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Threshold and multiple indicators for nitrogen saturation in subtropical forests

Qian Yu [a], Lei Duan [a, b, *], Longfei Yu [c, d], Xiao Chen [e], Gaoyue Si [a], Piaopiao Ke [a], Zhixiang Ye [e], Jan Mulder [c]

[a] *State Key Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China*
[b] *Collaborative Innovation Centre for Regional Environmental Quality, Tsinghua University, Beijing, 100084, China*
[c] *Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Box 5003, NO-1432 Ås, Norway*
[d] *Laboratory for Air Pollution & Environmental Technology, Empa, Ueberlandstr. 129, CH-8600 Duebendorf, Switzerland*
[e] *Air Environmental Modeling and Pollution Controlling Key Laboratory of Sichuan Education Institutes, College of Resources and Environment, Chengdu University of Information Technology, Chengdu, 610225, China*

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ABSTRACT

The influence of nitrogen (N) deposition on forest ecosystems largely depend on the N status. Developing threshold and practical indicators for N saturation in subtropical forests, with extremely high N deposition, would both enhance forest management and the assessments of global N balance and carbon (C) sequestration. Here, we quantified the N mass balance and assessed current N status at a number of subtropical forest sites in South China, using both N content, C/N ratio, and ^{15}N natural abundance ($\delta^{15}N$) as potential indicators of N saturation. Among the studied sites, N deposition ranged from 13.8 to 113 kg N ha^{-1} yr^{-1} in throughfall, and was dominated by ammonium (NH_4^+). The threshold for N leaching in subtropical forest was first found to be 26–36 kg N ha^{-1} yr^{-1}, which was 160% higher than in temperate forest (based on prescribed minimum). This indicates that critical parameter inputs in global models of the impact of N deposition are in need of revision, based on specific ecosystem characteristics. We found a critical C/N ratio of 20 for the O/A horizon as indicator of N saturation. Foliar N content and $\delta^{15}N$ were positively correlated with N deposition and were well suited to indicate regional N status. The $\delta^{15}N$ enrichment factor ($\mathcal{E}_{foli/So2}$, $\delta^{15}N_{foliage}$ - $\delta^{15}N_{Soil2}$) was between −10‰ and −1‰, and had similar trend to those obtained from other regions with increasing N deposition. These suggest that the enrichment factor could be used to investigate the influence of N deposition in forest ecosystems, regardless of spatial heterogeneity in $\delta^{15}N$ of N input, soil N availability and geomorphology.

1. Introduction

Enhanced atmospheric nitrogen (N) deposition has altered the status and dynamics of N and carbon (C) in forest ecosystems (Galloway et al., 2008). When N input exceeds the total biotic demand in forest ecosystem, the forest may be defined as "N-saturated" (Aber et al., 1989, 1998), indicated by enhanced rates of N mineralization and nitrification, and increased N losses through nitrate (NO_3^-) leaching and nitrous oxide (N_2O) emission (Aber et al., 1989, 1998). The negative effects of N saturation on forests, including soil and surface water acidification (Zhu et al., 2016; Yu et al., 2017b), nutrient leaching (Aber et al., 1989), forest decline (Lovett and Goodale, 2011), and biodiversity loss (Bobbink et al., 2010), have been addressed by many studies in temperate and boreal forests in Europe and North America over the last three decades (Aber et al., 1989, 1998; Dise et al., 2009; Gundersen et al., 2006). A common threshold for significant N leaching in temperate forests has been reported to be between 10 and 25 kg N ha^{-1} yr^{-1} (Aber et al., 1989, 1998; Gundersen et al., 2006; Dise et al., 2009).

In recent years, tropical and subtropical forests have been increasingly identified as hotspots for N deposition potentially with negative impacts on biodiversity, forest health and water quality (Gundersen et al., 2006; Liu et al., 2013). In south China, containing more than 45% of the world's subtropical forests (FAO, 2000), chronically elevated atmogenic N deposition up to

* Corresponding author. State Key Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China.
E-mail address: lduan@tsinghua.edu.cn (L. Duan).

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80–120 kg N ha^{-1} yr^{-1} has been reported (Yu et al., 2017b). However, due to the lack of threshold for N saturation in subtropical forest, much uncertainty remains for evaluating the impact of N deposition on global forests when using the similar threshold as that in temperate forest (Bobbink et al., 2010; Dentener et al., 2006). Recently, humid subtropical forests in south China were found to have efficient N retention in the organic surface and mineral soil under high N deposition (54 kg N ha^{-1} yr-1; Liu et al., 2017); and active denitrification as a significant N sink even in the well-drain soil (Zhu et al., 2013; Fang et al., 2015; Yu et al., 2016), which might result in a higher threshold for N saturation. A 7-year N mass balance study in Chongqing indicated that nearly all deposited atmogenic N (54 kg N ha^{-1} yr^{-1}) leached from the root zone (Huang et al., 2015). In contrast, Du et al. (2008) reported there were no symptoms of N saturation under a deposition of 26 kg N ha^{-1} yr^{-1} in a subtropical forest over four years in central China. Also N mass balances indicate that two other subtropical forests are far from N saturation at throughfall inputs of 23 kg N ha^{-1} yr^{-1} (Zhao et al., 2013b). These may suggest a threshold for N saturation (based on N leaching from the root zone) between 26 and 54 kg N ha^{-1} yr^{-1}. However, uncertainty remains with respect to the occurrence of N saturation and to what extent this differs from that in temperate forest.

Most evaluations for N status of forests are made with N mass balances based one long-term observation at multiple forest ecosystems under gradient N deposition (Aber et al., 1989, 1998; Dise and Wright, 1995; Fang et al., 2011b; Gundersen et al., 1998, 2006). However, the frequency and chronicity of measurement have limited its use (Pardo et al., 2007b), and stimulated the development of more practical indicators for forest N status. Proposed indicators include N contents of vegetation and soil as well as forest floor C/N ratios have been advised as excellent indicators for N saturation in tropical (Fang et al., 2011c), temperate and boreal forests (Nave et al., 2009; Niu et al., 2016). However, for example, forest floor C/N may not be as an excellent indicator in subtropical forests, where no or thin forest floor layer exists due to fast turnover of litter under warm and humid climate (Chen et al., 2004).

The natural abundance of ^{15}N (expressed as $\delta^{15}N$) in soil and vegetation has been used as an alternative characteristic of forest N status, because it provides an integrated measure of the long-term N cycle based on singular sampling (Pardo et al., 2007a; b). If a forest becomes N saturated (i.e., with elevated nitrification and consequently increasing losses of ^{15}N-depleted NO_3^-), the soil and plant would be expected to become enriched in ^{15}N (Pardo et al., 2007a; b). Thus, foliar and soil $\delta^{15}N$ have been used to assess the regional N status in temperate, boreal, and tropical forests (Emmett et al., 1998; Pardo et al., 2006; Fang et al., 2011a). However, some studies showed that N-saturated forests may not necessarily be characterized as elevated $\delta^{15}N$ in foliage and soil (Kranabetter and MacKenzie, 2010; Fang et al., 2011c; Fang et al., 2013) and that $\delta^{15}N$ could not be used to indicate N saturation. The application of $\delta^{15}N$ indicators for N saturation remains to be evaluated in other regions, particularly subtropical forests with large N deposition.

Here, we studied spatial and temporal variabilities of concentrations and fluxes of nitrate (NO_3^-) and ammonium (NH_4^+) in throughfall and soil water in 11 subtropical forest ecosystems along an N deposition gradient. The relationship between N mass balance and ecosystem indicators of N saturation (N content, C/N ratio, and $\delta^{15}N$ in soil and vegetation) is assessed. Specifically, we (1) quantified the threshold for N saturation based on the N mass balance, and (2) developed practical indicators of N status in the subtropical forest ecosystems. The warm and humid climate and the strongly weathered Acrisols in the subtropical region may lead to different N cycling processes compared with that in temperate and boreal regions.

2. Materials and methods

2.1. Study sites

This study was conducted at eleven subtropical forest ecosystems in Southwest China (Fig. 1). Seven of these were located in Chongqing municipality (C1 to C7), and another four were located in neighboring Sichuan province (S1 to S4). Details of these sites are listed in Table 1. These sites are all secondary *Pinus massoniana* forests with stand age of 40–50 years, a typical forest type of subtropical China, with minimum direct human impacts. All sites have a subtropical monsoonal climate, with annual precipitation of about 1000 mm, with most rainfall occurring from May through September. The annual average temperature ranges from 16 to 18 °C. Haplic Acrisol is the dominated soil type at all sites. The eleven sites represent a gradient of inorganic N deposition in throughfall, ranging from 13.8 to 113 kg N ha^{-1} yr^{-1} (Table 1). Literature data on N fluxes from another 11 subtropical forests (Fig. 1) were included for comparison. Detailed description of these additional sites, including location, annual precipitation, temperature, and vegetation type, are presented in Table S2.

2.2. Sampling

Samples of throughfall (TF) and soil water (SW) (at about 5 and 25 cm soil depth, respectively) were collected weekly from July 2016 to June 2017 at sites C1 to C7, and from August 2012 to July 2013 at sites S1 to S4. Throughfall was sampled in quintuplicate in self-made collectors. The collectors consisted of an 8.6-cm-diameter funnel with nylon gauze to exclude canopy litter and an opaque 3L bottle to store water. Soil water was sampled in quadruplicate by Rhizon lysimeters (Eijkelkamp, Wageningen, the Netherlands) in a vacuum through 50 ml syringe for 12 h in each week. Water samples were stored at 4 °C. Every four weeks, the samples from all throughfall collectors or the same lysimeter were pooled into monthly bulk samples prior to analysis, and the total volumes of throughfall were recorded. Due to drought, some soil water samples were unavailable in some months.

The surface soil (So1, 0–5 cm) and deeper soil layers (So2, 15–25 cm) were sampled in quadruplicate after collecting the litter layer (Oi) at all sites. Vegetation samples including needles and trunk (tree ring) of *Pinus massoniana*, and aboveground vegetation (pteridophytes, such as *Dryopteris*, *Woodwardia*, and *Dicranopteris*) were collected in triplicate in each season at sites C1 to C7.

2.3. Chemical analyses

All monthly water samples were measured for pH (SevenGo-SG2 pH meter) in a sub-sample without filtration. Next, each water sample was filtered (0.45 μm syringe filters, Millex, Millipore Corporation, Billerica, MA, USA) and analysed for the concentrations of major ions (Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, NO_3^-, SO_4^{2-}, Cl^-, and F^-) by ion chromatography (ICS-2000, Dionex Corp., Sunnyvale, CA, USA; the operation conditions were shown in Table S1). The N fluxes (in kg N ha^{-1} yr^{-1}) in water samples were calculated by multiplying the monthly mean concentration of ammonium (NH_4^+) and nitrate (NO_3^-) with the estimated water flux. The monthly soil water flux was estimated on the basis of the Na^+ balance assumption (Huang et al., 2015).

Soil and vegetation samples were air-dried, ball crushed, sieved and analyzed for total nitrogen (TN; Kjeldahl method) and total organic carbon (TOC; Vario EL cube, Elementar Inc., Germany). Powdered samples were further milled and weighed in tin capsules and analysed for ^{15}N natural abundance by Flash-EA-IRMS system (Flash EA coupled with DELTA V isotope ratio mass spectrometer,