ANNUAL ELEMENT BUDGET OF SOIL IN SNOW-DOMINATED FORESTED ECOSYSTEM

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Abstract. Seasonal fluctuation of concentration and flux of major inorganic ions in throughfall, stem flow, snowpack and soil solution was investigated at a natural cool temperate mixed forest in Hokkaido, northern Japan, in order to clarify the effect of snowmelt on the solute dynamics in the forest soil in snow-dominated region. Na+, Ca2+, Mg2+, Cl− and SO42− concentrations in soil solution showed a large fluctuation in the snowmelt period. The percentage of output of these elements from soil during the snowmelt period in the annual output was as follows: Mg2+: 51%, Na+ and Cl−: 59 and 60%, SO42−: 65%, Ca2+: 77%. Our results indicated that the snowmelt event was very important to quantify the annual elemental budgets in this region. Although the leaching of base cation from the soil was larger than that of inputs and accumulation into the vegetation, annual decreasing rate of acid neutralization capacity (ΔANCw) from the soil was mostly affected by the base cation accumulation into the vegetation, related that the base cations weathering accompanied with bicarbonate was slow due to the acidic and weathered soil in the studied site. It is suggested that the weakly acidic soil which has low ΔANCw in snow-dominated region will be relatively sensitive to the future increase of acidic deposition.

Keywords: element budget, forest soil, snow melt, solution chemistry, soil acidification

1. Introduction

The analysis of biogeochemical budgets is an important tool for assessing the effect of acidic deposition on forests and acid buffering mechanisms of forest ecosystem. In particular, elemental budgets and stocks in soil are very important not only for a living medium of vegetation but also for a quantitative analysis of soil acidification rate (van Breemen et al., 1984). The budgets of elements in soil are expected to be affected by the internal cycling by biota, water movement in soil and so on.

In the northern part of Hokkaido located in northern Japan, snowfall is a significant component of annual precipitation. The effect of snowmelt on chemical dynamics in soil may differ from that of rainwater. The atmospheric depositions were accumulated in snowpack temporarily, and a large amount of those were released and supplied to soil during the snowmelt period (Jeffries et al., 1979). It is reported that the preferential elements elution from accumulated snowpack affects the concentration of soil solution (Johannessen and Henriksen, 1978), and causes acidification of lake and stream waters during early snowmelt period (Jenkins et al., 1993).

Although a large number of studies about elemental budgets have been conducted
during snowmelt period, they mostly focused on the stream water on the watershed scales (Rice and Bricker, 1995; Stottlemeyer and Toczydlowski, 1999). Information about the chemical dynamic in a rooted soil during the melting season has been quite limited, resulting in a large uncertainty about the biogeochemistry in snowy forest ecosystems. One of the major reasons for the lack of these studies may be the technical difficulty of the sampling of soil solution under the snowpack in low temperature.

We observed the inorganic concentration and fluxes in the soil solution, throughfall, stem flow, snowpack and accumulation into the vegetation on an annual basis including the snowpack and snowmelt season in Hokkaido, northern Japan. The purpose of this paper is to determine the effect on snowmelt on the elemental flux and soil acidification rate in rooted soil in cold snowy forest ecosystems.

2. Materials and Methods

2.1. Site description

The study site was located in the Uryu Experimental Forest of Hokkaido University (42° 16' N, 142° 21' E) in the northern part of Hokkaido, northern Japan. The altitude of the site was 320 m.a.s.l. There is no source of acidic pollutants near this region. The soil is Dystrochrept (Soil Taxonomy, USDA 1994) and the parent material consists of andesite of Tertiary age. The soil is slightly acidic and pH (H₂O) of soil (10-80 cm) ranges from 3.9 to 4.5. The vegetation type is natural mixed forest composed of Quercus crispula and Abies sachalinensis predominantly among about 30 species. This study was carried out from July 1998 to June 1999. We divided the observation period into three periods: snowpack period (from November to March), snowmelt period (from April to middle of May) and non-snowy period (from middle of May to October). Annual precipitation in this study was 1729 mm, and 56% of that was supplied as mostly snow (from November to April). Mean annual temperature in this study was 7.1°C. The soil was unfrozen even during winter due to the thermal insulation effect of the dense snow (maximum snow depth was 2.4 m at March 13, 1999).

2.2. Field observation

Throughfall was collected using three polyethylene funnels (30 cm diameter) and bottles. Stem flow was collected using urethane forms, vinyl chloride tubes and bottles. Snowpack was collected by a cylindrical snowpack collector (5cm diameter). Soil solution below the rooted soil (70 cm depth) was collected using a ceramics tension lysimeter. Three sets of lysimeter were installed and connected each bottle separately. From November 1998, the soil solution collected under the snowpack was stored in one bottle from the three lysimeters and the collecting bottle was buried in unfrozen soil. The collecting tube from the bottle was extended above the snowpack and wrapped by the electric heating tape to avoid the freezing of soil solution during the sampling procedure.
The heating tape was only turned on below 4°C, controlled by a thermister. It was wrapped by the thermal insulation tape to prevent the artificial melting of snowpack. The volumetric soil moisture was measured hourly at depths of 10, 20, 30, 50 and 70 cm by use of Time Domain Reflectometry (TDR, Imco CO Ltd.) and datalogger. The frequency of collecting throughfall, stem flow and soil solution was once a week during the non-snowy period. During snowpack and snowmelt periods, snowpack and soil solution were collected once to three times a month.

2.3. Chemical analysis

After the pH measurement using a glass electrode, all water samples were filtered through a 0.2 μm membrane filter to analyze the ionic concentration of major inorganic cations (Na⁺, K⁺, NH₄⁺, Ca²⁺, Mg²⁺) and anions (Cl⁻, NO₃⁻, NO₂⁻, SO₄²⁻) by ion chromatography (Dionex Co Ltd.). Aluminum concentration analyzed by the induced coupled plasma optical emission spectrometry (ICP, Jarrell Ash Co Ltd). In this study, aluminum was treated as Al³⁺.

2.4. Elemental budget calculation

Water budget in soil is represented as Equation 1.

\[ W_{soil} = W_{in} - ET - \Delta S \]  \hspace{1cm} (1)

\( W_{soil} \) is the output water from rooted soil. Evapotranspiration (ET) was calculated from the Penman-equation based on meteorological data observed near the studied site. During the snowpack and snowmelt period, we assumed that ET was zero. \( \Delta S \) is the water storage change of soil (0-70 cm) calculated from the observed volumetric water contents in each soil depth during each period. \( W_{in} \) is the input water into the soil and the calculation method was different for each period. \( W_{in} \) was obtained from the water amount of throughfall and stem flow during the non-snowy period, and the melt water from the bottom of the snowpack during the snowpack period, respectively. \( W_{in} \) in snowmelt period was the sum of the snowpack water (March 24, 1999) and precipitation after the snowpack observation. Since the melt water from the snowpack bottom was not measured directly during the snowpack period, we assumed that melting velocity was 0.3 mm day⁻¹ as reported in northern Hokkaido (Nomura et al., 1999). The elemental outputs from soil were calculated from the amount of discharge water (\( W_{soil} \)) and mean ionic concentration of soil solution at 70 cm depth. Inputs fluxes of elements into the soil were calculated from the amount of input water (\( W_{in} \)) and mean ionic concentration of throughfall, stem flow or snowpack during each period, respectively.

2.5. Accumulation of elements in the vegetation

In September 1998, we collected wood samples at breast height from 25 trees (seven species) in duplicate using 5 mm diameter borer-cores. Rates of annual increment of wood were estimated by the average width of rings. The trunk dry mass per hectare was
calculated from diameter of breast height (DBH) observed in studied plots (25 × 25 m, Uryu Experimental Forest, unpublished data) using an allometric equation obtained in southeastern Hokkaido (Takahashi et al., 1999). After drying, milling, and wet digestion (HNO₃ and H₂O₂), elemental concentration in the extractions was measured by ICP. The average annual accumulation of elements in the vegetation was determined using the rates of annual increment of wood and wood elemental concentrations of each tree species.

2.6. CALCULATION OF ACID NEUTRALIZING CAPACITY

We quantified the annual soil acidification rate from the decreasing rate of acid neutralizing capacity of soil (∆ANCₒ) proposed by van Breemen et al. (1984). Acid neutralizing capacity of soil (ANCₒ) is given in the following equation:

\[ \text{ANCₒ} = \Sigma \text{base cation (Na + K + Ca + Mg)} + (\text{Al + Mn + Fe}) - (\text{SO₄ + Cl + P}) \]  \hspace{1cm} (2)

Since the concentration of Fe, Mn and P in the soil solution was undetectable, we neglected these elements in the calculation of ANCₒ. We also assumed that the aluminum input by throughfall, stem flow and snowpack was negligible. ∆ANCₒ was calculated from the annual budgets of ANCₒ in soil including leaching from rooted soil (Ls), accumulation into the vegetation (∆W) and inputs into the soil (In) as described by Equation 3.

\[ \Delta \text{ANCₒ} = L_s + \Delta W - I_n \]  \hspace{1cm} (3)

3. RESULTS AND DISCUSSION

3.1. IONIC CONCENTRATION AND FLUX IN ROOTED SOIL

During the observed period, Ca²⁺ concentration in the soil solution has a sharp peak in April (Fig. 1), suggesting the preferential elusion of Ca²⁺ from the snowpack was

![Figure 1](image-url)  
*Figure 1.* The seasonal fluctuation of mean Ca²⁺ concentration in soil solution below the rooted soil (70cm depth). Occurred at the early stage of snow melting (Johannesen and Henriksen, 1978). In the latter snowmelt period, Ca²⁺ concentration decreased to the same level during the snowpack period mainly due to the effect of dilution by the large amount of melt water. The same tendency was observed for Na⁺, Mg²⁺, Cl and SO₄²⁻. The initial disturbance due to the lysimeter installation may cause some increments of some ionic concentrations in soil solution at the beginning of the observation. Mean pH of input water and the soil solution during each period was 5.2 and ranged from 5.3 to 5.6, respectively, indicating that
the pH change in soil is relatively small although the soil itself is acidic.

The output flows of most elements, especially Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\) and SO\(_4^{2-}\), during the snowmelt period were the largest during the year (Table I), although insufficient

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>Element and water fluxes (mmol, m(^2) period(^{-1})) and mean pH of soil during each period.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>non-snowy period (from middle of May to October, 180days)</td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>722</td>
</tr>
<tr>
<td>output</td>
<td>223</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>-499</td>
</tr>
<tr>
<td>snowpack period (from November to March, 148days)</td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>59</td>
</tr>
<tr>
<td>output</td>
<td>65</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>6</td>
</tr>
<tr>
<td>snowmelt period (from April to middle of May, 37days)</td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>958</td>
</tr>
<tr>
<td>output</td>
<td>922</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>-36</td>
</tr>
</tbody>
</table>

\(\Delta = \text{output} - \text{input}\)  n.d. = not determined

Sampling frequency may cause some uncertainty for the quantification of the ionic flux during the snowmelt period. The contributions of Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\), SO\(_4^{2-}\) and water outputs during snowmelt to the annual fluxes were 59, 77, 51, 60, 65 and 76 %, respectively. The variation of the relative contribution between each ion and water probably related to that each ion has different hydrochemical and biogeochemical patterns including leaching from the snowpack, uptake by the vegetation, and decomposition and weathering in the soil. Since the snowmelt period is shorter than any other period, the difference of the daily elemental fluxes becomes large. This budget analysis clearly indicated that the snowmelt events were the most important to the annual elemental budgets in this region. HCO\(_3^-\) was a minor anion in the soil solution around a year, suggesting that the silicate weathering was minor in this soil. Since Cl\(^-\) is usually treated as an inert element in soil-vegetation systems, large net output of Cl\(^-\) during snowmelt period may suggest another source of dry deposition in canopy and forest floor during the snowpack period (Stottlemeyer and Toczydlowski, 1996).

3.2. Annual soil acidification rate

Since annual accumulation of base cations, aluminum and sulfur into the vegetation was 74, 3.3 and 5.2 mmol, m\(^2\) y\(^{-1}\), respectively, ANC\(_0\) (Equation 2) by vegetation increments corresponded to 72 mmol, m\(^2\) y\(^{-1}\). \(\Delta\)ANC\(_0\) of this study site was -0.04 mol, m\(^2\) y\(^{-1}\) (Equation 3) and the base cations accumulation into the vegetation was most important for soil acidification rate (\(\Delta\)ANC\(_0\)) compared to input – output budgets. Although annual net outputs of base cations (0.39 mol, m\(^2\) y\(^{-1}\)) were larger than the accumulation into
the biomass, $\Delta \text{ANC}_{\text{oil}}$ outputs from the soil were very small because conjugation anions of base cations were mostly $\text{Cl}^-$ and $\text{SO}_4^{2-}$. $\Delta \text{ANC}_{\text{oil}}$ of this study was relatively low compared to the previous study in a Japanese forest (-18 to -60 mmol m$^{-2}$ y$^{-1}$, Nambu et al., 1994; Shibata et al., 1998). The studied soil was already weathered and slightly acidic related to this small rate of $\Delta \text{ANC}_{\text{oil}}$, suggesting that the sensitivity of acidic deposition was relatively high in this region compared to the other forest which has large $\Delta \text{ANC}_{\text{oil}}$. The large output of elements during snowmelt period may also contribute to creating this acidic soil during previous long pedological period in a heavily snowed region.

4. Conclusions

In this snow-dominated region, snowmelt events were very important to assess the annual budget of soil systems. Although the annual output of base cations from the soil was relatively larger than that of the base cations accumulation into the vegetation, the effect of leaching of $\text{ANC}_{\text{oil}}$ from the soil on the $\Delta \text{ANC}_{\text{oil}}$ was small, because the soil was already acidic and absence of silicate weathering in the rooted soil. These result implies that the forest ecosystem on the acidic soil in snowy region has high sensitivity against the future increase of acidic pollutants.

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References