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Atmospheric nitrogen deposition to global forests: Status, impacts and management options☆

1. Introduction

The discovery of nitrogen (N), its chemical compounds and reactions has advanced human understanding of N cycling from the eighteenth century (Galloway et al., 2013). Until the early twentieth century, the anthropogenic creation of new reactive N was negligible compared with natural N flows (e.g., biological N fixation) (Fowler et al., 2013). This situation has changed due to the invention of industrial conversion of N_2 to ammonia (NH_3), known as the Haber–Bosch process, which has substantially increased N fertilizer for food production and consequently sustained the growth of global population thereafter. In turn, the growing population has further driven an increase in consumption of fossil fuels and increased the atmospheric emissions of N oxides (NO_x) as a by-product. Overall, the anthropogenic creation of reactive N has dramatically increased the losses of reactive N to the environment and resulted in a cascade of environmental impacts (Erisman et al., 2013; Stevens, 2019).

Covering approximately one third of the global land surface, forests provide multiple ecosystem services (e.g., conservation of soil, water and biodiversity) as well as fundamental cultural or spiritual values (Keenan et al., 2015; Miura et al., 2015). New N inputs via atmospheric deposition can result in both beneficial and deleterious effects on forest ecosystems, such as a stimulation of carbon (C) sequestration under N-limited conditions (De Vries et al., 2014; Schulte-Uebbing and De Vries, 2018), a loss of species diversity (Bobbink et al., 2010), soil acidification (Bowman et al., 2008) and nutrient imbalances (Du et al., 2016). Therefore, it is important to understand the current status of N deposition and how changing N deposition alters forest ecosystem structure and function from regional to global scales. This is crucial to project the future changes in forest ecosystem services, and to better guide forest management to improve the ecological resiliency of natural and planted forests.

The International Union of Forest Research Organizations (IUFRO) is the largest international network of forest scientists, which aims to promote global cooperation in forest-related research and enhances the understanding of the ecological, economic and social aspects of forests and trees (https://www.iufro.org/). During the IUFRO 125th Anniversary Congress (18–22 Sep., 2017, Freiburg, Germany), IUFRO Research Group 7.01.03 (Atmospheric deposition, soils and nutrient cycles) organized a session entitled “Nitrogen deposition: spatial-temporal change and ecological impacts”. This session inspired an idea to organize a special issue in Environmental Pollution to summarize the recent research progress on the spatiotemporal patterns of N deposition in global forest ecosystems and its ecological impacts through a variety of monitoring, modelling and experimental efforts. As a result, this special issue includes ten papers to synthesize recent cutting-edge studies on 1) the characteristics of N deposition to global forests, 2) the impacts of N deposition on forest structure and function, 3) the responses of forest ecosystems to regional trends of N deposition and 4) the management options to mitigate negative impacts of N deposition in forest ecosystems (see Fig. 1 for a framework of the special issue).

2. Status, impacts and management options of nitrogen deposition to global forests

2.1. Spatial variation in nitrogen deposition to global forests

Although extensive monitoring and modelling efforts have recently been made to assess global patterns of N deposition (Lamarque et al., 2013; Vet et al., 2014), few assessments have focused specifically on N deposition to forests. Characterized by high canopy surface area, forests are a significant sink of N deposition with higher atmospheric N capture efficiency than other land use types. An assessment of N deposition to forests is a prerequisite to quantify its consequent ecological impacts.

Modelling approaches are often used to estimate spatial pattern of atmospheric N inputs due to scarce measurements of N deposition across the globe (Vet et al., 2014). In this special issue, Schwede et al. (2018) reviewed the approaches used to calculate N deposition in atmospheric chemical transport models. Using a multi-model mean from the Task Force on Hemispheric Transport of Air Pollution (HTAP2) (Tan et al., 2018), Schwede et al. (2018) further mapped atmospheric N inputs to global forests via dry, wet and total deposition (base year 2010). The estimates of total N deposition to global forest biomes ranged from 19 to 23 Tg N yr^{-1} based on different modelling approaches and criteria of forest coverage. Moreover, a comparison of model predictions (EMEP rv4.17) of forest-specific N deposition with that of grid cell average N deposition, indicates that the differences between the two values could be as much as a factor of two at grid scale, up to more than five in some extreme cases (Schwede et al., 2018). Differences of that magnitude have a profound impact on the determination of critical load exceedance for forest biomes. This analysis thus demonstrates the value of using forest-specific N deposition to assess forest ecosystem responses, instead of grid-based values, used in most existing studies on the impacts of N deposition.

☆ This paper has been recommended for acceptance by Yong Sik Ok.

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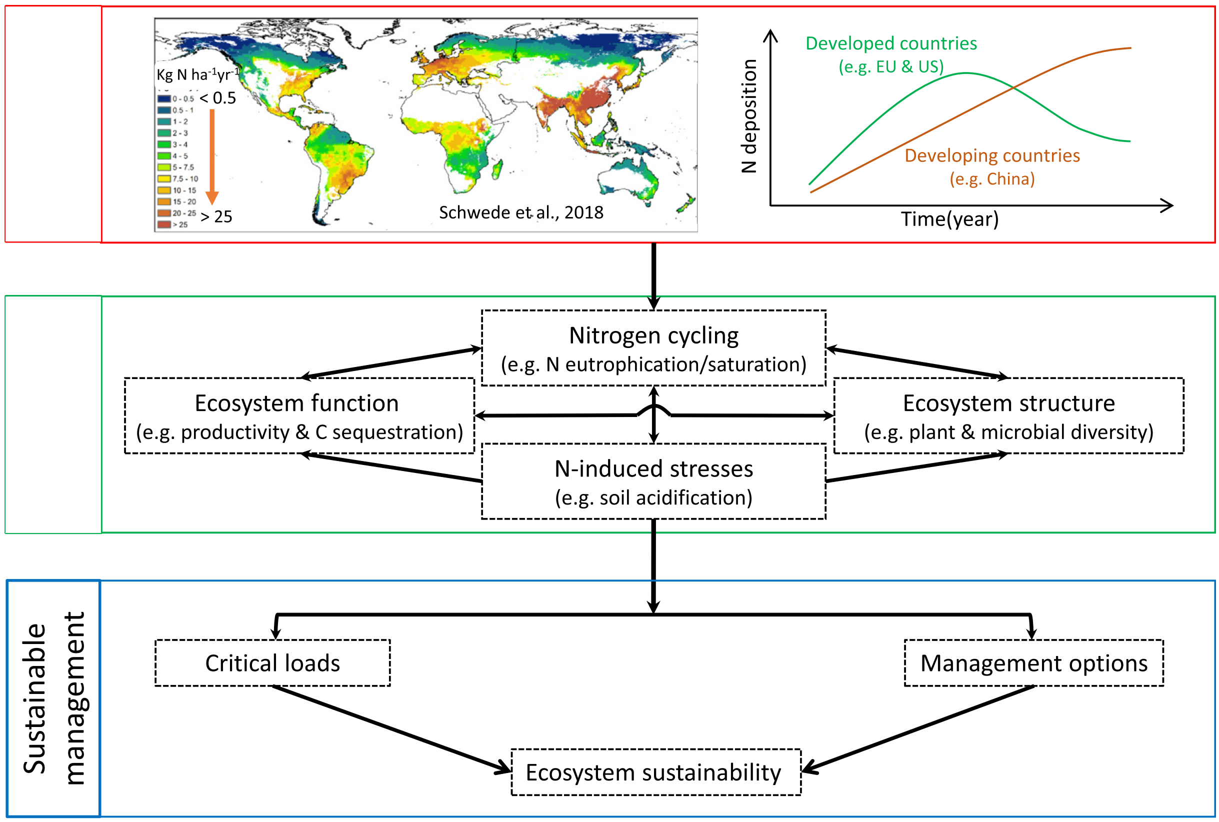

Fig. 1. Patterns, impacts and management options in view of nitrogen (N) deposition in forest ecosystems. This figure encapsulates the framework of this virtual special issue.

2.2. Impacts of nitrogen deposition on forest structure and function

As an external N source, N deposition directly increases N availability and consequently affects N cycling as well as the structure and function of forest ecosystems. In this special issue, we invited four papers to review the impacts of N deposition on soil N transformations (Cheng et al., 2019), mycorrhizal fungal community (Lilleskov et al., 2019), plant diversity (Perring et al., 2018), and net primary production (NPP) and C sequestration (Du and De Vries, 2018) in forest ecosystems.

Cheng et al. (2019) reviewed the factors controlling soil N transformations (i.e., N mineralization, nitrification and immobilization) and synthesized the responses to N deposition of net and gross N transformations in forest ecosystems. They found that N deposition significantly increased net rates of mineralization and nitrification. However, the effect of N deposition on gross N transformation rates, such as autotrophic nitrification, heterotrophic nitrification, dissimilatory nitrate reduction to ammonium, N mineralization, and N immobilization are poorly understood. Compared with net soil N transformation, Cheng et al. (2019) highlighted the importance of assessing the rates of gross soil N transformation processes and their responses to N deposition, which can shed new light on the ecological consequences in the context of changing N deposition.

Trees benefit from associations between roots and certain root-inhabiting fungi (e.g., ectomycorrhizal fungi, arbuscular mycorrhizal fungi) mainly due to improved nutrient supply and increased resistance to stressors (e.g., drought, pests and diseases). Lilleskov et al. (2019) reviewed the impacts of N deposition on the structure and function of mycorrhizal communities in forest ecosystems. The strong sensitivity of ectomycorrhizal fungi to N deposition suggests a disappearance of key ectomycorrhizal species or genera, which would reduce the capacity to access organic N and/or phosphorus and suppress the decomposition of organic matter. In boreal and temperate forests, ectomycorrhizal associations of conifers are more sensitive than those of deciduous trees, with current estimates of N critical loads of 5–6 kg ha^{-1} yr^{-1} for the former, and 10–20 kg ha^{-1} yr^{-1} for the latter (Lilleskov et al., 2019). However, the effects of N deposition on arbuscular mycorrhizal and tropical ectomycorrhizal communities are poorly understood. To gain more insights into the functional consequences of mycorrhizal community change due to N deposition, future efforts are needed to integrate phylogenomic methods with physiological, community, and ecosystem studies.

The negative impact of N deposition on plant diversity has gained increasing attention because of potential consequences for ecosystem services. Understory communities can dominate forest plant diversity and strongly affect overstory recruitment and ecosystem function. In this special issue, Perring et al. (2018) proposed a conceptual framework of context-dependent responses of understory plant community to N deposition. By analyzing data from 1814 European temperate forest plots that differed in levels of N deposition, community composition, local conditions and management history, Perring et al. (2018) concluded that the responses of understory species and community to N deposition varied greatly and depended on particular contexts (e.g., historical management, light and pH conditions). This information has important implications for the assessment of critical loads, and for conservation and restoration of plant biodiversity in forest ecosystems.

Forest C sequestration is driven by net primary production, which is widely limited by N availability (LeBauer and Treseder, 2008). New reactive N inputs to forest ecosystems include N deposition and biological N fixation (BNF). Until now, few studies have simultaneously quantified the contribution of these two external N inputs to NPP and consequent C sequestration in global forests. Based on a stoichiometric scaling approach, Du and De Vries (2018) estimated the N-induced new NPP, i.e., NPP due to external N inputs from BNF and N deposition, and its contribution to long-term C sinks in global boreal, temperate and tropical forest biomes. The results indicate that N-induced new NPP (3.46 Pg C yr^{-1}) contributes to a C sink of 1.83 Pg C yr^{-1} in forests globally, which approximately matches an independent estimate of the C sink in global established forests (Pan et al., 2011). This match suggests that C sinks in global forests are strongly driven by N-induced new NPP. Compared with BNF, N deposition makes a minor contribution to new NPP (0.41 vs 3.07 Pg C yr^{-1}) and C sinks (0.25 vs 1.58 Pg C yr^{-1}) in global forests (Du and De Vries, 2018). The new NPP and C sequestration from N deposition might be partially offset due to a down-regulation of BNF, but this effect has not been assessed.

In some extreme cases, N inputs via atmospheric deposition may result in ecosystem N saturation and this phenomenon has been first evidenced in several temperate and boreal forests in Europe and North America (Ågren and Bosatta, 1988; Aber et al., 1998). In this special issue, Yu et al. (2018) quantified the N mass balance across 11 subtropical forests (N deposition ranged from 13.8 to 113 kg N ha^{-1} yr^{-1} via throughfall) in South China and assessed the thresholds for N saturation by using a number of indicators, including N content, C/N ratio and ^{15}N in soil and vegetation. Their analysis indicates an N deposition threshold of 26–36 kg N ha^{-1} yr^{-1} for N leaching in these subtropical forests, being higher than the reported thresholds in temperate, Mediterranean and boreal forests (MacDonald et al., 2002; Aber et al., 2003; Dise et al., 2009; Fenn et al., 2015). The results suggest that the thresholds of ecosystem N saturation are context-dependent across forest types and spatial scales (Yu et al., 2018).

2.3. Responses of forest ecosystems to regional trends of nitrogen deposition

As a result of emissions abatement policies, N deposition, particularly in oxidized forms, has decreased substantially in European countries and the U.S. since the middle 1990s (Waldner et al., 2014; Du et al., 2014; Du, 2016). However, N deposition has been increasing dramatically in many developing countries, such as China and India (Liu et al., 2013; Kulshrestha et al., 2014). In this special issue, we invited three papers to critically review the responses of forest ecosystems to regional trends in Europe (Schmitz et al., 2019), the United States (Gilliam et al., 2019), and China (Tian et al., 2018), respectively.

Most existing work has emphasized the effects of excess N inputs on forest ecosystems, while ecosystem recovery with decreasing N deposition has been less studied. Schmitz et al. (2019) reviewed large-scale observational studies on European forest responses to decreasing N deposition based on trends in five well-monitored indicators, including soil solution N, foliar N concentrations, understory vegetation composition, tree growth and tree vitality. This synthesis indicates limited decreases in soil solution nitrate and foliar N concentrations in response to decreasing N deposition, while no large-scale responses for understory vegetation, tree growth or vitality were observed. By synthesizing responses of soil acidification, plant diversity, soil microbial communities, forest C and N cycling, and surface water chemistry, Gilliam et al. (2019) reviewed the impacts of declining N deposition on forest ecosystems in eastern North America. They further proposed a hysteretic model to project the likely forest recovery from future declines in atmospheric N deposition. Similar to the results of Schmitz et al. (2019), Gilliam et al. (2019) also indicate varying time lags for ecosystem recovery toward pre-N impact conditions, suggesting a considerable delay in ecosystem responses to achievements of clean-air policy.

By synthesizing experimental and observational results, Tian et al. (2018) reviewed the impacts of increasing N deposition on China's forests, with a special focus on soil biogeochemistry, plant nutrient stoichiometry, understory biodiversity, forest growth, and C sequestration. The overview indicates that N deposition generally results in an increase of soil N availability, leaf N content, leaf phosphorus resorption and soil N leaching, and a decrease of soil pH and microbial biomass in China's forests (Tian et al., 2018). In addition, N deposition significantly shifts the species composition in understory communities, but few experiments report a loss of plant species richness. Based on a further meta-analysis, Tian et al. (2018) showed that N deposition increased both the primary production and soil respiration in temperate forests, while it usually had a neutral effect on tree growth and a negative effect on soil respiration in subtropical and tropical forests. In light of stricter national ambient air quality standards, the rate of N deposition and the ratio of oxidized versus reduced N forms are expected to decrease in China, following the trends in Europe and the USA (Waldner et al., 2014; Du et al., 2014; Du, 2016). Therefore, the overview of the responses of European and U.S. forests to decreasing N deposition (Gilliam et al., 2019; Schmitz et al., 2019) may shed light on the responses of China's forests in the future.

2.4. Management options to mitigate negative impacts of nitrogen deposition

Although N deposition has declined in many parts of the U.S. and Europe since the 1990s, the recovery from the impacts of decades of elevated N deposition appears to be slow in time. Management interventions may have a potential to reduce the negative effects of N deposition and promote ecosystem recovery. Recently, Jones et al. (2017) assessed the role of several management approaches in mitigating the negative impacts of N deposition in European grasslands and heathlands. These remediation approaches include prescribed burning, carbon addition, thinning, liming, topsoil removal, mowing, grazing, planting and harvesting of plant biomass, and replanting desired target species either as seed, seedlings, or mature plants (Jones et al., 2017). However, no such analysis has yet been conducted for forests. In this special issue, Clark et al. (2019) reviewed the effects of four forest management approaches (prescribed burning, thinning, liming, C addition) on three indicators of recovery from N deposition (decreased soil N availability, increased soil alkalinity, increased plant diversity). Their results indicate a significant increase in soil N availability and understory plant diversity as a result of prescribed burning, an increase in understory plant diversity following thinning, an increase of soil alkalinity following liming, and a significant decrease of soil N availability following C addition. However, no single treatment is effective in promoting whole-ecosystem recovery from N deposition, suggesting that a combination of treatments should be considered.

3. Challenges and outlook

Significant achievements have been made to understand the impacts of N deposition on global forest ecosystems. However, many studies have focused on the single-factor effect of N deposition. We thus highlight research efforts to jointly consider multiple abiotic factors (e.g., climate warming, CO_2 enrichment, drought and increase in surface ozone) and biotic factors (e.g., insect outbreaks and invasive species), when evaluating ecological impacts of N deposition in the future.

Future trends of N deposition likely vary significantly by region across the globe (Fowler et al., 2013; Vet et al., 2014; Schwede et al., 2018). For instance, the relative importance of N deposition as a stressor is likely to increase in many developing countries, while it is declining in Europe and the U.S. In regions with increasing N deposition, the ecological effects of elevated N deposition need further assessment. In regions showing a decrease of N deposition, future efforts are needed to gain more insights into the trends and mechanisms of ecosystem recovery from elevated N deposition. Moreover, forest management options might also be considered to mitigate negative impacts of N deposition and facilitate ecosystem recovery, especially in the hotspot regions of N deposition.

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