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Response to Nitrogen Loading in a P-limited Larch Forest Ecosystem in Sapporo, Japan

By

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Summary

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We investigated nitrogen cycling in five adjacent small catchments with Andisol soils supporting mature larch plantation in Sapporo, Japan. The foliar N:P weight ratio ranged from 35 to 71, which was higher than published threshold P-limitation values of 12.5 to 26.3, suggesting that the forest ecosystem was highly P-limited. The bulk dissolved inorganic N (DIN) input was 3.0 kg N ha^{-1} y^{-1}, which was lower than in N-saturated forests in Europe (more than 10 kg N ha^{-1} y^{-1}). The throughfall DIN inputs in the snow-free season quantified at five to six sites in each catchment (28 sites in total) was low and varied between 0.02 and 1.32 kg N ha^{-1} 6 $months^{-1}$. The stream DIN concentration was low (between 10 and 20 μmol_C L^{-1}). Foliar N contents (1.83 to 2.23%) was not significantly correlated with throughfall DIN inputs. These results suggest that the forest ecosystem was not affected by N-loading. On the other hand, some biogeochemical processes may have responded to the low level of N deposition. The mean stream DIN concentration in the five catchments (13.6 to 34.2 μmol_C L^{-1}), the N_2O flux (0.01 to 0.07 kg N ha^{-1} 6 $months^{-1}$), and the net primary production (4.83 to 15.6 m^3 ha^{-1} y^{-1}) increased significantly with increasing throughfall DIN input, possibly due to the soil's strong P retention. The results of our study suggest that the responses of forest ecosystems on volcanic soils differ from those of European forest ecosystems on nonvolcanic soils.

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Introduction

Reactive nitrogen (N) created by humans is leaking into the environment, including forest ecosystems (GALLOWAY & COWLING 2002). Most undisturbed forest ecosystems in temperate regions are N-limited and, as a result, discharge little nitrate (ABER & al. 1989). Reactive N deposited into forest ecosystems causes changes such as an increase in N mineralization and nitrification (MAGILL & al. 2000), a decrease in net primary production (NPP) (BOXMAN & al. 1998), nitrate leaching into streams (DISE & WRIGHT 1995), and an increase in N_2O emission (BUTTERBACH-BAHL & al. 2002). These effects have been observed in forests that received N deposition at levels greater than 10 kg N ha^{-1} y^{-1} (e.g., DISE & WRIGHT 1995).

Although temperate or boreal forests are generally N-limited (VITOUSEK & al. 2002), the growth is more strongly limited by elements such as phosphorus (P) or calcium (Ca) (MATSON & al. 2002) in some forests. P-limitation has been observed in highly weathered tropical soils (MATSON & al. 2002) and in Andisols containing allophane or imogolite, which show strong P retention (WADA 1977, SHOJI & al. 1993). Forest ecosystems that have developed on these soils would respond more to N loads (HALL & MATSON 1999).

NAKAHARA & al. 2003 studied spatial variation in the throughfall of dissolved inorganic nitrogen (DIN) and stream nitrate concentration in a larch (*Larix leptolepis* Gord.) forest ecosystem that developed on an Andisol in Sapporo, Japan, and found that nitrate concentrations in stream water were significantly correlated with DIN deposition despite a quite low input of N via throughfall (0.02 to 1.32 kg N ha^{-1} 6 $months^{-1}$). On this basis, we hypothesized that P-limitation had caused N cycling in this forest ecosystem to become highly responsive to relatively low loads of N. The first objective of the present study was to determine whether this forest was N-limited or P-limited. Second, we observed the effects of N deposition on biogeochemical processes other than the enhanced nitrate concentration in stream water.

Material and Methods

Mt. Shirahata (covering about 1000 ha and reaching an elevation of 300 m) is located in Sapporo City, Japan (42°56' N, 141°25' E). About 72% of the mountain, which is covered by Andisols (Hapludands) derived from volcanic ashes from a series of eruptions that occurred between 300 and 3000 years ago (unpublished data), supports stands of 50- to 60-year-old larch trees (*Larix leptolepis* Gord.). The mean annual temperature is 8.2 °C. The mean annual precipitation is 1130 mm, of which 380 mm falls as snow. Five small catchments on Mt. Shirahata, designated as Catchments A to E (Fig. 1), were selected for this study.

We established a rain collector (1.8 m long by 0.1 m wide) at one of the summits of Mt. Shirahata that had no trees (Fig. 1) and used the collector to collect bulk DIN deposition during the snow-free season. During the winter, snow was collected using steel cylinders (20 cm diameter by 25 cm hight). Snowfall and rainfall were collected using three plastic buckets (38 cm in diameter) during the spring thaw. We performed this collection once or twice per month from May 2001 to May 2003. The methods used to collect throughfall and stream water samples and to analyse water samples are described by NAKAHARA & al. 2003. We established all sample sites in larch stands.

N_2O emission was measured using a closed-chamber technique (KUSA & al. 2002) at 10 sites where throughfall samples were collected (Fig. 1) every 3 weeks from June to November 2003.

We installed three stainless-steel cylinders (20 cm diameter and 10 cm height) to a depth of 5 cm into the soil. All plants inside the cylinders were removed. During our measurements, hollow cylindrical steel caps (20 cm in diameter and 25 cm in height) were placed on top of the cylinders and 20-mL gas samples were taken in the chamber at 0, 60, and 120 minutes after installation of the cap. We also measured the air temperature around the chambers with a digital thermometer. We calculated N_2O fluxes following the method of KUSA & al. 2002.

We collected larch foliage at nine sites where N_2O emission was measured (Fig. 1). We cut a sample branch 2 to 3 m above ground level at each site during early September 2003 for foliar analysis. We collected mineral soil (to a depth of 50 cm) at one site on May 2004. Foliar samples were dried for 48 hours at 70 °C, and then they were weighed and ground using a mill. The ground samples were then analysed to determine their N and P contents using an NC analyser (NC-1000, Sumika Chemical Analysis Service, Ltd., Osaka, Japan) and acid digestion – colorimetric analysis, respectively. Soil samples were air-dried and sieved through a 2-mm sieve, and then analysed for inorganic P using the Bray II procedure and P retention (SAUNDERS 1965).

Net primary production (NPP, on a volume basis) of the aboveground wood of larch was estimated from the forest inventory data reported by the Greenery Promotion Department of Sapporo City (unpublished data). We estimated NPPs from these data based on sites where more than two measurements had been performed from 1989 to 2003. We excluded sites where the number of larch trees in the later measurement were less than 80% of the number during the earlier measurement as a result of thinning or tree mortality. We calculated NPP as follows:

$$NPP = (BM_F - BM_P) / (Y_F - Y_P) \quad (1)$$

where NPP is the net primary production of the aboveground wood ($m^3\ ha^{-1}\ y^{-1}$); BM_F and BM_P are the biomasses of the larches at the second and first measurements, respectively ($m^3\ ha^{-1}$); and Y_F and Y_P are the dates (years) of the second and first measurements, respectively.

The relation between the DIN flux and each parameter that we studied was investigated by Pearson's correlation coefficient test. Logarithmic transformations were made for all the variables if needed.

Results and Discussion

Foliar N:P ratios of plants have been applied to identify the thresholds of nutrient limitation (KOERSELMAN & MEULEMAN 1996), and the threshold of P limitation was considered to lie at a ratio of between 12.5 and 26.3 (TESSIER & RAYNAL 2003). The high foliar N:P ratios (35 to 71; Fig. 2) that we observed at Mt. Shirahata suggest that this forest was highly-P limited. The soils at Mt. Shirahata also showed low available P (13 mg kg^{-1}) and high P retention (85%). The observed available P was much lower than the values reported for European soils (50 mg kg^{-1}, NEYROUD & LISCHER 2003) and similar to those for the soils exposed to a high degree of weathering (<10 mg kg^{-1}, e.g., ABEKOE & SAHRAWAT 2001).

The bulk DIN input at Mt. Shirahata was 3.0 kg N $ha^{-1}\ y^{-1}$. DISE & WRIGHT 1995 reported that European forests receiving less than 10 kg N $ha^{-1}\ y^{-1}$ retained nearly all the deposited N and did not discharge significant amounts of N. ABER & al. 1989 proposed that N saturation could be characterized by an excessive accumulation of mineral N in soils or by increased leaching of nitrate or ammonium below the rooting zone. Thus, in Europe, forests receiving less than 10 kg N $ha^{-1}\ y^{-1}$ would not be N-saturated. The bulk DIN input at Mt. Shirahata was below this threshold.

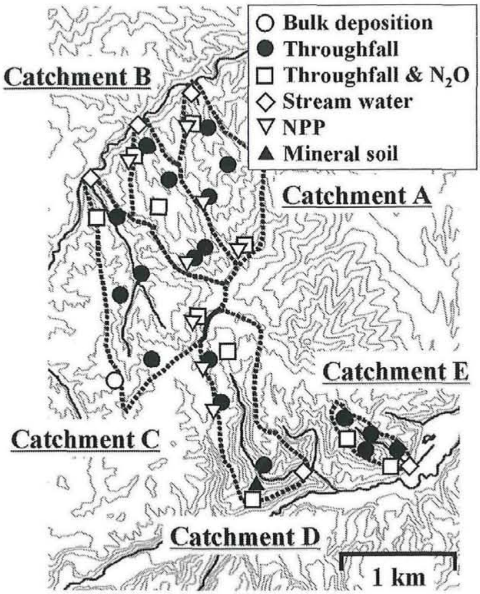

Fig. 1. Map of Mt. Shirahata with the Five catchments (A to E) and the plots.

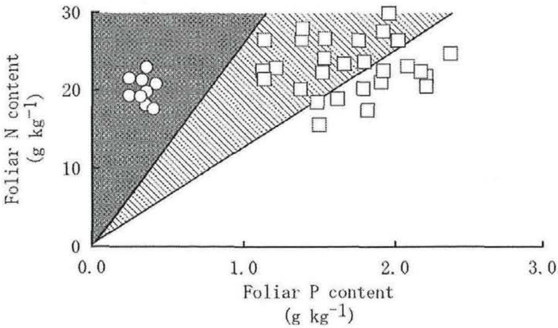

Fig. 2. Foliar P and N concentrations in the larch trees in this study (open circles) and in other studies (open squares; PÂQUES 1994, SON & GOWER 1992). TESSIER & RAYNAL 2003 proposed that a forest ecosystem whose foliar N:P ratio was greater than 26.3 kg kg^{-1} (grey zone) was P-limited and that a forest with a foliar N:P ratio less than 12.5 kg kg^{-1} was not P-limited (white zone). The striped zone represents the threshold of P limitation.

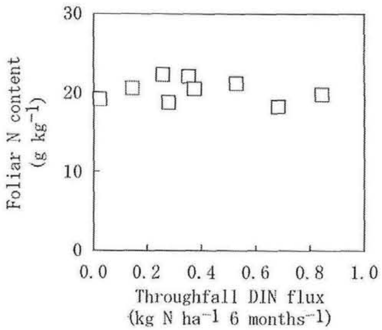

Fig. 3. The relationship between throughfall DIN and foliar N content..

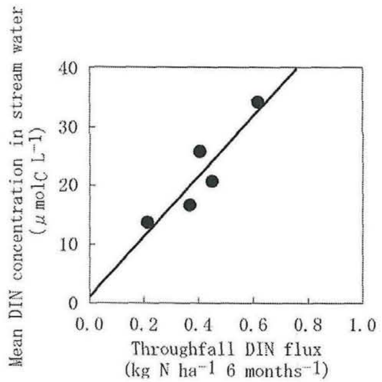

Fig. 4. The relationship between throughfall DIN flux and mean DIN concentration in Stream water.

Some previously reported data have indicated that the forest ecosystem at Mt. Shirahata was not affected by N-loading—that is, the forest was not N-saturated (ABER & al. 1989, WRIGHT & al. 2001). Throughfall DIN fluxes measured at 28 sites in our study (0.02 to 1.32 kg N ha^{-1} 6 $months^{-1}$) were very low. The concentration of DIN in stream water measured at the outlets of the five catchments was low, and ranged from 13.6 to 34.2 μmol_C L^{-1}. The foliar N contents measured at nine sites where we had established throughfall collectors (1.83 to 2.23%) were not significantly correlated with the throughfall DIN fluxes, and appeared to be constant irrespective of the DIN fluxes (Fig. 3).

Some biogeochemical processes in Mt. Shirahata were affected by N-loading. The mean concentrations of DIN in stream water measured at the outlets of the five catchments showed a significant positive correlation with the mean throughfall DIN fluxes in the five catchments ($P<0.05$; Fig. 4). The nitrate concentration in stream water at Mt. Shirahata did not change seasonally (data not shown).

N_2O fluxes (0.01 to 0.07 kg N ha^{-1} 6 $months^{-1}$) measured at 10 sites where we installed throughfall collectors was also correlated with the throughfall DIN fluxes ($P<0.05$; Fig. 5). NPP (4.83 to 15.6 m^3 ha^{-1} y^{-1}) increased with increasing throughfall DIN fluxes ($P<0.05$, Fig. 6).

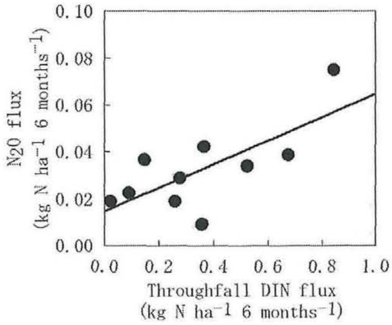

Fig. 5. The relationship between throughfall DIN and N_2O flux.

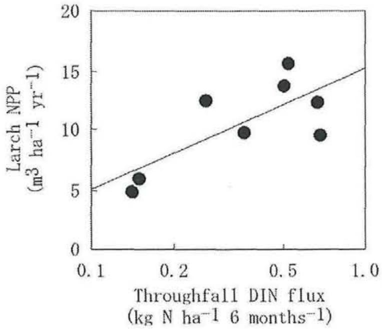

Fig. 6. The relationship between throughfall DIN and larch NPP.

The DIN inputs at Mt. Shirahata were extremely low compared with the maximum values for other forest ecosystems that have been reported to be affected by N loading (Table 1). In general, forest ecosystems have been reported to respond to N loading when the forests received more than 20 kg N ha^{-1} y^{-1}, but our study site at Mt. Shirahata received only 3.0 kg N ha^{-1} y^{-1}.

We conclude that the correlations between DIN deposition and stream DIN concentration, N_2O fluxes, and NPP that we observed at Mt. Shirahata resulted from a high degree of P-limitation. HALL & MATSON 1999 also concluded that a P-limited tropical forest responded to N loading more than was observed with an N-limited forest. The results of our study suggest that the responses of forest ecosystems on volcanic soils differ from those of European forest ecosystems on nonvolcanic soils.

Table 1. N inputs reported in the literature on the effects of N deposition in forest ecosystems.

Reference	Deposited N (kg N ha^{-1} y^{-1})	Source of the N	Location
BOXMAN & al. 1998	60	N deposition	Netherlands
BUTTERBACH-BAHL & al. 2002	15-22	N deposition	Germany
GUNDERSEN & al. 1998	13-59	N deposition	Europe
HALL & MATSON 1999	0-175	N application	Hawaii
LAMONTAGNE & SCHIFF 2000	40	N application	Canada
MAGILL & al. 2000	50-150	N application	USA
SOLBERG & al. 2004	1.7-19	N deposition	Norway

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References

ABEKOE M. K. & SAHRAWAT K. L. 2001. Phosphate retention and extractability in soils of the humid zone in West Africa. - Geoderma 102: 175-187.

ABER J. D., NADELHOFFER K. J., STEUDLER P. & MELILLO J. M. 1989. Nitrogen saturation in northern forest ecosystems - Excess nitrogen from fossil fuel combustion may stress the biosphere. - BioScience 39: 378-386.

BOXMAN A. W., VAN DER VEN P. J. M. & ROELEFS J. G. M. 1998. Ecosystem recovery after a decrease in nitrogen input to a Scots pine stand at Ysselsteyn, the Netherlands. - For. Ecol. Manage 101: 155-163.

BUTTERBACH-BAHL K., BREUER L., GASCHE R., WILLIBALD G. & PAPEN H. 2002. Exchange of trace gases between soils and the atmosphere in Scots pine forest ecosystems of the northeastern German lowlands 1. Fluxes of N_2O, NO/NO_2 and CH_4 at forest sites with different N-deposition. - For. Ecol. Manage 167: 123-134.

DISE N. B. & WRIGHT R. F. 1995. Nitrogen leaching from European forests in relation to nitrogen deposition. - For. Ecol. Manage 71: 153-161.

GALLOWAY J. N. & COWLING E. B. 2002. Reactive nitrogen and the world: 200 years of change. - Ambio 31: 64-71.

GUNDERSEN P., EMMETT B. A., KJONAAS O. J., KOOPMANS C. J. & TIETEMA A. 1998. Impact of nitrogen deposition on nitrogen cycling in forests: a synthesis of NITREX data. - For. Ecol. Manage 101: 37-55.

HALL S. J. & MATSON P. A. 1999. Nitrogen oxide emissions after nitrogen additions in tropical forests. - Nature 400: 152-155.

KOERSELMAN W. & MEULEMAN A. F. M. 1996. The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. - J. Appl. Ecol. 33: 1441-1450.

KUSA K., SAWAMOTO T. & HATANO R. 2002. Nitrous oxide emissions for 6 years from a gray lowland soil cultivated with onions in Hokkaido, Japan. - Nutr. Cycl. Agroecosys. 63: 239-247.

LAMONTAGNE S. & SCHIFF S. L. 2000. Response of soil microorganisms to an elevated nitrate input in an open *Pinus banksiana* - *Cladina* forest. - For. Ecol. Manage 137: 13-22.

MAGILL A. H., ABER J. D., BERNTSON G. M., MCDOWELL W. H., NADELHOFFER K. J., MELILLO J. M. & STEUDLER P. 2000. Long-term nitrogen additions and nitrogen saturation in two temperate forests. - Ecosystems 3: 238-253.

MATSON P., LOHSE K. A. & HALL S. J. 2002. The globalization of nitrogen deposition: consequences for terrestrial ecosystems. - Ambio 31: 113-119.

NAKAHARA O., YAMAGAMI T., KOIDE T., SAKAI K. & HATANO R. 2003. Spatial variation in nitrogen deposition over five adjacent catchments in a larch forest. - Soil Sci. Plant Nutr. 49: 741-746.

NEYROUD J. A. & LISCHER P. 2003. Do different methods used to estimate soil phosphorus availability across Europe give comparable results? - J. Plant Nutr. Soil Sci. 166: 422 - 431.

PÂQUES L. E. 1994. Relationship between foliar nutrient concentrations and growth of hybrid larch (*Larix* x *eurolepis* Henry). - For. Ecol. Manage 63: 153-167.

SAUNDERS W. M. H. 1965. Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter, and other soil properties. - N.Z. J. Agric. Res. 8: 30-57.

SHOJI S., NANZYO M. & DAHLGREN R. 1993. Productivity and utilization of volcanic ash soils. - In: SHOJI S., NANZYO M. & DAHLGREN R. (Eds.), Volcanic ash soils, pp. 209-251. - Elsevier Amsterdam.

SOLBERG S., ANDREASSEN K., CLARKE N., TORSETH K., TVEITO O. E., STRAND G. H. & TOMTER S. 2004. The possible influence of nitrogen and acid deposition on forest growth in Norway. - For. Ecol. Manage 192: 241-249.

SON Y. & GOWER S. T. 1992. Nitrogen and phosphorus distribution for five plantation species in southwestern Wisconsin. - For. Ecol. Manage 53: 175-193.

TESSIER J. T. & RAYNAL D. J. 2003. Use of nitrogen to phosphorus ratios in plant tissue as an indicator of nutrient limitation and nitrogen saturation. - J. Appl. Ecol. 40: 523-534.

VITOUSEK P. M., HÄTTENSCHWILER S., OLANDER L. & ALLISON S. 2002. Nitrogen and nature. - Ambio 31: 97-101.

WADA K. 1977. Allophane and imogolite. - In: DIXON J. B. & WEED S. B. (Eds.), Minerals in soil environments, pp. 603-638. - Soil Science Society of America, Madison, Wisconsin.

WRIGHT R. F., ALEWELL C., CULLEEN J. M., EVANS C. D., MARCHETTO A., MOLDAN F., PRECHTEL A. & ROGORA M. 2001. Trends in nitrogen deposition and leaching in acid-sensitive streams in Europe. - Hydr. Earth System Sci. 5: 299-310.