THE RELATION BETWEEN WATER MIGRATION AND CHEMICAL PROCESSES IN A FOREST ECOSYSTEM

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ABSTRACT The hydrochemistry of the Tsukuba experimental forest (67.5 ha) has been monitored since 1984, including rainfall, throughfall, stemflow, soilwater, groundwater and streamwater. The cycled amounts of the essential elements available for forest growth are approximately ten times as high as the rainwater input and streamwater output. The element cycle within the forest ecosystem results firstly in an alteration of the element content of the soil, and secondly, in the creation of a soilwater chemistry unique to the forest ecosystem. In particular, essential elements such as nitrogen and potassium exhibit higher concentrations in surface soilwater than in deeper soilwater and groundwater. Consequently the near-surface soilwater runoff results in an increase in stream solute concentrations with increasing flow rate during the summer.

INTRODUCTION

The hydrochemical behavior of solutes in forested catchments has been identified as a major control on their streamwater chemistry (e.g. Muraoka & Hirata, 1988; Bishop et al., 1990; Muscutt et al., 1990; Neal et al., 1990). Catchment studies have been undertaken to demonstrate the interrelationship between chemical changes and water pathways in terms of element budgets (Likens et al., 1977; Hirata & Muraoka, 1991; Reynolds et al., 1992).

Many elements cycle between forest trees and the soil within forest ecosystems. In the case of the elements essential for forest growth, the cycled amounts are considerably larger than those of the minor or non-essential elements. The element cycle, through uptake by trees and return to the forest floor by litterfall and leaching of the forest canopy, will alter the element content of the soil from its original level, depending on the amount of each chemical constituent cycled.

The element content of the soil is the most important control on the soilwater chemistry, and consequently the solute concentration profile of the soilwater exhibits a pattern similar to that of the soil chemistry. The element cycle within forest ecosystems can be expected to result in firstly a change in the element content of the soil and secondly production of a soilwater chemistry characteristic of the element cycle within the forest ecosystem. In addition, solute transport by soilwater during storm events causes changes in streamwater chemistry (Muraoka & Hirata, 1988).

To explore the origin of the streamwater chemistry and the water pathways involved, the chemical changes associated with water migration through the forest ecosystem have been monitored in a small basin in the Tsukuba experimental forest. Firstly, with respect to the chemical constituents, rainwater input and streamwater output are evaluated, and the
internal cycling of elements within the forest ecosystem is described in relation to the element content of the soil and the soilwater chemistry. Secondly, the role of the solutes contained in soilwater in influencing streamwater chemistry is examined both on a storm-event and a seasonal basis.

STUDY SITE DESCRIPTION

The Tsukuba experimental forest extends over 67.5 ha and is located in the Tsukuba Mountains 60 km northeast of Metropolitan Tokyo. The altitude of the basin ranges between 200 and 380 m a.m.s.l. Three streams run through the basin and their confluence is just upstream of site A1, as illustrated in Fig. 1. Coniferous trees cover the whole basin, and the dominant species is Japanese cedar (Sugi, Cryptomeria Japonica), Japanese cypress (Hinoki, Chamaecyparis obtusa) and burned pine, which account for 52.5, 17.7, and 13.2% of the basin area, respectively. In particular, the Sugi stand extends along the streams.

The experimental basin was designed to investigate the chemical changes associated with water movement through the forest ecosystem from rainfall input to the streamwater output. The streamwater level has been measured by a float type level recorder at site A1 and converted into the streamwater flow rate. Ten minute rainfall intensities have been monitored with a tipping bucket rain gauge near site A1, and rainwater for chemical analysis was also collected with a storage rain gauge. The streamwater was sampled biweekly, and the rainwater every week or after every rainfall event. In addition to the biweekly routine work, changes in streamwater chemistry during storm events were also monitored to examine the role of solute transport by soilwater in influencing streamwater chemistry.

With respect to the internal element cycle within the forest ecosystem, throughfall, stemflow, litterfall and soilwater were collected biweekly at plot 2 in the Sugi stand.

INPUT-OUTPUT BUDGETS AND THE MAGNITUDE OF INTERNAL CYCLING

The annual chemical fluxes associated with rainwater inputs and streamwater outputs in the Tsukuba experimental forest are collated in Table 1, on the basis of the data collected during the 4 year period since April 1985. In this paper the water year is defined as extending from April to March of the following year. With respect to the essential elements, Fig. 2 presents the internal element cycling fluxes within the forest ecosystem, including the input and output loads. The annual growth rate of the Sugi trees was estimated from the difference between two surveys of the standing dry biomass, which were performed in February.
1984 and October 1985. Chemical analysis of the forest soil, which was sampled in the Sugi stand at 1m depth below the ground surface, provided an estimate of the standing stock of chemical constituents in the soil.

**TABLE 1 An input-output budget of chemical constituents obtained for the Tsukuba experimental forest during a 4 year period from April 1985 to March 1989.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Water amount (mm)</th>
<th>Mean conc. (mg l⁻¹)</th>
<th>Conc. range (mg l⁻¹)</th>
<th>Loading (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>Apr. 1985-Mar. 1986</td>
<td>1576.5</td>
<td>0.389 0.307 0.015 0.177 1.66 1.47 0.834 0.271 0.195 0.314</td>
<td>5.1 14.9</td>
</tr>
<tr>
<td>Streamwater</td>
<td></td>
<td>733.7</td>
<td>0.037 0.003 1.07 0.010 21.1 5.79 3.76 5.89 1.01 1.87 3.59 7.0 75.2</td>
<td></td>
</tr>
<tr>
<td>Mean conc. (mg l⁻¹)</td>
<td>1.53 0.030 1.77 0.130 2.00 4.19 5.00 2.70 2.34 0.70 1.60 3.5 57.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading (kg ha⁻¹)</td>
<td>4.56 0.067 5.51 0.116 2.70 26.2 22.7 10.2 3.87 3.46 9.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Rainfall | Apr. 1986-Mar. 1987 | 1952.5 | 0.294 0.024 0.355 0.008 0.174 1.70 1.50 0.860 0.313 0.223 0.586 5.0 14.6 |
| Streamwater | | 711.4 | 0.034 0.003 1.77 0.007 21.7 5.83 3.38 5.50 0.786 1.85 3.90 6.7 74.4 |
| Mean conc. (mg l⁻¹) | 1.53 0.030 1.77 0.130 2.00 4.19 5.00 2.70 2.34 0.70 1.60 3.5 57.9 |
| Loading (kg ha⁻¹) | 4.56 0.067 5.51 0.116 2.70 26.2 22.7 10.2 3.87 3.46 9.09 |

| Rainfall | Apr. 1987-Mar. 1988 | 1293.0 | 0.255 0.004 0.313 0.006 0.164 1.39 1.21 0.517 0.213 0.242 0.971 4.6 19.1 |
| Streamwater | | 363.3 | 0.025 0.002 1.40 0.008 21.7 5.78 3.12 5.53 0.876 1.62 3.39 6.6 79.2 |
| Mean conc. (mg l⁻¹) | 1.53 0.018 0.911 0.020 0.40 3.70 3.95 3.98 0.840 0.410 3.26 2.2 58.5 |
| Loading (kg ha⁻¹) | 2.84 0.043 4.04 0.075 2.11 18.0 15.8 9.68 2.75 3.43 6.87 |

| Rainfall | Apr. 1988-Mar. 1989 | 1227.0 | 0.272 0.010 0.288 0.017 0.315 1.48 1.86 0.532 0.328 0.381 1.33 5.7 18.5 |
| Streamwater | | 1075.4 | 0.089 0.009 1.94 0.008 21.4 6.32 3.72 5.63 1.02 1.90 3.75 7.1 75.3 |
| Mean conc. (mg l⁻¹) | 3.86 0.105 1.84 0.020 1.0 4.44 6.32 2.48 1.83 0.750 2.27 2.4 70.0 |
| Loading (kg ha⁻¹) | 5.25 0.181 5.55 0.334 6.06 28.2 32.0 10.2 6.31 7.54 25.7 |

When the annual uptake by the Sugi trees is taken to represent a cycled amount, all the chemical constituents illustrated in Fig. 2 demonstrate internal fluxes within the forest ecosystem which are one order of magnitude or more higher than the rainwater input and streamwater output fluxes. The result implies that the element cycle plays a dominant role in altering the element content of the soil and consequently in creating the soilwater chemistry of the forest ecosystem.

Phosphorus, potassium, magnesium and calcium, are present in rainwater in low concentrations as shown in Table 1, and these elements originate primarily from the soil and bedrock. Therefore, the major proportion of these elements is stored in the soil. Conversely, nitrogen is not a major constituent of the soil and bedrock, and its source in the natural water environment is thought to reflect microbial fixing of atmospheric nitrogen.
Nitrogen continues to accumulate in the surface soil during the development of the forest, and the nitrogen stock in the surface soil of the Tsukuba experimental forest currently amounts to 14.7 t ha\(^{-1}\). Because the annual uptake by the living biomass required for growth is 21.7 kg ha\(^{-1}\) year\(^{-1}\), the nitrogen stock in the forest soil would allow the Sugi trees to grow and survive for about seven hundred years.

During the two-year period 1987-1989, 0.205 kg ha\(^{-1}\) year\(^{-1}\) of phosphorus were added by rainfall and 0.0445 kg ha\(^{-1}\) year\(^{-1}\) were lost in streamwater in the Tsukuba experimental forest. In this context, the forest ecosystem fulfils a purification function for the water en-
vvironment. In the case of nitrogen, the streamwater output exceeds the rainfall input, and is not in balance. However, considering the total input to the forest floor by throughfall and stemflow, more nitrogen enters the forest than is lost in streamwater. The most likely explanation is that the vegetation canopy captures dry fallout and aerosols, which are transported to the forest floor by throughfall and stemflow. As a result the source of nitrogen in throughfall and stemflow must be considered. The nitrogen contained in throughfall and stemflow is derived: (1) from airborne nitrogen captured by the forest plant and (2) by leaching from the vegetation. At present it is very hard to separate these two sources.

ELEMENT CONTENT OF THE SOIL AND SOILWATER CHEMISTRY

Element content of the soil

The element stock in the forest soil was examined at sites B4 and A4 in the Sugi stand to investigate the influence of the element cycle on soilwater chemistry. The brown forest soil covers the whole basin. The A₀ horizon is less then 1 cm in thickness, due to the coniferous tree cover, and the base of the soil was not reached until 1 m depth at both sampling locations. Fig. 3 illustrates vertical profiles of the element content of the soil, which are distinguished as Type I, Type II and others. Type I comprises substances which are non-essential or which are cycled in only small amounts and Type II includes the essential major elements. The reason for classifying the chemical constituents into Type I and Type II will be discussed in more detail later.

Silicon and sodium, the main constituents of the soil, are not the major essential elements, and the amounts cycled are less than for the essential elements. Consequently, the

![FIG. 3 Vertical profiles of the element content of soils in the Sugi stand. The soil was collected to a depth of 1 m at sites A4 and B4 on 20 March 1987. The element content is expressed as a fraction of the dry weight of the soil.](image-url)
content of elements belonging to Type I in the surface soil becomes lowered during the process of incorporating organic substances such as litterfall and dead roots.

Conversely, nitrogen which belongs to Type II, shows clear evidence of accumulation in the surface soil. Carbon seems to behave in a way similar to nitrogen. With respect to the minerals, phosphorus and calcium tend to be further enriched in the surface soil, as they are primary constituents of the soil and bedrock, whereas magnesium appears to be essentially uniform with depth.

**Soil water chemistry**

During the 3 year period since February 1986, soilwater was collected biweekly at site B4 in the Sugi stand. The sampling depths were 10, 20, 30, 50, 75, 95, 125, and 175 cm from the ground surface (Hirata & Muraoka, 1992). The soilwater tension and the groundwater level were also monitored in this plot. The soilwater taken from the 125 and 175 cm depths was confirmed to be groundwater, since the groundwater table never dropped below 1 m depth throughout the period of observation.

The seasonal variation of solute concentrations in soilwater in relation to rainfall amount, on a 5 day basis, since April 1986, is shown in Fig. 4. As could be reasoned from the vertical profile of element contents in the soil, the concentrations of silicon and sodium in the groundwater sampled from 125 and 175 cm depths are higher than in the surface soilwater from 10 and 30 cm depths. There is also evidence of seasonal variation, with the SiO$_2$ concentration beginning to rise in April and reaching a peak in August. Despite temporary reductions in the concentration due to storm runoff leaching during the period April to August every year, the increased temperature causes higher SiO$_2$ concentrations because it promotes the dissolution of new material from the soil. After September, however, the dissolution rate declines due to the reducing temperature. Storm runoff leaching therefore induces further reductions in the soilwater concentrations toward the spring. This is also the case for Na$^+$ concentrations.

Most of the nitrogen in the soil is stored in organic form and is mineralized first to NH$_4^+$-N and NO$_2^-$-N, and second to NO$_3^-$-N through biodegradation. The NH$_4^+$-N ion is also contained in rainwater and follows the same pathway as NO$_3^-$-N during water migration through the forest soil zone. It is well known that the nitrification rate doubles with a temperature increase of 10°C. Therefore, NO$_3^-$-N concentrations in surface soilwater increase during the summer season as shown in Fig. 4. The microbial activity declines from autumn through to winter due to the reduced temperatures. In addition, soilwater runoff during storm events facilitates the removal of solutes near the ground surface, and thereby reduces the solute concentration in a way similar to Type I substances.

Potassium, calcium and magnesium originate in the soil and bedrock, and also exist there in organic form within decaying plant material. As in the case of NO$_3^-$-N, the K$^+$ concentrations in the surface soil increase during summer due to biodegradation. In addition, the increased microbial activity releases carbon dioxide gas into the soil pores, and creates carbonates in the soilwater. In the summer, since the surface soil is ready for acid-base reactions to replace the H$^+$ discharged in the above process with K$^+$, the dissolution of K$^+$ might be promoted (Stumm & Morgan, 1981).

As NO$_3^-$-N is an anion, it is strongly resistant to adsorption into the negatively charged soil, and is highly mobile in the soil zone. NO$_3^-$-N is one of the major essential elements for plant growth, and uptake by the forest vegetation during percolation is thought to reduce its concentration in deeper soilwater and groundwater.
Cations such as Na\(^+\) and K\(^+\) are easily absorbed into the negatively charged soil. In particular, Na\(^+\) has a weaker ionic bonding force than K\(^+\) or Ca\(^{2+}\). Therefore, it may be released from the soil after being replaced by other cations, and percolates easily through the soil zone. In contrast, the K\(^+\) concentration in groundwater varies to only a small extent, due to uptake by the forest vegetation and adsorption onto soil during percolation.
STREAMWATER CHEMISTRY

Soilwater contains two types of solutes; firstly, the Type I substances, which show lower concentrations near the surface and higher values at depth, and, secondly, the Type II substances, which exhibit higher concentrations near the surface than in deeper soilwater and groundwater. As a result, runoff of surface soilwater gives rise to chemical changes in the streamwater. Chemical analysis of the streamwater sampled during storm events revealed that almost all solutes reduced their concentrations during the rising limb of the hydrograph. As the solute concentrations in rainfall are lower than those in throughfall, stemflow, soilwater and streamwater, the rapid runoff of rainwater as overland flow can readily account for the reduction of the stream solute concentrations during the rising limb. Conversely, during the recession limb after the peak discharge, the stream solute concentrations recover. Towards the end of the recession limb, two types of stream solute behavior could be identified as follows: firstly, Type I substances, which show approximately the same concentration as at baseflow prior to the runoff event, and secondly, Type II substances, which show an increase over the baseflow level. SiO$_2$, Na$^+$ and Cl$^-$ belong to Type I, and NO$_3^-$, Ca$^{2+}$, Mg$^{2+}$ and K$^+$ to Type II. This is the reason for classifying solute behavior into Type I and Type II, which closely depend on the element cycle characteristics within the forest ecosystem (Muraoka & Hirata, 1988).

Evidence of the influence of soilwater runoff appears in the seasonal changes in stream solute concentrations. The time-dependent changes in stream solute concentrations in relation to rainfall amount and the hydrograph, on a 5 day basis, since April 1985, are shown in Fig. 5. In the case of Type I substances, changes in the stream solute concentrations are not generally marked, but are stable varying around the average level and often show a reduction during storm runoff events. In contrast, Type II substances, and in particular, NO$_3^-$ concentrations, exhibit a distinctive seasonal trend. As illustrated in Fig. 5, the concentration rise is striking during the summer every year, and is closely related to the flow rate increase caused by typhoons 8506 and 8610. The concentrations of K$^+$ and Ca$^{2+}$ show, to some extent, a similar pattern to the NO$_3^-$ behavior, although the range of variation is smaller than that exhibited by the NO$_3^-$ concentrations.

Type II solute concentrations in soilwater increase in summer, due to the increase in microbial activity as the temperature rises. In addition, the frequent rainfall facilitates soilwater runoff and thereby reinforces the upward trend in stream solute concentrations. Type II substances demonstrate higher concentrations on the recession limb of a storm event than during baseflow. When a new storm event takes place, while the effects of a previous event are still evident, Type II substances increase their concentrations more during the wet season. This is the mechanism for interpreting the increase in the concentration of Type II substances in summer. Consequently, Type II substances demonstrate a positive correlation with the flow rate as illustrated in Fig. 6. Similar correlations between the NO$_3^-$ concentration and flow rate have been reported by Likens et al. (1977), Tsutsumi & Fukushima (1983), and Webb & Walling (1985).

SUMMARY

The element cycle within the forest ecosystem was shown to play a dominant role in modifying the element content of the forest soil and in creating a soilwater chemistry corresponding to the element content of the soil. As the soilwater contains two types of solutes which differ in the vertical distribution of concentration, soilwater runoff resulted in chemical changes during streamwater both in storm events and on a seasonal basis. In addition,
FIG. 5 Temporal variations in the stream solute concentrations observed in the Tsukuba experimental forest during the 4-year period from April 1985 to March 1989. The number in parentheses given with the typhoon is the total typhoon rainfall, in mm.

investigations of the origin of streamwater chemistry provide a means of determining water pathways through the forested basin. In this context, the processes controlling the evolution of the soilwater chemistry are able to provide a physical interpretation for the hydrochemical behavior of streamwater.

With respect to rainwater input and streamwater output budgets, nitrogen is not precisely in balance. To provide a full explanation of the nitrogen budget, amounts reaching the forest floor, and in particular that contained in throughfall, need further examination in
terms of the chemical and biological reactions involved. This is because the foliage of coniferous trees contains considerable amounts of wax on its surface, and this is capable of capturing airborne organic substances. Further investigation of the interrelationships between biochemical reactions and water migration may contribute to revealing not only the function of the forest ecosystem within the water environment, but also the water pathways in the forested basin.

REFERENCES


