Hydrobiogeochemistry of a Hill-Evergreen Forest in Northern Thailand

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ABSTRACT Studies on hydrobiogeochemistry were carried out in a hill-evergreen forest in northern Thailand. In this study forest climate conditions are characterized by a clear seasonal pattern of precipitation with dry and rainy season. Chemical properties of precipitation, throughfall and drainage waters were measured from December 1993 through February 1995. During the study period, annual precipitation was 2784 mm in the rainy season from March to October. Annual throughfall was 2936 mm. Higher throughfall would be attributed to fog interception by the canopy. Elemental fluxes in bulk precipitation and throughfall were high in the early rainy season from March to May. Elemental concentrations in forest drainage water of this watershed were in the lower range of concentration reported in other studies for tropical forests. Especially, Ca^{2+} , Mg^{2+} , Cl^- and NO_3^- were very low concentrations. For SO_4^{2-} , NO_3^- , NH_4^+ , and Si concentrations in drainage water declined in the rainy season and increased during the dry season. These results suggest the minimum element losses from this tropical watershed.

Key words: dry season / element cycling / rainy season / water chemistry / watershed

The deforestation has been progressing in tropical forests and its effects on hydrology in tropical forest were serious problem (Bruijnzeel, 1996). In the monsoon Asia, montane forests are important as water reservoirs for the people living in downstream area. In the mountain forests, tree canopy has an important role for their fog interception and reduction of evapotranspiration, and then supply more water to the forest vegetation and the people on the foot of the mountain (*e.g.*, Cavelier & Goldstein, 1989; Cavelier *et al.*, 1997; Zadroga, 1981). Therefore, forest canopy or cover is important for the functioning of hydrological and nutrient cycling in the forest watersheds of the monsoon Asia.

But the reviews of nutrient budgets (*e.g.*, Bruijnzeel, 1991), throughfall (*e.g.*, Parker, 1983), and nutrient cycling (*e.g.* Vitousek & Sanford, 1986) have indicated that studies of tropical forests have

been less common, particularly in tropical seasonal forests. Recently, the studies on nutrient budgets (*e.g.*, Lesack & Melack, 1996), export of elements (*e.g.*, McDowell & Asbury, 1994) and estimation of weathering rates (*e.g.*, Lewis *et al.*, 1987), etc. have been progressing in tropics, particularly south America. There are rather few hydrological studies in the mountain forest in the southeast Asia (*e.g.*, Chunkao *et al.*, 1981). In this region, climate is characterized by a distinct rainy and dry season, which provides particular regimes of hydrological and nutrient cycling in forested ecosystems.

The objective of the present study was to evaluate the hydrobiogeochemistry of a hill evergreen forest located at an altitude of 1160 m in northern Thailand. Although the nutrient budgets of this watershed were constructed from April 1974 through March 1975 by Naprakob *et al.* (1976), elements measured were limited. In the present study, the elements referred to as major, such as NO_3^- , NH_4^+ , Na^+ , K^+ , Mg^{2+} , Ca^{2+} , SO_4^{2-} and Cl^- , were measured. Then, ion fluxes and concentrations in bulk precipitation, throughfall and forest drainage water were studied in a hill-evergreen forest. This study was aided by previous investigations by Chunkao *et al.* (1981) on precipitation volumes.

STUDY SITE AND METHODS

Site Description

The study was carried out in a small watershed of 23 ha at Doi Suthep National Park, near Chiang Mai City in the northern Thailand ($18^\circ 47' \text{N}$, $98^\circ 37' \text{E}$; Fig. 1). The watershed is located at 1160 m in altitude. The mean annual temperature was 20.0°C and the mean annual precipitation was 2084 mm. A rainy season usually occurs from April through November followed by a dry season from December through March (Chunkao *et al.*, 1981). The overstory vegetation in the watershed is classified as a hill-evergreen forest (Rundel & Boonpragob, 1995). In this study site, the forest consisted of 46 tree species with the dominance of two species *Castanopsis accuminatissima* and *Schima waichii*.

The bedrock is highly weathered granite that is overlaid by Ultisols (Chunkao *et al.*, 1981). The amount of exchangeable basic cations in this forest was investigated by Haibara (Table 1, personal communication). The amount of exch. Ca and Mg sharply decreased below 10 cm depth. Exch. K in

Fig. 1. Location of study site.

● : study site

Table 1. Amount of basic cations in the soils at the lower slope.

layer(cm)	Exch. K (eq/ha)	Exch. Ca (eq/ha)	Exch. Mg (eq/ha)	Exch. Na (eq/ha)	Exch. K (kg/ha)	Exch. Ca (kg/ha)	Exch. Mg (kg/ha)	Exch. Na (kg/ha)
0-10	1841.4	13373.3	11184.2	304.5	72	268	136	7
10-20	3836.3	2045.9	3865.1	348	150	41	47	8
20-40	2173.9	898.2	2302.6	261	85	18	28	6
40-70	5012.8	598.8	164.5	130.5	196	12	2	3
70-100	3324.8	898.2	328.9	304.5	130	18	4	7
total to 70 cm	12864.5	16916.2	17516.4	1043.9	503	339	213	24
total to 100 cm	16189.3	17814.4	17845.4	1348.4	633	357	217	31

* Haibara, personal communication.

Fig. 2 (a). Monthly change in mean precipitation from 1966 to 1980 and discharge from 1966 to 1978. Bar is standard deviation. ○ : Mean precipitation. ● : Mean discharge.

(b). Seasonal changes in precipitation and throughfall. Bar is S.E. ▲: Precipitation in the present study. □: Throughfall in the present study.

the deep soil was abundant relative to other three cations (Na, Ca, Mg). Exch. Na was less than Ca and Mg.

Sampling Methods

Bulk precipitation and throughfall were collected twice a month during the period from December 1993 through February 1995. Bulk precipitation was measured in an open area at the base of the watershed using a polyethylene funnel (22.5 cm diameter) and sample container. Throughfall were measured using the same devices at 5 sites, each located at 20 m intervals along two belt transects of each 100m in length. Forest drainage water was also sampled at the same time at the base of the

Fig. 3. Composition of ion flux in bulk precipitation and throughfall.
BP denotes bulk precipitation, TF throughfall.

watershed. During the present study, hydrological flux measurements for the drainage waters were not carried out, but the data from previous years (1966-1978) were available (Chunkao *et al.*, 1981).

Chemical Analysis

Solution samples were stored in a refrigerator in the laboratory of Chiang Mai University and were brought back to the laboratory of Forest Ecology, Kyoto University for the chemical analysis. After arrival, pH (converted to H^+) was measured by glass electrode, and electrical conductivity (EC) using a meter. The water samples were passed through a $0.45 \mu m$ Millipore filter and then analyzed. Chemical analysis included: Na^+ , NH_4^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , NO_3^- and SO_4^{2-} using ion chromatography (Shimadzu, HIC-6A); dissolved Si by Inductively Coupled Plasma Spectroscopy (Seiko, SPS 1500). Units were reported in either in $mEq L^{-1}$ or $mMol L^{-1}$.

RESULTS

Amounts of Precipitation and Throughfall

During the present study, annual precipitation was 2784 mm, and was higher than the maximum of 2653 mm in the previous observation from 1966 to 1980 (Chunkao *et al.*, 1981). In this year, the first rainfall was observed in late March 1994, and therefore the rainy season was longer than usual year (Fig. 2a, b). Based on the variability of precipitation, rainy season was divided into early, middle and late rainy season as shown in Fig. 2(b). In each rainy season, coefficients of variation were 86.4, 42.1 and 78.8, respectively. Twenty seven, thirty five and thirty eight percents of annual precipitation distributed in early, middle and late rainy season, respectively.

Seasonal changes were similar between throughfall and precipitation (Fig. 2b). Annual throughfall

Fig. 4. Seasonal changes in ion fluxes in bulk precipitation and throughfall. Bar is S.E..
ER: Early Rainy season, MR: Middle Rainy season, LR: Late Rainy season.

was 2969 mm indicating that throughfall was greater than precipitation inputs of 2784 mm. This excess throughfall was not concordance with the general observations that the amount of throughfall is lower than precipitation.

Composition of Ion Fluxes in Bulk Precipitation and Throughfall

Cation fluxes in the bulk precipitation flux showed no dominant ion. While the anion fluxes showed the dominance of Cl^- and SO_4^{2-} (Fig. 3). Measured ions were almost balanced electrically in bulk precipitation. A composition of ions in the throughfall flux showed the dominance of K^+ for cations, and that of Cl^- and SO_4^{2-} for anions (Fig. 3). Anion deficiency, i.e., unmeasured anion, in throughfall was apparently found.

Seasonal Changes in Ion Fluxes of Bulk Precipitation and Throughfall

Fig. 4 shows the seasonal changes in elemental fluxes in bulk precipitation and throughfall during the study period. Based on the seasonal changes in ion fluxes, the measured ions were divided into two groups, i.e., (type I): mainly supplied in the early rainy season, including NO_3^- , Mg^{2+} , NH_4^+ , SO_4^{2-} , Ca^{2+} , and Na^+ , and (type II): supplied throughout the rainy season, represented by K^+ , H^+ , and Cl^- . In type I ions, about fifty percent of annual fluxes in bulk precipitation and throughfall were supplied

Table 2. Coefficient of regression and determination between ion deposition and water amount in bulk precipitation and throughfall every half a month.

(n=13)

Y = a × X; Y denotes ion flux (eq/ha) and X precipitation or throughfall (mm).

	Bulk precipitation			Throughfall			Difference#
	a	R ²	p	a	R ²	p	p
H ⁺	0.023	0.63	0.001	0.023	0.84	<0.001	0.949
Na ⁺	0.094	0.67	<0.001	0.064	0.67	<0.001	0.200
K ⁺	0.126	0.75	<0.001	0.503	0.86	<0.001	<0.001
Ca ²⁺	0.070	0.47	0.007	0.129	0.60	0.001	0.131
Mg ²⁺	0.027	0.28	0.050	0.103	0.62	<0.001	0.010
NH ₄ ⁺	0.119	0.41	0.014	0.116	0.52	0.003	0.943
NO ₃ ⁻	0.024	0.09	0.303	0.040	0.40	0.016	0.539
Cl ⁻	0.218	0.55	0.003	0.342	0.53	0.003	0.270
SO ₄ ²⁻	0.260	0.66	<0.001	0.373	0.65	<0.001	0.259

The difference in coefficients of the two regressions (analysis of covariance).

Fig. 5. Distribution of water amount and ion flux in bulk precipitation and throughfall through the year. WA: Water Amount, ER: Early Rainy season, MR: Middle Rainy Season, LR: Late Rainy season.

during the early rainy season. While the seasonal changes in fluxes of type II such as K^+ , H^+ , and Cl^- were similar to those of precipitation and throughfall.

Table 2 shows the results of a regression analysis for the relationship between water and element flux in bulk precipitation and throughfall. Coefficients of determination for bulk precipitation fluxes ranged from 0.09 to 0.75, and for throughfall fluxes ranged from 0.40 to 0.86 (Table 2). In bulk precipitation, low coefficients of determination (<0.50) were found for the some ions of type I, i.e., NO_3^- , Mg^{2+} , NH_4^+ , Ca^{2+} . (Fig. 5). High coefficients of determination (>0.80) were found in the throughfall fluxes of type II (K^+ and H^+ fluxes).

Elemental Concentrations in Precipitation, Throughfall and Forest Drainage Water

Changes in ion fluxes from precipitation to throughfall are shown in Fig. 3. Annual fluxes of H^+ , NO_3^- , and NH_4^+ show no significant differences between the precipitation and throughfall (Fig. 3). Na^+ flux was lower in throughfall than in precipitation, showing the decrease of this ion after passage through canopy. The annual fluxes of K^+ , Mg^{2+} , Cl^- , and SO_4^{2-} were significantly higher in the throughfall than in the precipitation, showing the increments of these ions after passage through the canopy (pair-wised t-test, $p<0.001$ for K^+ and $p<0.05$ for Mg^{2+} , Cl^- , and SO_4^{2-}).

Fig. 6 shows the mean annual ion concentrations (volume-weighted) in precipitation and throughfall and arithmetic mean concentrations in forest drainage water. EC values increased from the precipitation to throughfall. But there were no significant differences between the throughfall and the drainage water. Concentrations of H^+ , NO_3^- and NH_4^+ ions show no significant differences between the precipitation and throughfall, but show significant decreases in the drainage water. Concentrations of Na^+ decreased from the precipitation to throughfall, and showed a significant increment in the drainage water. Concentrations of K^+ , Ca^{2+} , Mg^{2+} , Cl^- , and SO_4^{2-} showed significant increments from precipitation to throughfall. While the concentrations in the drainage water significantly decreased from the throughfall to the drainage water. Input of Si from atmosphere is generally negligible (e.g., Lewis *et al.*, 1987; Shimada *et al.*, 1993), so Si in drainage water was released from the forest soil.

Seasonal Changes in Forest Drainage Water Chemistry

Fig. 7 shows the seasonal changes in ion concentrations of drainage waters. During the study period, EC was rather stable over the rainy and dry seasons. The concentrations of NO_3^- , NH_4^+ , SO_4^{2-} , and Si were lower in the rainy season than in the dry season. While concentration of H^+ was higher in the rainy season than in the dry season. For the other ions, such as Ca^{2+} , Mg^{2+} , Cl^- , K^+ , and Na^+ their concentrations were variable through the study period.

DISCUSSION

Amount of Precipitation and Throughfall

During the study period, the amounts of throughfall were significantly higher than those of precipitation. This excess of throughfall was uncommon phenomenon, because interception ratio of rainfall by canopy generally ranged from 13 to 51 % (Tsukamoto, 1992). In the present site, fogs were very common during the rainy season and fog drip may be contributed to the increments of water flux under the canopy. Zadroga (1981) suggested (1) the contribution of the interception of liquid water

Fig. 6. Mean concentrations of major ions in bulk precipitation, throughfall (volume-weighted) and drainage water (arithmetic). Bar is standard deviation. BP... Bulk precipitation, TF... Throughfall, DW... Drainage water.

Table 3. Concentrations of dissolved ions and Si in forest drainage water in other tropical regions.

	H^+ (meq/l)	Na^+	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	SO_4^{2-}	Si (mmol/l)	n
Perto Rico ¹⁾ (SD)	0.0001 (<0.001)	0.2450 (0.073)	0.0009 (<0.001)	0.0086 (0.004)	0.1967 (0.104)	0.1927 (0.149)	0.2057 (0.038)	0.0001 (0)	0.0530 (0.005)	0.2825 (0.111)	3
Terra firme ²⁾	0.0216	0.0067	0.0008	0.0007	0.0016	0.0016	0.0131	0.0113	0.0040		1
Caura River ³⁾	0.0002	0.0500	0.0030	0.0150	0.0320	0.0200	0.0120	0.0040	0.0080	0.1346	1
Gunung Silam ⁴⁾	0.0000	0.0870	0.0044	0.0026	0.0254	1.0280	0.1497	0.0500	0.0333		1
Chiang Mai ⁵⁾	0.0001	0.0534	0.0010	0.0216	0.0049	0.0026	0.0061	1.9E-5	0.0076	0.2269	1

1): McDowell & Asbury (1994), 2): Lesack & Melack (1996), 3): Lewis *et al.* (1987), 4): Bruijnzeel *et al.* (1993), 5): present study.

Fig. 7. Seasonal changes in concentrations of chemicals.

ER: Early Rainy season, MR: Middle Rainy season, LR: Late Rainy season.

droplets and (2) vapor condensation by crown foliage for the increments of throughfall. The present site was located at altitude of 1160 m, and is not typical moss forests. But the crown of foliages may contributed to the increments of throughfall as in the moss forest.

Elemental Fluxes in Bulk Precipitation and Throughfall

Fluxes of type I ions such as NO_3^- , Mg^{2+} , NH_4^+ , SO_4^{2-} , Ca^{2+} , and Na^+ were supplied mainly in early rainy season (Fig. 5). Particles and gases would be suspended in the atmosphere and deposited on the leaf surface during the dry season. These suspended and dry-deposited materials would be washed off, especially in early rainy season. On the other hand, type II ions such as H^+ , K^+ , and Cl^- would be continuously supplied to the forest soil through the rainy season.

H^+ flux generally decreases after passage through the canopy at broad-leaved forests (Parker, 1983, 1990), but not for the present forest. Fluxes of K^+ , Mg^{2+} , Cl^- , and SO_4^{2-} showed significant increment from bulk precipitation to throughfall. Canopy leaching of K^+ and Mg^{2+} was generally observed (*e.g.*, Parker, 1983, 1990; Vitousek & Sanford, 1986). Canopy leaching of Cl^- has some debate, but it was suggested in some studies (*e.g.*, Forti & Moreira-Nordemann, 1991; Peters, 1991). The canopy leaching of Cl^- would occur in this site during middle rainy season (Fig. 4). For these ions, internal cycling with water flow was significant in the nutrient retention within a forest ecosystem. Increased SO_4^{2-} flux in throughfall was generally derived from dry deposition (*e.g.*, Lindberg & Garten, 1988; Garten, 1988; Johnson & Lindberg, 1992). Increments of K^+ , Mg^{2+} , and Cl^- would be also attributed to the washoff of dry-deposited material, especially in early rainy season for Mg^{2+} . This indicates the importance of dry deposition as external nutrient sources to the forest ecosystem. In this forest, higher throughfall than precipitation would enhance the leaching and

washoff of dry-deposited material.

Chemistry of Forest Drainage Water

The concentrations of all solutes in drainage waters from this watershed except Na^+ and K^+ were in the lower range of other studies, especially for Ca^{2+} , Mg^{2+} , Cl^- , and NO_3^- (Table 3). Concentration of Si was in the middle range in the tropical forests. For all the ions except for Na^+ and K^+ , the concentrations in drainage water were lower than in bulk precipitation (Fig. 6). Higher concentration of Na^+ in drainage water might be due to weathering and this lead to higher EC. For essential elements, plant uptake and microbial immobilization would lower the concentrations in drainage water, especially for NO_3^- , NH_4^+ , and SO_4^{2-} . Concentration of these ions declined during the rainy season. Moreover, SO_4^{2-} would be adsorbed in the soil as shown in other Ultisols (Reuss & Johnson, 1986; Swank & Waide, 1988) and NH_4^+ also would so. Thus, these retention mechanisms highly restricted the element losses from this watershed.

For ions which had lower concentrations in drainage water than in bulk precipitation, the nutrient budgets would be positive, because water discharge was lower than precipitation amount. Jordan (1982) suggested that, in the balanced ecosystem with nutrient output lower than atmospheric input, the forest apparently maintained itself on nutrients derived from the atmosphere. In the present site, the nutrient supplements from atmosphere, especially during early rainy season, were considered to play an important role for the maintenance of the forest ecosystem.

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五郎 タイ北部の丘陵常緑林における水質水文学的研究

著者らはタイ北部の丘陵常緑林における水質水文学的研究を行った。この森林の気候条件は雨季と乾季を伴う明瞭な降水量の季節パターンで特徴づけられる。1993年12月から1995年2月まで、降水、林内雨、流出水の水質が測定された。研究の行われた期間、3月から10月にわたる雨季に見られた年間降水量は2784 mmであった。年間林内雨量は2969 mmになり、これは林冠による雲霧の遮断によるものであろう。降水中和と林内雨による元素フラックスは3月から5月の雨季の初期に高かった。この集水域からの森林流出水の元素濃度は他の熱帯の森林での報告値の低い範囲にあり、特に Ca^{2+} , Mg^{2+} , Cl^- , NO_3^- にあてはまっていた。流出水中の SO_4^{2-} , NO_3^- , NH_4^+ , Si 濃度は雨季に低下し、乾季に上昇した。これらのことはこの集水域からの元素の流出が少ないことを示す。