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Throughfall and stemflow nutrient depositions to soil in a subtropical evergreen broad-leaved forest in the Wuyi Mountains*

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Abstract—A study concerning the throughfall and stemflow chemistry in the *Castanopsis eyrei* forest was conducted during 1993—1994. The results showed that the net throughfall nutrient fluxes showed consistent canopy effects on precipitation chemistry. In general, potassium, calcium, magnesium, sodium and sulphur were added to precipitation by foliage, whereas the canopy absorbed nitrogen and phosphorus from precipitation. In stemflow, negative net deposition occurred for phosphorus only, and the rest nutrients were added to precipitation by tree stems and branches. The total net depositions of nutrients in both throughfall and stemflow followed the sequence of potassium > calcium > sodium > magnesium > sulphur, ranging between 2.56—52.54 kg/($hm^2 \cdot a$). For potassium and calcium, net throughfall was the largest pathway, and the net throughfall contribution to the total yearly nutrient return to the forest soil was 54% and 42% respectively. Although the net stemflow contribution to the total yearly nutrient return was small (between 0 and 13%), stemflow represented the largest pathway of water and nutrient input to the stemflow zone of the forest floor in the *C. eyrei* forest ecosystem.

Keywords: throughfall; stemflow; nutrient deposition; nutrient return; Wuyi Mountains.

1 Introduction

Precipitation is an important source of nutrient input to forested ecosystems, especially where rock weathering is slow (Parker, 1983). The quality of precipitation falling on forests is dramatically altered during a brief but significant interaction with the surface of trees, resulting in the deposition of additional mineral matter by throughfall and stemflow to the forest floor, which may be important in plant nutrition and soil fertility (Eaton, 1973; Lovett, 1984). Throughfall and stemflow are also major pathways in nutrient cycling, and the annual nutrient return to the forest soil for the elements K, Na and S is predominantly via these fluxes (Parker, 1983). Therefore, estimation of the fluxes of elements in incident precipitation, throughfall and stemflow is now a routine part of nutrient budget studies in forest ecosystems (Likens, 1967; Jordan, 1982). The need for study of forest precipitation chemistry has taken on added importance as precipitation acidification has increased in recent decades (Potter, 1991). Budgets of nutrient inputs and outputs along with rainfall cycling for undisturbed forest ecosystems provide a conceptual and empirical framework both for examining ecosystem function in diverse geographic regions and for evaluating man's impact on the natural landscape (Swank, 1987).

Studies of forest precipitation chemistry have received great attention since as early as in the

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end of last century, and are now commonplace and increasing in number. In the past, interest was directed at (1) the quantification of nutrient fluxes under various climate and canopies; (2) the examination of factors and processes controlling throughfall composition, its seasonality and heterogeneity. Recently, much attention is being focused on the external and internal sources of throughfall enrichment (Parker, 1983).

The composition of throughfall and stemflow had been studied in a number of locations in the world, especially in populated Europe and America. In China, there are only a few descriptions of this kind, some of the most extensive forests remain unstudied (Li, 1994).

In this paper, an evergreen broad-leaved forest in the Wuyi Mountains in subtropical China was chosen to (1) quantify the depositions of nutrients in incident precipitation, throughfall and stemflow; (2) examine factors controlling throughfall and stemflow composition, its seasonality, and (3) compare throughfall and stemflow pathways with other nutrient return pathways in the ecosystem.

2 Study area

Research was conducted in the Fujian Wuyi Mountains Nature Reserve in east-central China (27°33′—54′N, 117°27′—51′E), from January 1993 to April 1994. The study area is in the central part of the Wuyi Mountains, with an average elevation of about 1200m. The climate is monsoon subtropical with an 8.5—18℃ annual mean temperature, and an average annual rainfall of about 2096.6 mm. There is considerable monthly and yearly variability in rainfall. The topography consists of steep and severely rolling hills that rise up to 50m above the surrounding terrain.

The study plot was located at the Xianfeng Ridge 10 km south-west of the headquarters of the nature reserve. The site has a south-east-facing aspect, with the altitude being 1270m, and slope being 20°. The soil is mountain yellow earth, and 110 cm in depth covered with a 5 cm litter layer. The forest was an even-aged stand of old-growth dominated by *Castanopsis eyrei*, and recognized as a subtropical evergreen broad-leaved forest (He, 1994), with a continuous canopy 12m in height, and a density of approximately 250 trees hm^2 (>10 cm DBH). The understory was fairly open, consisting of *Eurya loquaiana*, *Rhododendron latoucheae*, and *Ologostachyum oedogonatum*, with a poorly developed herbaceous layer.

3 Methods

3.1 Incident precipitation, throughfall and stemflow

Incident precipitation was collected in five plastic narrow-mouth bottles randomly laid in an open flat area about 100m from the forest edge. The narrow mouths of the bottles (3 cm diameter) acted as convenient proportional samplers, this procedure automatically resulted in volume-weighted samples. The narrow mouths also prevented overflow of the bottles. The mouths were covered with a thin layer of fiberglass wool to prevent insects from entering bottles (Jordan, 1982).

Three metal troughs (2.0m × 0.2m × 0.2m) covered inside with plastic were used to collect throughfall. All troughs and plastic bottles were rinsed thoroughly with distilled water between storms. Stemflow was collected from three living stems of different size. Cement stemflow-collecting troughs were built around the bases of trees, and a plastic tube under a hole in each trough was used to drain stemflow into a sample container. Phenyl mercuric acetate (PMA) was sprayed into all sample containers to inhibit bacterial growth (Potter, 1991). Water collection was made for every rainfall event. All the water in the collectors was transferred into the storage jugs. Chemical analysis was made bimonthly.

Methods for measuring the quantity of incident precipitation, throughfall, stemflow, and relevant results have been reported in another paper by Li *et al*. (Li, 1997).

3.2 Chemical analysis

Calcium, potassium and magnesium were determined by standard atomic-absorption methods. Phosphorus was determined by the molybdenum blue colorimetric procedure. Sulphur was determined photometrically. Total nitrogen was analyzed by Kjeldahl digestion method. Sample pH was measured using a Corning model 120 pH meter.

3.3 Data calculation

The fluxes of a given nutrient in different precipitation portions were determined by multiplying their amounts of water by the respective solute concentrations of the nutrient (Parker, 1983). If Di, Dt and Ds represent the amounts of water sampled in incident precipitation, throughfall and stemflow, Ci, Ct and Cs are the respective solute concentrations of nutrients, related items can be calculated as below: Gross deposition by incident precipitation (INC) = $Di \cdot Ci$; Gross deposition by throughfall (THF) = $Dt \cdot Ct$; Gross deposition by stemflow (STF) = $Ds \cdot Cs$; Net deposition by throughfall (NTF) = $Dt(Ct - Ci)$; Net deposition by stemflow (NSF) = $Ds(Cs - Ci)$. The net effect of the forest is the sum of net throughfall and net stemflow:

$$NFW = DtCt + DsCs - DiCi = THF + STF - INC \approx NTH + NSF.$$

4 Results and discussion

4.1 Throughfall nutrient deposition

Net throughfall nutrient fluxes showed consistent canopy effects on precipitation chemistry in the *C. eyrei* forest (Table 1). In general, potassium, calcium, magnesium, sodium and sulphur were added to precipitation by foliage, whereas the canopy absorbed nitrogen and phosphorus from precipitation. The increase in potassium concentration in throughfall was largest, and 18 times greater than the concentration in precipitation. For calcium, magnesium, sodium and sulphur, increases were between 20% to 1.5 times. Concentrations in throughfall for nitrogen and phosphorus decreased by 22%—52% of those in precipitation. Net throughfall nutrient depositions for potassium, calcium, magnesium, sodium and sulphur ranged between 1.94 and 50.57 kg/($hm^2 \cdot a$), and for nitrogen and phosphorus were −5.89 and −0.77 kg/($hm^2 \cdot a$) respectively. The highest net throughfall deposition occurred for potassium again, and the deposition ratio (NTF/INC) was 14.2. Calcium also exhibited a significant rate of deposition in throughfall (second to potassium).

High potassium deposition rate and negative net nitrogen deposition in throughfall have been reported in a number of studies both in China (Xu, 1996; Gan, 1996) and abroad (Lovett, 1984; Potter, 1991). A summary of throughfall chemistry based on the extensive data in the world indicated that potassium commonly showed the highest throughfall concentrations of the inorganic nutrients, and its deposition ratio averaged 11.2 (Parker, 1983). Since ambient atmospheric dry deposition of the element were low in the area, while its mobility and foliar levels were extremely high in the forest, the high net throughfall potassium deposition derived almost entirely by foliar leaching. Negative net throughfall deposition was most commonly reported for NH_4-N though NO_3-N and total nitrogen were also removed from precipitation (Parker, 1983). Foliar levels were usually high (1.0%—3.5%, second only to calcium) yet leaching was very low (Tucky, 1970).

Table 1 Nutrient concentrations in and net depositions via throughfall in the *C. eyrei* forest

	Throughfall, mm	Ca	Mg	K	Na	P	S	N
Seasonal concentration in throughfall, mg/L								
1993 (Mar. to Apr.)	333.5	1.86	0.24	3.99	0.99	0.00	0.00	0.83
1993(May to June)	1164.9	0.89	0.12	1.24	0.33	0.01	0.90	0.95
1993(July to Aug.)	281.3	1.72	0.15	1.33	0.15	0.00	0.11	1.00
1993(Sept. to Dec.)	172.1	8.93	0.08	8.72	0.82	0.26	0.15	1.10
1994(Jan. to Feb.)	131.1	4.43	0.90	5.23	0.96	0.03	0.19	1.70
Volume-weighted concentration, mg/L	2082.78*	2.044	0.189	2.561	0.492	0.029	0.568	0.997
Volume-weighted concentration in incident precipitation, mg/L	2687.78	0.858	0.077	0.133	0.249	0.066	0.475	1.280
THF, kg/(hm^2·a)		42.57	3.94	53.34	10.25	0.60	11.83	20.77
NTF, kg/(hm^2·a)		24.70	2.33	50.57	5.06	−0.77	1.94	−5.89

*: Total amount of throughfall during the period of the study

Rapid foliar uptake dominates the net throughfall process which has been observed when biological agents were added to throughfall samples to prevent microbial uptake of nitrogen (Schlesinger, 1978). Therefore, foliar uptake should be the major process for the negative net throughfall nitrogen deposition in our study. For other nutrient elements, the two primary mechanisms influencing throughfall chemistry in the forest may be (1) wash off atmospheric dry depositions of these elements from leaf surfaces, and (2) canopy exchange, through leaching of plant nutrients from the foliage, though we were not able to distinguish between their individual contributions.

Concentrations of most nutrient elements in throughfall exhibited great seasonality in the *C. eyrei* forest. Concentrations of potassium, calcium, magnesium and sodium were low during rainy seasons, and high in dry seasons. On the contrary, sulphur concentration was highest in summer, becoming more even throughout the year. Nutrients such as nitrogen and phosphorus were lowest at the beginning of the growing season, becoming progressively higher until foliar abscission.

4.2 Stemflow nutrient deposition

Calcium was the most predominant nutrient constituent in stemflow in the *C. eyrei* forest, and its concentration being distinctly higher than other nutrients by up to an order of magnitude. The rest nutrients were in the order of potassium > nitrogen > sulphur > magnesium > sodium > phosphorus (Table 2).

Table 2 Nutrient concentrations in and net depositions via stemflow in the *C. eyrei* forest

	Stemflow, mm	Ca	Mg	K	Na	P	S	N
Seasonal concentration, mg/L								
1993 (Mar. to Apr.)	13.81	15.76	1.27	5.64	0.48	0.02	0.25	0.60
1993 (May to June)	72.86	7.92	0.67	1.31	0.11	0.03	1.44	1.80
1993 (July to Aug.)	6.95	1.72	0.00	0.00	0.00	0.01	0.13	1.27
1993 (Sept.) to 1994 (Feb.)	6.34	7.15	0.84	5.81	1.45	0.05	0.13	3.20
Volume-weighted concentration, mg/L	99.96*	8.53	0.72	2.10	0.24	0.026	1.10	1.68
STF, kg/(hm^2·a)		8.52	0.72	2.10	0.24	0.026	1.10	1.68
NSF, kg/(hm^2·a)		7.66	0.64	1.97	0.00	−0.04	0.62	0.40

*: Total amount of stemflow during the period of the study

The general pattern of stemflow nutrient fluxes was different from that in throughfall. Negative net deposition in stemflow occurred for phosphorus only, and the rest nutrients were added to precipitation by tree stems and branches. Increases in concentrations of potassium, calcium and magnesium in stemflow were most considerable, and about 15, 9 and 8 times greater respectively than those in precipitation. Nitrogen and sulphur slightly increased (0.13—1.31 times greater), and there was no change in sodium concentration. Phosphorus decreased by 61 percent of that in precipitation. A comparison of the volume-weighted concentration of nutrients in stemflow, throughfall and precipitation showed that nitrogen, sulphur, calcium and magnesium were highest in stemflow, while potassium and sodium were highest in throughfall. Lowest values occurred in precipitation for all the nutrients but nitrogen and phosphorus.

Net stemflow nutrient depositions of calcium, potassium, magnesium, sulphur and nitrogen ranged between 0.40 and 7.66 kg/($hm^2 \cdot a$), and for phosphorus was −0.04 kg/($hm^2 \cdot a$). Calcium exhibited the highest rate of deposition in stemflow, and the deposition ratio (NSF/INC) was 0.33 (second to that of potassium which was 0.55). Proportional stemflow nutrient fluxes, calculated as stemflow/(stemflow + throughfall), provide a relative index of the importance of stemflow as an input to soil in the forest nutrient cycle (Potter, 1992). In the *C. eyrei* forest, percentage contributions of calcium, potassium, magnesium and sulphur in stemflow were 24%, 4%, 22% and 24% respectively, averaging 18.5%. The water borne sodium was completely from throughfall, whereas total below-canopy fluxes of nitrogen and phosphorus derived completely from stemflow. Though having similar seasonal patterns, concentrations of nitrogen, sodium and potassium in stemflow were more seasonal than those in throughfall, whereas concentrations of calcium, magnesium, phosphorus and sulphur were less seasonal than in throughfall.

A number of studies of the stemflow chemistry in forests showed that nutrient concentrations in stemflow were considerably higher than those in throughfall, by up to an order of magnitude (Parker, 1983). Stemflow commonly had high concentrations of calcium, potassium, sulphur and magnesium (Mahendrappa, 1974), provided large nutrient depositions of calcium, sulphur and magnesium (Mayer, 1972). The percentage contribution of nutrients in stemflow, based on numerous studies in the world, was between 1% and 20%, averaging about 12% (Parker, 1983). It can be noticed that our results generally fitted these studies.

Though it is more infrequent than throughfall, stemflow is almost always the largest pathway of water and nutrient input to the stemflow zone of the forest floor (Potter, 1992). From an ecosystem perspective, stemflow can be a particularly important transfer route for nutrients such as calcium, magnesium and sulphur in the *C. eryrei* forest.

4.3 Total water borne nutrient fluxes

The total net depositions of nutrients in both throughfall and stemflow followed the sequence of potassium > calcium > sodium > magnesium > sulphur, ranging between 2.56—52.54 kg/($hm^2 \cdot a$) (Table 3). Negative net depositions occurred for nitrogen and phosphorus, being −5.49 and −0.81 kg/($hm^2 \cdot a$) respectively. These values were within the range of those reported in other subtropical forests in China (Li, 1994), and those reported in the world (Parker, 1983).

The total deposition ratio, calculated as $(NTF + NSF)/INC$, showed the contribution of the sum of nutrient materials by canopy leaching and stem washing as a percentage of the input of nutrients by precipitation. In our study, the ratio ranged between −0.46 to 14.8, and decreased in the order of potassium > magnesium ≈ calcium > sodium > sulphur > nitrogen > phosphorus. The sequence was fairly similar to that summarized by Parker (Parker, 1983), i.e., potassium (11.20) > magnesium (4.00) > calcium (2.86) > sodium (2.41) > sulphur

(2.26) > nitrogen (1.90). High deposition ratios of potassium, magnesium, calcium and sodium in our study indicated that these nutrients were transported to the forest floor much more by throughfall and stemflow than by precipitation.

Table 3 Total net nutrient depositions via throughfall and stemflow and the deposition ratios

Total net deposition	Water amount, mm	Ca	Mg	K	Na	P	S	N
(*NTF* + *NSF*), kg/(hm²·a)	2182.74	32.36	2.97	52.54	5.06	−0.81	2.56	−5.49
INC, kg/(hm²·a)	2678.78	22.98	2.06	3.56	6.67	1.77	12.72	34.29
(*NTF* + *NSF*)/*INC*	0.81	1.41	1.44	14.76	0.76	−0.46	0.20	−0.16

Various nutrient-return pathways in the biological cycling of nutrients in the *C. eyrei* forest and their relative contributions are summarized in Table 4. For potassium and calcium, net throughfall was the largest pathway, and the net throughfall contribution to the total yearly nutrient return was 54% and 42% respectively. There were also some litterfall and root death contributions of potassium (22% and 19%) and calcium (31% and 9%), and the stemflow contributions were relatively minor (13% for calcium and 2% for potassium). Phosphorus and magnesium return to the forest soil derived largely from litterfall (54% and 41%), with some root death (41% and 28%) and net throughfall (20% for magnesium only) contribution. Nitrogen transfers to the forest soil derived mainly from root death (50%) and litterfall (46%), and very little from coarse woody debris (CWD, 4%). The throughfall contribution to the total yearly nutrient fall in forest ecosystems world wide ranged from 40%—65% for potassium, 15%—35% for magnesium, 10%—20% for calcium and phosphorus, and 0—15% for nitrogen (Parker, 1983). In our study, the corresponding values for potassium and magnesium were fairly in the range, with calcium being higher, nitrogen and phosphorus being much lower.

Table 4 Comparison of nutrient return pathways and their relative contributions in the *C. eyrei* forest ecosystem, kg/(hm²·a)*

Pathway	N	P	K	Ca	Mg
Throughfall	−5.89	−0.77	50.57	24.70	2.33
Stemflow	0.40	−0.04	1.97	7.66	0.64
Litterfall	48.78	1.52	20.59	18.47	4.87
Coarse woody debris (CWD)	4.27	0.12	1.80	2.89	0.56
Root death	52.08	1.20	17.96	5.41	3.34
Total	105.13	2.84	92.89	59.13	11.74

*: Data for other nutrient return pathways were cited from Li *et al*. (Li, 1996)

The above results indicated that the annual nutrient return to the forest soil was predominantly via throughfall and litterfall in the *C. eyrei* forest, and CWD and stemflow pathways were basically minor. On the whole, throughfall and stemflow may have played a very important role in the nutrient cycling in a *C. eyrei* forest in the Wuyi Mountains.

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