Inorganic nitrogen dynamics of throughfall following fertilization in a red pine stand

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ABSTRACT

Inorganic nitrogen fluxes caused by rainfall and throughfall following fertilizer applications were measured in a red pine stand located in the Wola National Experimental Forest in Jinju, Korea. Fertilizer (N3P4K1 = 113:150:37 kg ha−1 yr−1) was applied for 2 years, and inorganic nitrogen fluxes were monitored from April 2011 to March 2013. Monthly variations in inorganic nitrogen concentrations were generally higher in the throughfall than in the rainfall, whereas monthly variations in concentrations were similar between the fertilized and control treatments. The mean NH4+ and NO3− concentrations during the study period were 0.39 and 0.21 mg L−1 for the rainfall, 1.06 and 1.06 mg L−1 for the control, and 1.01 and 0.89 mg L−1 for the fertilizer treatments, respectively. Inorganic nitrogen fluxes were generally higher during the growing season (May–October) than during the dormant season (November–April). Inorganic nitrogen fluxes were higher in the throughfall (17.03 kg ha−1 yr−1 in the control treatments and 14.93 kg ha−1 yr−1 in the fertilizer treatments) than in the rainfall (10.66 kg ha−1 yr−1). This result indicates that inorganic nitrogen concentrations and fluxes of throughfall are affected by the amount of throughfall rather than by fertilizer application in a red pine stand.

Introduction

Throughfall is the part of the incident rainfall that either falls to the soil surface directly through gaps in the canopy or drips from branches and foliage (Crockford and Khanna 1997; Bhat et al. 2011). Throughfall is the one of the main pathways of nutrient input and cycling in forest ecosystems because canopy exchange regulates the chemical composition of throughfall that reaches forest soils (Verry and Timmons 1973). The NH4+ and NO3− concentrations in throughfall may either decrease or increase through the canopy. Decreases reflect nutrient absorption by foliage, whereas increases result from nutrient leaching from foliage (Fan and Hong 2001). For example, NO3− concentrations can be reduced in throughfall compared with rainfall because tree foliage absorbs nutrients from rainfall (Crockford and Khanna 1997). The absorption and release processes occurring in the canopy affect elemental concentrations in throughfall.

The responses of inorganic nitrogen (NH4+, NO3−) concentrations in throughfall are associated with leaching, volatilization, and uptake in foliage. The difference in nutrient status in foliage following fertilizer application can influence the inorganic nitrogen status in throughfall because of both NH4+ volatilization and increases in needle nitrogen concentrations following fertilization (Mahendraappa and Ogden 1973). The NH4+ and NO3− in throughfall can increase as rainfall passes through forest canopies because fertilizer application increases both the needle mass and nitrogen concentration in needle tissue (Crockford and Khanna 1997). However, the nutrient dynamics of throughfall are a function of tree species, stand density, canopy size, precipitation, holding capacity, and many other factors. Although these factors are potentially important regulators of nutrient dynamics in throughfall, experimental data concerning fertilizer application are limited in the forest ecosystems of Korea.

Despite the progress made in quantifying the throughfall nutrient balance of many coniferous forests in Korea (Joo et al. 1999; Park et al. 2002; Joo et al. 2003), data concerning the chemistry of throughfall due to forest management practices such as fertilization are scarce. The objective of this study was to compare the inorganic nitrogen status in rainfall and throughfall, and to determine the effects of fertilizer application on the inorganic nitrogen dynamics of throughfall in a red pine (Pinus densiflora S. et Z.) stand.

Materials and methods

This study was conducted in c. 40-year-old natural red pine stands in the Wola National Experimental Forest administered by Southern Forest Resources Research Center of the National Institute of Forest Science, Korea. The annual mean precipitation and temperature in this area are 1490 mm yr−1 and 13.1 °C. The soil is slightly dry, dark-brown forest soil (mostly inceptisols, United States Soil Taxonomy) originating from sandstone or shale. The understory vegetation was Lespe-deza spp., Quercus variabilis Blume, Quercus serrata Murray, Smilax china L., and Lindera glauca Blume. The site index of 8–10, based on the height of dominant pine trees, indicates low forest productivity at 20-year-old base age. Stand and soil characteristics of the study site are presented in Table 1.

The experimental design consisted of a completely randomized block design with two blocks (35°12′32″N,
128°10′23″E; 180 m; 35°12′26″N, 128°10′25″E, 195 m) in red pine stands (Figure 1). The experiment involved 12 plots (plot size 10 × 10 m²); two treatments (fertilization, control) × three replications × two blocks. Fertilization treatments included control (no fertilization) and a standard fertilization treatment (N₃P₄K₁ = 113:150:37 kg ha⁻¹) that is used in the forest ecosystems of Korea.

Throughfall was collected by using a polyethylene funnel (diameter of 210 mm) mounted to a polyethylene reservoir (capacity of 20 L). Twelve polyethylene reservoirs (two treatments × three replication plots × two blocks) were installed randomly in each treatment. The sampling reservoirs were covered with black paint to minimize the impact of irradiation and algal growth. The funnels were equipped with a plastic mesh screen (mesh width of 1.0 mm) that covered the bottom of the collectors to prevent litter, needles, and debris from entering the collectors (Figure 1). Open-field rainfall was collected in three replicates from three open areas using collectors of the same type. The distance from the throughfall plots ranged from 50 to 100 m. Throughfall and rainfall was measured monthly from April 2011 to March 2013 except during the frozen winter season. The volume of each sample was determined on site using a volumetric cylinder. Polyethylene bottles (capacity of 100 mL) were used to collect rainfall and throughfall samples for chemical analysis. Prior to collection, the bottles were soaked in deionized water and rinsed with sample water. The water samples were transferred to the laboratory, immediately filtered after collection and then stored at 4 °C. The pH and electrical conductivity (EC) in the rainfall and throughfall samples were measured using an ion-selective glass electrode (ISTEC Model pH-220L, Seoul, Korea) and an EC meter (Thermo Fisher Scientific Orion 3-star, Singapore). Ammonium (NH₄⁺) and nitrate (NO₃⁻) concentrations in the water samples were determined using an auto analyzer (AQ2 Discrete Analyzer, Southampton, UK). The study employed a completely randomized block design and blocks were considered a random factor. Data were analyzed via one-way-analysis of variance (ANOVA) to determine the treatment effects at a significance level of P < 0.05 using the general linear model procedure in SAS (SAS Institute Inc. 2003). When significant differences were observed, treatment means were compared with Tukey’s test.

**Results**

**Monthly variation in inorganic nitrogen dynamics, pH, and EC in rainfall and throughfall**

Monthly inorganic nitrogen concentrations, fluxes, and EC during the 2 year study period were generally lower in the rainfall than in the throughfall (Figure 2), whereas those values in the throughfall were not significantly affected (P > 0.05) by fertilizer application (Figure 2). The inorganic nitrogen concentration and EC in the throughfall showed clear monthly peaks (October 2011, June 2012) in which the concentration increased during the lowest rainfall month; however, those values of the rainfall were not related to monthly rainfall patterns. There were significant negative correlations (P < 0.05) between rainfall volume and inorganic nitrogen concentration (NH₄⁺: r = −0.23 to −0.27; NO₃⁻: r = −0.34 to −0.42) or EC (r = −0.37 to −0.43) in the throughfall (Table 2). Monthly inorganic nitrogen fluxes showed a similar monthly pattern of rainfall. There was considerable variability among sampling events in monthly inorganic nitrogen fluxes, and these fluxes were similar to the rainfall flux patterns.

![Figure 1. Location of the study site. Red pine stand (a), fertilized plot (b), throughfall collector (c).](image-url)
Table 2. Pearson correlation coefficient for inorganic nitrogen concentration and flux, pH, electrical conductivity, and volume of rainfall and throughfall in a red pine stand.

| Component                  | Volume (mm) | \(\text{NH}_4^+\) (mg L\(^{-1}\)) | \(\text{NO}_3^-\) (mg L\(^{-1}\)) | \(\text{NH}_4^+\) flux (kg ha\(^{-1}\)) | \(\text{NO}_3^-\) flux (kg ha\(^{-1}\)) | \(\text{NH}_4^+ + \text{NO}_3^-\) flux (kg ha\(^{-1}\)) | pH |
|----------------------------|-------------|----------------------------------|----------------------------------|----------------------------------------|----------------------------------------|------------------------------------------------|----|
| **Rainfall**               |             |                                  |                                  |                                        |                                        |                                                |    |
| \(\text{NH}_4^+\) (mg L\(^{-1}\)) | 0.19        | –                                 | –                                | –                                      | –                                      | –                                              |    |
| \(\text{NO}_3^-\) (mg L\(^{-1}\)) | –0.41\(^{**}\) | –0.07                            | –                                | –                                      | –                                      | –                                              |    |
| \(\text{NH}_4^+\) flux (kg ha\(^{-1}\)) | 0.78\(^{\ast\ast}\) | 0.62\(^{\ast\ast}\)            | –0.30\(^{\ast}\)                | –                                      | –                                      | –                                              |    |
| \(\text{NO}_3^-\) flux (kg ha\(^{-1}\)) | 0.69\(^{\ast}\) | 0.08                             | 0.10                             | 0.53\(^{\ast\ast}\)                   | –                                      | –                                              |    |
| \(\text{NH}_4^+ + \text{NO}_3^-\) flux (kg ha\(^{-1}\)) | 0.82\(^{\ast\ast}\) | 0.58\(^{\ast\ast}\)            | –0.26                            | 0.99\(^{\ast\ast}\)                   | 0.63\(^{\ast\ast}\)                   | –                                              |    |
| pH                         | –0.00       | –0.08                            | –0.36\(^{\ast}\)                | –0.03                                 | –0.12                                 | –0.05                                          |    |
| Conductivity (us cm\(^{-1}\)) | –0.51\(^{\ast\ast}\) | 0.08                             | 0.48\(^{\ast\ast}\)            | –0.35\(^{\ast\ast}\)                 | –0.44\(^{\ast\ast}\)                 | –0.38\(^{\ast\ast}\)                      | –0.12 |
| **Throughfall (control)**  |             |                                  |                                  |                                        |                                        |                                                |    |
| \(\text{NH}_4^+\) (mg L\(^{-1}\)) | –0.27\(^{\ast\ast}\) | –                                | –                                | –                                      | –                                      | –                                              |    |
| \(\text{NO}_3^-\) (mg L\(^{-1}\)) | –0.42\(^{\ast\ast}\) | 0.82\(^{\ast\ast}\)            | –                                | –                                      | –                                      | –                                              |    |
| \(\text{NH}_4^+\) flux (kg ha\(^{-1}\)) | 0.53\(^{\ast\ast}\) | 0.28\(^{\ast\ast}\)            | –0.06                            | –                                      | –                                      | –                                              |    |
| \(\text{NO}_3^-\) flux (kg ha\(^{-1}\)) | 0.10        | 0.32\(^{\ast\ast}\)            | 0.28\(^{\ast\ast}\)            | 0.44\(^{\ast\ast}\)                   | –                                      | –                                              |    |
| \(\text{NH}_4^+ + \text{NO}_3^-\) flux (kg ha\(^{-1}\)) | 0.45\(^{\ast\ast}\) | 0.34\(^{\ast\ast}\)            | 0.05                             | 0.94\(^{\ast\ast}\)                   | 0.71\(^{\ast\ast}\)                   | 0.00                                           |    |
| pH                         | 0.14        | 0.14                             | –0.04                            | 0.11                                 | –0.23                                 | 0.00                                           |    |
| Conductivity (us cm\(^{-1}\)) | –0.43\(^{\ast\ast}\) | 0.52\(^{\ast\ast}\)            | 0.71\(^{\ast\ast}\)            | –0.17                                 | 0.05                                 | –0.11                                          | –0.16 |
| **Throughfall (fertilization)** |             |                                  |                                  |                                        |                                        |                                                |    |
| \(\text{NH}_4^+\) (mg L\(^{-1}\)) | –0.23\(^{\ast}\) | –                                | –                                | –                                      | –                                      | –                                              |    |
| \(\text{NO}_3^-\) (mg L\(^{-1}\)) | –0.34\(^{\ast\ast}\) | 0.50\(^{\ast\ast}\)            | –                                | –                                      | –                                      | –                                              |    |
| \(\text{NH}_4^+\) flux (kg ha\(^{-1}\)) | 0.52\(^{\ast\ast}\) | 0.45\(^{\ast\ast}\)            | –0.08                            | –                                      | –                                      | –                                              |    |
| \(\text{NO}_3^-\) flux (kg ha\(^{-1}\)) | 0.37\(^{\ast\ast}\) | 0.01                             | 0.12                             | 0.44\(^{\ast\ast}\)                   | –                                      | –                                              |    |
| \(\text{NH}_4^+ + \text{NO}_3^-\) flux (kg ha\(^{-1}\)) | 0.54\(^{\ast\ast}\) | 0.37\(^{\ast\ast}\)            | –0.92                            | 0.35\(^{\ast\ast}\)                   | 0.70\(^{\ast\ast}\)                   | –                                              |    |
| pH                         | –0.01       | 0.32\(^{\ast\ast}\)            | 0.16                             | 0.13                                 | –0.02                                 | 0.11                                           |    |
| Conductivity (us cm\(^{-1}\)) | –0.37\(^{\ast\ast}\) | 0.39\(^{\ast\ast}\)            | 0.51\(^{\ast\ast}\)            | –0.05                                 | –0.03                                 | –0.05                                          | –0.19 |

Note: \(P < 0.05; \text{\^P} < 0.01.\)

Figure 2. Monthly patterns of inorganic nitrogen concentration and flux, pH, electrical conductivity, and volume of rainfall and throughfall (C: control; F: fertilization) in a red pine stand. Vertical bars indicate standard error. Different letters on the bar represent a significant difference at \(P < 0.05.\)
Annual variation in inorganic nitrogen fluxes

The annual mean of inorganic nitrogen concentration was significantly higher in the throughfall than in the rainfall (Figure 3), and fertilizer had no significant effects on the concentration (Figure 3). The mean annual NH$_4^+$ flux was not significantly different between rainfall and throughfall. In contrast, the mean annual NO$_3^-$ flux was significantly higher in the throughfall than in the rainfall. In addition, the mean annual NH$_4^+$ and NO$_3^-$ fluxes (kg ha$^{-1}$ yr$^{-1}$) were similar between the control (NH$_4^+$: 8.75; NO$_3^-$: 6.67) and the fertilized (NH$_4^+$: 8.99; NO$_3^-$: 5.94) treatments, whereas the inorganic nitrogen fluxes were higher in the throughfall (17.03 kg ha$^{-1}$ yr$^{-1}$ in the control and 14.93 kg ha$^{-1}$ yr$^{-1}$ in the fertilizer treatments) than in the rainfall (10.66 kg ha$^{-1}$ yr$^{-1}$).

Discussion

The annual volume of rainfall events was 1757.8 mm yr$^{-1}$, whereas that of throughfall was 1469.5 mm yr$^{-1}$ in the control and 1385.6 mm yr$^{-1}$ in the fertilized treatments. The rainfall volume was slightly lower in the fertilized treatments than in the control treatments. Throughfall rates can be altered by forest management practices such as thinning (Park et al. 1999) and fertilization (Mahendrappa and Ogden 1973; Samuelson et al. 2014). For example, fertilization induced a 30% reduction in throughfall in loblolly pine (Pinus taeda L.) plantations that had increased leaf area (Wightman et al. 2016). In this study, interception rates by tree canopies ranged from 15% to 16%. The mean values of interception rates were similar or lower than the 15% to 26% rates in coniferous forests reported for the forest ecosystems of Korea (Park et al. 2002; Joo et al. 2003).

Figure 3. Annual mean inorganic nitrogen concentration and flux, pH, electrical conductivity, and volume of rainfall and throughfall (C: control; F: fertilization) in a red pine stand. Vertical bars indicate standard error. Different letters on the bars represent a significant difference at $P < 0.05$. 

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The monthly concentrations of NH$_4^+$ and NO$_3^-$ in the dry months (e.g. October 2011, June 2012) were significantly higher in the throughfall than in the rainfall. This result reflected the enrichment of the canopy with N compounds via total deposition during the dry months. The patterns of NH$_4^+$ and NO$_3^-$ concentrations in throughfall may be attributed to the dilution effect of the dry deposits found in the needles following the evaporation of intercepted rainfall under conditions of lower amounts of rainfall. There was a negative correlation ($r = -0.27$ to $-0.42$, $P < 0.05$) between volume and inorganic nitrogen concentration in the throughfall. However, no significant differences in the monthly concentrations of NH$_4^+$ and NO$_3^-$ between the fertilized and control treatments could be due to a similar amount of throughfall.

The mean NH$_4^+$ and NO$_3^-$ concentrations during the study period were 0.39 and 0.21 mg L$^{-1}$ for the rainfall, 1.06 and 1.06 mg L$^{-1}$ for the control and 1.01 and 0.89 mg L$^{-1}$ for the fertilizer treatments of throughfall, respectively. High concentrations of NH$_4^+$ and NO$_3^-$ in throughfall compared with rainfall may be due to both dry deposition and leaching as water passed through the needles (Rodrigo et al. 2003), rather than the absorption of nitrogen ions in tree canopies (Fan and Hong 2001). There was a strong positive correlation ($r = 0.39–0.71$) between the EC values and NH$_4^+$ and NO$_3^-$ concentrations in the throughfall. However, inorganic nitrogen concentration in the fertilized treatments of throughfall was not affected by nitrogen concentration of the needles, which increased significantly following the fertilized treatments (9.6 mg g$^{-1}$) compared with the control (8.8 mg g$^{-1}$) treatments in the same study site (Kim et al. 2013). This result indicates that inorganic nitrogen concentrations in throughfall were due to the amount of rainfall becoming throughfall rather than increased needle nitrogen concentration by fertilization. In contrast to this result, fertilization resulted from increased inorganic nitrogen concentrations in throughfall due to the increased needle leaching by throughfall (Mahendrappa and Ogden 1973; Crockford and Khanna 1997).

The annual mean NH$_4^+$ and NO$_3^-$ fluxes were not significantly affected by fertilization. Although nutrient absorption by the canopy, canopy area, and nutrient leaching ability from the canopy also influence flux values, the NH$_4^+$ and NO$_3^-$ flux values in throughfall between the fertilized treatments and the control treatments were mostly due to differences in throughfall water flux ($r = 0.45–0.82$). The annual mean NH$_4^+$ fluxes were not significantly different between rainfall and throughfall despite a significant NH$_4^+$ concentration difference. In contrast to NH$_4^+$ fluxes, the annual mean NO$_3^-$ fluxes were significantly higher in the throughfall than in the rainfall.

**Conclusion**

The NH$_4^+$ and NO$_3^-$ concentrations in throughfall were similar between the fertilized and control treatments. Inorganic nitrogen fluxes were 17.03 kg ha$^{-1}$ yr$^{-1}$ in the throughfall control treatments, 14.93 kg ha$^{-1}$ yr$^{-1}$ in the throughfall fertilized treatments, and 10.66 kg ha$^{-1}$ yr$^{-1}$ in the rainfall. The results indicate that inorganic nitrogen concentration and fluxes of throughfall are not affected by fertilizer application in a red pine stand.

**Disclosure statement**

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