RETENTION PROCESSES OF ANTHROPOGENIC NITROGEN DEPOSITION IN A FOREST WATERSHED IN NORTHERN JAPAN

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Abstract: Understanding the response of forest ecosystems to anthropogenic nitrogen deposition is important to discussions on future scenarios of ecosystem functioning. In this study we clarified the changes that occur in nitrogen dynamics and budgets in two adjacent forest sub-catchments in northern Japan by manipulating nitrogen deposition in the watershed. This experiment was conducted by adding ammonium nitrate (50 kgN⋅ha\(^{-1}\)⋅yr\(^{-1}\)) to one of the two sub-catchments in the Nakagawa Experimental Forest, Hokkaido University, Japan. Approximately 90% of the nitrogen added to the experimental sub-catchment was retained in the watershed for the first year after application. Soil solution chemistry, potential nitrogen mineralization and the nitrogen storage capacity of the organic horizon and mineral topsoil were investigated at ridge sites, and at sites along the middle and lower slopes of each watershed. There were significant differences in nitrogen mineralization processes in the surface soil between the different sites along the slope. Higher net nitrification rates, in both the Oe/Oa horizon and in the mineral topsoil, were observed at sites on the lower slopes. Nitrogen addition also decreased the rate of net nitrogen mineralization in the Oe/Oa horizon significantly at sites on the lower slopes 1 month after the application of ammonium nitrate. Laboratory incubation experiments using \(^{15}\)N as a tracer indicated that the rapid immobilization of nitrogen by microorganisms in the Oe/Oa horizon was a very important processes by which the added nitrogen was retained within the system. Our results suggest that the relative interaction of immobilization and mineralization of nitrogen in surface soil is a very critical process, and that it affected the ability of the whole forest watershed to retain nitrogen under conditions of increased anthropogenic nitrogen deposition in this region.

Key words: atmospheric deposition, biogeochemistry, forest ecosystem, nitrogen budget, stream chemistry

Introduction

Current predictions of increased nitrogen emissions in the East Asian region in the coming decades (Galloway and Cowling 2001) have prompted scientists to address the question of how the natural forest ecosystems in this region will respond to increased nitrogen deposition. Although numerous studies of the effect of nitrogen deposition in forest ecosystems using budget analyses and experimental manipulation of atmospheric nitrogen inputs have been conducted in Europe and the United States (Dise et al. 1995; Emmett et al. 1998; Nadelhoff er et al. 1999), few such studies have been undertaken in Asian forests to date. The fate and dynamics of nitrogen in natural ecosystems are driven by biotic factors such as vegetation and microorganisms, and abiotic factors such as atmospheric deposition, infiltration of water through the soil and chemical adsorption. Consequently, case studies that assess the components of nitrogen cycling and budget...
are very important to the understanding of the response of forest ecosystems to increased nitrogen deposition, particularly in regions where such studies have been limited.

Experimental manipulation of atmospheric nitrogen deposition in forest ecosystems is a powerful tool with which to assess perturbations to the budget and dynamics of nitrogen in situ. Comparisons of nitrogen concentrations in soils and streams from treated and control sites facilitate assessments of the effect of nitrogen deposition in an environment. Stable isotope techniques ($^{15}$N dilution method) are also important experimental tools that can be employed to distinguish between enriched and preexisting nitrogen in the soil. This information can be used to determine the gross rates of transformation of nitrogen in soil.

In this study, we focused on the nitrogen budget and the role of the forest ecosystem against the increase nitrogen deposition in northern Hokkaido, Japan. The study area is considered to be a pristine ecosystem in Japan, and one that has received a very limited amount of nitrogen deposition. Consequently, the findings of this study could be considered as being representative of the response of unpolluted forest basins to the increase of nitrogen deposition predicted for the future. The objectives of this study were to clarify the quantitative changes in the nitrogen budget during the initial stage of increased nitrogen input, and to determine the mechanisms of nitrogen retention in the ecosystem, particularly in the organic layers of the surface soil.

**Materials and Methods**

1. **Study site**

This study was conducted in a pair of adjacent sub-catchments within the Dohran experimental watershed (6.0 ha) of the Nakagawa Experimental Forest, Field Science Center for Northern Biosphere, Hokkaido University (N44° 48', E142° 6'). The annual mean temperature and precipitation for this region are 5.8 °C and 1444 mm yr$^{-1}$, respectively. About 40% of the precipitation falls as snow, mainly from December to March. The vegetation can be categorized as a natural cool-temperate mixed forest, mainly dominated by Abies sachalinensis, Quercus crispula, Betula ermanii, Tilia japonica, Kalopanax pictus, Acer mono among about thirty species. The forest floor is covered by dense stands of Sasa dwarf bamboo (Sasa senanensis and Sasa kurilensis). The predominant bedrock and soil are Cretaceous sedimentary rock and Dystric Cambisols (FAO/Unesco 1988), respectively. The watershed was divided into two sub-watersheds - a control basin (1.1 ha) and an experimental (1.4 ha) basin - within which the experimental manipulation of nitrogen deposition, as detailed below, was assessed. The elevation of each basin ranged from 100–190 m a. s. l.

2. **Nitrogen addition experiment**

50 kgN ha$^{-1}$ of ammonium nitrate (NH$_4$NO$_3$) was added manually in particular form to the experimental basin. Given the difficulties associated with walking through the dense Sasa dwarf bamboo (1.5–2.0 m in height) during the growing season, the application of NH$_4$NO$_3$ in the basin was conducted once in early April of 2002 during the latter stages of snowmelt. Eleven personnel took two hours to carry out the application of nitrogen. The amount of nitrogen applied corresponded to twenty times amount derived from extant rates of atmospheric deposition.

Stream water was collected from the lower slopes of the treated and control basins at intervals of approximately 1–2 weeks from June 2001. The stream was gauged (90°, V-notch) at the lowest position of the whole experimental watershed (6.0 ha) and the water height was measured 10 minuets interval using a pressure transducer and data logger at the V-notch station. We assumed that the runoff from each sub-basin was equivalent to the total for the whole watershed. This was quantified from water height and the empirical relationship between the observed discharge and water height (Q-H curve). Tension lysimeters (DAIKI Co Ltd. DIK-8390) were installed to collect soil solutions from depths of 5 cm at ridges, and the middle and lower slopes of each sub-catchment, with four replicates taken for each sub-catchment on August 2001. A three-plate lysimeter (42 × 200 mm) was installed under the organic layer to collect leachate at ridge, middle and lower slopes in each basin. Soil leachate from the organic layer and soil solutions from the mineral soil were collected and analyzed monthly when there was no snowfall. All water samples were filtered (GF/F, Whatmann Co. Ltd.) and analyzed for concentrations of nitrate (NO$_3$), ammonium (NH$_4$) (Ion chromatography, DIONEX DX-500, Japan Dionex Co Ltd.), dissolved total nitrogen (Total nitrogen analyzer, TN-100, Mitsubishi Chemicals Co Ltd.) at the chemical laboratory of the Northern Forestry and Development Office, Field Science...
Center for Northern Biosphere, Hokkaido University. Net nitrogen mineralization and nitrification rate in organic (Oe/Oa) and mineral top soil (0–10cm) was determined by laboratory incubation at 25°C for 30 days. Inorganic nitrogen content before and after incubation was analyzed using flow injection analyzer (FI-500V, Aqua Lab Co. Ltd.) after the extraction using 2M-KCl.

3. Gross nitrogen transformation in soil

We used 15N as a tracer for laboratory incubation to determine the gross rate of nitrogen immobilization, nitrification and mineralization (Davidson et al. 1991; Wakamatsu et al. 2004). Samples collected from the Oa/Oe and A horizons (0–10 cm) were used for laboratory incubation. 1.8 mgN kg soil⁻¹ of (15NH₄)₂SO₄ and Na¹⁵NO₃ was supplied for 10 g (dry weight) of soil from the Oa/Oe horizon, respectively. Similarly, 3.0 mgN kg soil⁻¹ of (15NH₄)₂SO₄ and Na¹⁵NO₃ was supplied for 20 g (dry weight) of soil for the A horizon, respectively. Each sample was incubated for 15 minutes, 24 hours, 1 day and 1 month at 25°C, respectively, and sample moisture was controlled manually (Soil: Water = 1: 1.25 for Oa/Oe horizon, 60% of field capacity for A horizon) using distilled water during the incubation period. After the incubation period, samples were extracted using 2N-KCl for isotope analysis. 15N in the extracted solutes was trapped using a combination of procedures (Wakamatsu et al. 2004) of diffusion (Brooks et al. 1989; Hart et al. 1994a; Davidson et al. 1991) and Teflon-bag methods (Downs et al. 1999). Isotope ratios were determined using a mass spectrometer (Finnigan, MAT252) and an element analyzer (ThermoQuest, NC2500) in the chemical laboratory of Nagoya University. Gross nitrogen transformation (mineralization, nitrification and immobilization) was calculated based on the isotopic nitrogen budget during the incubation (Wakamatsu et al. 2004; Hart et al. 1994b).

Results and Discussion

1. Nitrogen metabolism in soil from various locations along the catchment slope

Dissolved organic nitrogen was dominant nitrogen species in soil solution from Oe/Oa horizon and soil solution from the mineral top soil (Table 1). Nitrate concentration in soil solution tended to be higher at the lower position than those at another slope position. Nitrate concentration in leachate from Oe/Oa horizon at the lower position was significantly higher than those in the ridge and the middle slope (p<0.05). Net nitrification rate in the Oe/Oa horizon and the mineral top soil at the both sub-catchments also closely related to the each position of the slope (Fig. 1): the nitrification rates in the lower position were higher than those in the ridge and the middle slope. These results suggested that soil moisture gradient with slope has strong influence on the nitrogen metabolisms and solute concentration in soil. The dynamics of the gross nitrogen transformation in soil also agree with above mentioned gradient with slope (Fig. 2). Gross ammonium production and immobilization was the dominant flow-pass of nitrogen metabolisms in both Oe/Oa and mineral soil, implying that this ecosystem is still nitrogen-limited and that nitrogen was tightly cycled between organic nitrogen and ammonium via microbial metabolisms (Table 2). Approximately 90 % of ammonium labeled by 15N-NH₄⁺ was retained as an organic form during the 24 hours in the Oe/Oa horizon, while only 50% of 15N-NH₄⁺ was retained as organic form in the mineral soil during the same period (data are not shown). Gross and net nitrification rate in mineral soil was higher at the lower slope compared to that in the ridge, although the gross nitrate immobilization in the Oe/Oe horizon was still high at both the ridge and lower slope. One month after the experimental nitrogen addition, net mineralization (laboratory incubation) in the Oe/Oa horizon at the lower position significantly decreased in the treatment sub-basin than in the control basin, suggesting that the nitrogen addition affected nitrogen metabolisms in the soil.

Table 1. Mean concentration of dissolved nitrogen in leachate from Oe/Oa horizon and soil solution from mineral soil (5cm depth) in the control watershed

<table>
<thead>
<tr>
<th></th>
<th>NH₄⁺</th>
<th>NO₃⁻</th>
<th>DON</th>
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<tbody>
<tr>
<td>Leachate from Oe/Oa horizon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ridge</td>
<td>39</td>
<td>87</td>
<td>159</td>
</tr>
<tr>
<td>middle slope</td>
<td>21</td>
<td>8</td>
<td>69</td>
</tr>
<tr>
<td>lower slope</td>
<td>21</td>
<td>114</td>
<td>161</td>
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<tr>
<th></th>
<th>NH₄⁺</th>
<th>NO₃⁻</th>
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<td>Soil solution from mineral soil (5cm depth)</td>
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<tr>
<td>ridge</td>
<td>21</td>
<td>31</td>
<td>119</td>
</tr>
<tr>
<td>middle slope</td>
<td>14</td>
<td>66</td>
<td>89</td>
</tr>
<tr>
<td>lower slope</td>
<td>9</td>
<td>80</td>
<td>130</td>
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</tbody>
</table>

2. Effect of nitrogen addition on stream chemistry and the nitrogen budget of the basin

Nitrate concentration in stream water increased sharply just after the addition of ammonium nitrate in the treatment
basin (data are not shown). However, concentration of nitrate, ammonium and dissolved organic nitrogen in stream water reached same level between control and treatment watershed about two months after the treatment. Annual nitrogen export from the treatment sub-catchment was more than two times higher than that in the control basin during first year after the treatment (Fig. 3). While dissolved organic nitrogen was dominant nitrogen species in stream water in the control basin, nitrate was dominant as dissolved nitrogen in the stream water in the treated basin. It was suggested the initial increase of nitrate concentration just after the addition contributed to increase the nitrate export in the treated basin. Nitrogen budget indicated that approximately 90 % of added nitrogen was retained in the watershed against sum of the ambient bulk nitrogen deposition (2.3 kgN·ha\(^{-1}\)·yr\(^{-1}\)) and experimentally added nitrogen (50 kgN·ha\(^{-1}\)·yr\(^{-1}\)). In northwestern Europe region, significant nitrate has been leached from the forest soil where receive 30–50 kgN·ha\(^{-1}\)·yr\(^{-1}\) of atmospheric N deposition. (Dise and Wright 1995). Our results indicated that the current forest ecosystem has high ability to retain the deposited nitrogen in the ecosystems. Since ecosystem function to retain nitrogen and the stage of nitrogen saturation are thought to shift temporally (Aber et al. 1998), more continuous monitoring and investigation will be need to understand the temporal response of forest ecosystem against anthropogenic nitrogen deposition.

Table 2. Gross nitrogen transformation (mgN·kg\(^{-1}\)·d\(^{-1}\)) in Oe/Oa horizon and mineral soil (0–10 cm) at the ridge and the lower slope in the control basin during 24 hours incubation

<table>
<thead>
<tr>
<th>Incubation horizon</th>
<th>gross ammonium production</th>
<th>gross ammonium immobilization</th>
<th>gross nitrification</th>
<th>gross nitrate immobilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oe/Oa horizon</td>
<td>ridge</td>
<td>148</td>
<td>149</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>lower slope</td>
<td>139</td>
<td>6.0</td>
<td>4.6</td>
</tr>
<tr>
<td>mineral soil (0–10 cm)</td>
<td>ridge</td>
<td>47</td>
<td>2.6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>lower slope</td>
<td>20</td>
<td>0.4</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Conclusion

To clarify the effect of nitrogen deposition on the nitrogen biogeochemistry and the budget in pristine forest ecosystem, experimental manipulation of nitrogen deposition was conducted in the sub-catchments in Nakagawa experimental forest, Hokkaido University, northern Japan. Based on the monitoring of soil and stream chemistry and the laboratory incubation to understand net and gross nitrogen transformation, we found that approximately 90 % of added nitrogen was retained in the basin during the initial year of the nitrogen addition. It was suggested that the rapid microbial immobilization in the surface soil, especially in organic layer was important mechanisms to retain the deposited nitrogen in the ecosystem.
Fig. 3. Dissolved nitrogen exports to the stream in the nitrogen added (50 kg N ha\(^{-1}\) yr\(^{-1}\)) and control watersheds for the initial year after the nitrogen was added (Control; control basin, Treatment; nitrogen-added watershed)

Acknowledgements

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References


