far beyond the estimated N-limited level of 3 billion people (Erisman et al., 2015). Emissions of ammonia (NH_3) and N oxides (NO_x) have strongly increased in the second half of the twentieth century (e.g., Sutton et al., 2008). Ammonia is volatilized from agricultural systems, such as dairy farming and intensive animal husbandry, whereas NO_x originates mainly from burning of fossil fuel by vehicles, the power generation sector and industry. Because of short- and long-range transport of these nitrogenous compounds, atmospheric N deposition has increased substantially in many natural and semi-natural ecosystems (Dentener et al., 2006). Areas with high atmospheric N deposition are nowadays found in Europe, eastern USA and, since the 1990s, Asia. It is currently considered one of the main threats for biodiversity in ecosystems of high conservational value across the globe (Sala et al., 2000; Bobbink et al., 2010; Steffen et al., 2015).

The series of events occurring when N inputs increase in a region with originally low background N deposition rates is highly complex. Many ecological processes interact and operate at different trophic levels and spatio-temporal scales. Despite this highly diverse sequence of events, the following main types of impact have been recognised thus far. Long-term N enrichment may gradually increase the availability of N, leading to competitive exclusion of characteristic plant species by more nitrophilic plants. Soil acidification (with losses of buffering capacity and increased concentrations of toxic metals) is especially important in weakly buffered environments when acid-tolerant plant species become dominant while several plants typical of intermediate acidity disappear. In addition, the ensuing change in the balance between ammonium and nitrate may also affect the performance of typical plant species. Finally, increased susceptibility to secondary stress (drought, frost) and disturbance factors such as pathogens or herbivores have been observed under high N loads. This has indeed been documented for a range of terrestrial and wetland ecosystems, especially in Europe and Northern America (e.g. Bobbink et al., 1998; Dise et al., 2011; Pardo et al., 2011). The severity of these impacts depends on the biogeochemistry of the particular ecosystem, but is especially severe under oligo- to mesotrophic, weakly buffered soil conditions. To control the negative consequences of atmospheric N deposition, critical loads for N deposition have been determined for ecosystems in Europe (Bobbink and Hettelingh, 2011) and North America (Pardo et al., 2011), but remain to be established for other parts of the world.

For some of the affected ecosystems, such as species-rich grasslands, heathlands, moorlands, bogs and shallow soft water lakes, the challenge is now moving from scientific understanding of the impacts of N deposition on plant communities to the development of effective measures for restoration and conservation. The understanding of N deposition effects on the functioning of soil biota is also rapidly increasing (Treseder, 2008; Farrer et al., 2013; Wei et al., 2013; Liu et al., 2014). However, the influences of atmospheric N deposition on higher levels in the food web are still poorly understood, both in terms of driving mechanisms and impacts on animal biodiversity (Haddad et al., 2000; Throop and Lerdau, 2004; WallisDeVries & Van Swaay, 2006; Pöyry et al., 2016). In this special issue, we aim to bring together evidence on the effects of enhanced N deposition on biogeochemistry, soil community and plant diversity, as well as the knowledge on effects at higher trophic levels. These insights are presented in the conservational context which is the focus of this journal. Hence, we also address their application to the monitoring, restoration and conservation of biological diversity under anthropogenic N deposition.

2. Scope of the special issue

In this special issue, we have assembled twelve papers on a range of aspects relating to the impacts of atmospheric N deposition on terrestrial ecosystems and biodiversity conservation. We have restricted ourselves to the effects of N deposition on terrestrial ecosystems, including wetlands. The effects on aquatic ecosystems should also be considered as substantial (see Rabalais, 2002; De Vries et al., 2015; Erisman et al., 2015), but given the large difference in ecosystem processes and environments, we have not included them in this special issue.

The first four papers give an overview of the impacts of N deposition on terrestrial plant communities. Soons et al. (2017) present a meta-analysis of long-term nutrient addition experiments to disentangle the effects of N and P (phosphorus) and their interaction, where they find that N but not P enrichment reduced plant species richness in herbaceous vegetation across the globe. The three following papers focus on dune ecosystems, where the effects of N deposition have previously been underestimated. Bird and Choi (2017) show that N enhances grass dominance and reduces plant species diversity in American inland dunes. Kooijman et al. (2017) investigated coastal dunes in the

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Netherlands and also found plant species loss due to increased grass dominance at high N deposition. Furthermore, they show that effects differ between soil types with decalcified or acidic dunes being more vulnerable for grass encroachment, due to higher P-availability. Aggenbach et al. (2017) compared coastal dunes in the Netherlands and the United Kingdom and focussed on N dynamics during dune succession. They emphasize that high N deposition accelerates acidification and decreases plant diversity in the long term.

The three following papers examine effects of N deposition at the higher trophic levels of animal communities, where the evidence is still scarce. Nijssen et al. (2017) review existing knowledge and provide a conceptual framework of ten different pathways affecting animal communities. In these pathways, indirect effects predominate through changes in habitat structure, plant species composition, host plant quality and food web structure. Vogels et al. (2017) focus on the plant quality aspect in a study of heathland Carabid beetles and Diptera flies. They find a negative correlation between plant N:P ratio and invertebrate species richness and abundance, suggesting that N deposition increases P-limitation through changes in plant stoichiometry. Furthermore, the supposed restoration by sod cutting only appears to aggravate this unbalance. WallisDeVries and Van Swaay (2017) analyse changes in butterfly communities in the Netherlands on the basis of extensive monitoring data covering 25 years. They find an increasing abundance in a minority of species from high-N habitats relative to the decline in the majority of species from low-N habitats. These contrasting species groups also show different traits relating to growth rate, generation time and mobility. They use species-specific N optima to develop a biotic indicator of N deposition showing an increase that levels off as N exceedance levels are falling.

Rowe et al. (2017) continue on the development of tools to monitor changes in N deposition in relation to the implementation of policies to reduce N emissions into the environment. They review a range of potential indicators and conclude that a new Moss Enrichment Index (MEI) based on species-specific ranges of tissue N content (at low N deposition) and measurements of N leaching (at high N deposition) provide promising metrics for evaluating the ecological benefits of decreased N deposition.

In the context of restoration, Stevens (2016) examines how long it takes for soils and plant communities to recover from high levels of N deposition. She concludes that, unfortunately, recovery rates are (very) slow for both soils and vegetation. Besides a reduction of N emissions, active restoration and mitigation therefore appear crucial and highly needed in the coming years. Jones et al. (2017) review effects of restoration measures, such as grazing, cutting, sod cutting, burning and hydrological management in grasslands, heathlands and bogs. They show that while most activities improve habitat suitability, quite severe measures, such as heavy cutting, scrub clearance or sod cutting, are needed to reduce the amount of N accumulating in soil pools at current deposition rates. Moreover, the adverse effects on biodiversity of an increased frequency or intensity of management methods to achieve higher N removal present a clear risk in the large-scale implementation of mitigating measures. Thus, sod cutting and top soil removal may be effective options for N removal, but due to their drastic impact, the former is applied at small spatial scale only and the latter is usually applied only on former agricultural fields. Van der Bij et al. (2017) studied whether sod cutting and topsoil removal were effective techniques for restoring oligotrophic conditions on former agricultural sites under high N deposition. They found that only topsoil removal was sufficiently effective in N removal. However, the resulting vegetation development also depended strongly on the soil microbial system, suggesting an important bottom-up impact of soil biota on vegetation. Unless high N deposition levels are reduced, the success of such restoration measures will remain temporary, however, and necessitate repeated restoration measures.

In the final paper, Schoukens (2017) reviews the policy instruments that are applied to address the negative effects of N deposition on the quality of sensitive habitats in Europe. He focuses in particular on the Programmatic Approach Nitrogen that has been developed in the Netherlands specifically for this purpose and has been implemented since 2015. This policy instrument uses the expected positive effects of reductions in N emissions in combination with on-site mitigation and restoration measures as a means to create additional space for economic development. Schoukens argues that the strong reliance on the positive effects of active restoration measures may be a risky strategy under continued high N exceedance in the face of the precautionary principle underlying the European strategy for the conservation of biodiversity.

3. Future perspectives

The papers in this special issue show that anthropogenic N inputs are changing plant and animal communities to a significant extent, with an overall effect of biodiversity loss. Spontaneous recovery of soils and vegetation after reducing N deposition appears to be very slow. Hence, active restoration and mitigation is essential to preserve biodiversity under long-term excessive N. The options for mitigation appear limited, however, as measures for N removal can be found to be detrimental to the pools of P and other nutrients, with consequences for plant stoichiometry and the associated animal community. Therefore, as argued by Schoukens (2017), mitigation does not appear a safe long-term strategy for the conservation of biodiversity in the face of excessive N deposition. The only viable long-term option for the conservation of biological diversity seems a substantial reduction of N emissions into the environment.

Understanding the impacts of N deposition on biodiversity ultimately requires knowledge on ecosystem processes at multiple levels, from soil biota to plants and animals, and their interactions. In this special issue, knowledge gaps have been identified particularly with respect to mechanisms determining the response of animal communities. The causal chain from excess N to food-plant chemistry, invertebrate herbivore performance and prey availability to higher trophic levels deserves special attention. At the same time, there is a need for more research on the impacts of N deposition at lower trophic levels of soils biota as determinants of plant physiology and the performance of characteristic plant species of low-N environments.

A further challenge is that the impacts of N excess are not isolated from other environmental changes. With growing N availability for food production, Earth's human population has grown spectacularly, leading to cascading effects on land use and climate (Erisman et al., 2015). Understanding the complex interactions between these environmental changes will present a major challenge for biodiversity research in the coming decades. These interactions may reinforce each other, as in the combined impacts of land use intensification and N fertilisation (e.g., Öckinger et al., 2006). But less obvious interactions may also arise, such as the cooling of spring microclimates in temperate regions with a combination of N deposition and climatic warming (WallisDeVries & Van Swaay, 2006; Nijssen et al., 2017).

Overall, in compiling this special issue, we realised that the scientific community studying the effects of N deposition on ecosystem functioning and biodiversity is still relatively small compared to the magnitude of the problem. When comparing the research field to that of climate change, it is evident that we are still a long way from an International Panel on Nitrogen Change, although the urgency is no less severe (Steffen et al., 2015). Most research, including this special issue, still concentrates in Europe and North America. Research efforts in China are rapidly increasing (see Liu et al., 2011; Wei et al., 2013; Soons et al., 2017) but there is a great need to collect similar evidence from (sub)tropical parts of the globe where N deposition is increasing, especially southeast Asia. This will inform us to what extent the effects from N excess differ between temperate and tropical environments.

The effects of N deposition on biodiversity present a global challenge, both for science and for conservation. We hope that this special issue will help to meet this challenge by presenting new evidence and reviewing current experience on restoration and conservation practices with respect to N deposition.

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