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Research Article

Leachate Nutrient Analysis and Dynamics of Litter and Topsoil of a *Quercus variabilis* Forest in the West Mountains near Beijing

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Abstract: Rainfall is a major source of nutrients for forest ecosystems and the subsequent leaching from forest litter contributes to nutrient cycling. In an effort to examine leachate dynamics from forest litter and topsoil, a field experiment was conducted over 7 months in a *Quercus variabilis* forest in the West Mountains, near Beijing. The seasonal patterns of concentrations of the nutrients studied differed. Concentrations of NH_4-N, TP (Total P), K, Ca and Mg in litter leachate were higher than those in the topsoil leachate. In both leachates, Ca had the highest overall proportion of the nutrients studied, followed by K, NO_3-N, NH_4-N, TP and Mg in the litter leachate and by NO_3-N, K, NH_4-N, TP and Mg in the topsoil leachate. NH_4-N, NO_3-N and Ca in both leachates had significant positive relationships. The rain-based fluxes of Ca, inorganic N (NH_4-N, NO_3-N) and K from the litter leachate were 73, 43 and 23 kg/ha/year, respectively. Consequently, forest litter appears to be a nutrient source in the *Quercus variabilis* forest, especially for Ca, inorganic N and K and nutrients from the forest litter appear to have an important effect on topsoil. This can provide data support for forestry engineering.

Keywords: Leachate, litterfall, nutrient flux, *Quercus variabilis*, topsoil

INTRODUCTION

Trees naturally lose leaves and twigs as they grow, providing the forest with a continuous litter layer. As a part of the forest ecosystem and a nutrient medium, forest litter links plants and the soil and plays an important role in nutrient circulation, energy flow and the maintenance of soil fertility (Madeira and Ribeiro, 1995; Loupe *et al*., 2007). The nutrients released from forest litter and through fall are the most important nutrient source for plant growth (Parker, 1983; Yavitt and Fahey, 1986; Alewell *et al*., 1999), but the amount of nutrients taken up by root systems and returned subsequently to the soil through litter remains an unanswered question in forest plant nutrition and forest ecology.

Rainwater constitutes an important pathway for nutrient transfer to forest floor and so the nutrient input from rainfall plays an important role in the forest nutrition and forest soil fertility maintenance. The role of rainfall in nutrient leaching was reviewed by Parker (1983).

Many studies, in a variety of settings, have focused on forest rainfall chemistry: pine plantations in Canberra (Crockford and Khanna, 1997) and in the west Mountains in Beijing (Nie *et al*., 2007), adjacent primary and secondary forests of the Gran Sabana, southern Venezuela (Dezzeo and Chacon, 2006), a *Coffea arabica*-Eucalyptus deglupta agroforestry system in southern Costa Rica (Harmand *et al*., 2007), three species in Mediterranean holm oak forest (Bellot and Escarre, 1991), a montane subtropical moist forest on Ailao Mountains in Yunnan, south-west China (Liu *et al*., 2002), a successional hardwood forest, near Franklin (Potter, 1992) and a central African rain forest dominated by ectomycorrhizal trees (Chuyong *et al*., 2004).

Current research into the chemical characteristics of rainfall has focused primarily on the tree or shrub layer of the forest and few reports on nutrients released from the litter layers. Although many authors recognize that the litter layer plays an important role in nutrient circulation, most focus on organic matter turnover. Crockford and Richardson (1998), Turner and Lambert (2002) and Scherer-Lorenzen *et al*. (2007) focused on forest litter yield, while Wilcke *et al*. (2002), Fröberg *et al*. (2005), Funk (2005) and Powers *et al*. (2009) focused on litter decomposition and nutrient content.

Attiwill and Adams (1993) showed that litter is the main biological route in plant-soil nutrient flow and that litter is one of the most important and dynamic aspects of nutrient circulation in forest ecosystems. Nutrients released from the decomposition of forest litter accounted for 69 and 81% of the nutrients needed by forest growth every year. While circulating in the plant-soil ecosystem, water serves as the medium and transportation force for nutrient circulation and is also affected by the forest vegetation and the forest soil it passes through. Most nutrients released from the

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decomposition of litter move downward in the soil, changing the nutrient concentration of the soil solution.

Quercus variabilis typically grows with *Pinus tabulaeformis* Carr to form natural needle and broadleaf mixed forests in temperate northern China. It is also one of the main tree species for afforestation and vegetative restoration in China.

This study aims to quantify the downward fluxes of nutrients in the *Quercus* forest, from the canopy to the soil. The overall goal is to provide information for effectively managing the nutrient sources of the forest litter and maintaining the fertility of forest soils.

METHODOLOGY

Study site: The study site (lat 39°54′N, long 116°28′E) is located in Yanerling, within Jiufeng National Forest Park, 30 km western of Beijing. A major feature of the park is Miaofeng Mountain, which lie within the West Mountain range that connects the northern part of Taihang Mountain and the eastern part of Yanshan Mountain. The summit of Miaofeng Mountain is 1153 m above sea level. The upper part of the mountain consists of granite and tuff while the lower part is sandstone and limestone. The site has a typical warm-temperate, continental monsoon climate with distinct seasons. It is warm, dry and windy in spring, warm and humid in summer, sunny and humid in the fall and cold and dry in winter. The annual average temperature is 11.7°C with a maximum of 39.7°C and a minimum of -19.6°C. Annual rainfall is about 645 mm with peak rainfall occurring between July and September.

Basic soil properties of study area are provided in Table 1. The area was afforested in the 1950s and 1960s and the *Quercus variabilis* trees are of uniform age covering an area of about 200 ha on a south slope. The average *Quercus* tree height is 10.5 m and the average breast diameter is 13.4 cm. The tree density is 1335 trees/ha. Shrub undergrowth includes *Zizyphus jujube* var. inermis and *Rhamnus parvifolia*. Herbaceous plants include *Arthraxon hispidus* and *Eriophorum vaginatun*. The litter layer averages 4 cm thick and consists of un-decomposed and semi-decomposed material.

Sampling: Three plots (20×20 m) were selected for the investigation of soil and vegetation. In each plot, three 1×2 m areas were randomly selected as a sample area based on litter composition, thickness and uniformity. Each sample area was divided into two 1×1 m sub-sample areas, one designed for litter leachate collection and the other for topsoil leachate collection.

Litter from the litter leachate sub-sample area was removed and a net (0.5 mm mesh width) was laid down immediately on top of a polyethylene sheet, after which the litter was replaced. The downslope side was connected by a plastic tube to a 20-L plastic bottle to hold the leachate. The collection bottles and tubes were treated with a solution of concentrated HNO_3 diluted to 20% for 3 days and then rinsed 6 times with distilled water before they were installed.

For the topsoil leachate collection, the litter and a 5 cm thickness of topsoil was removed. Similarly to the litter leachate collection, a net (0.5 mm mesh width) was laid down immediately on top of a polyethylene sheet used to cover the area and the topsoil and litter were replaced. The down slope side was connected by a plastic tube to a plastic tub that had been treated with a solution of concentrated HNO_3 diluted to 20% HNO_3 for 3 days and then washed prior to receiving leachate.

The volume of leachate was measured from each sample area after each rainfall event. A combined sample for each plot was produced by compositing the single samples directly in the field. The final subsamples of 500 mL were collected in plastic bottles (rinsed with sample when possible) and transported to the laboratory where they were refrigerated (<3°C) until analysis.

Two rain gauges collected rainwater along the forest cap; this water served as a control. Samples were collected from March to October 2009.

Nutrient analysis: Water samples were analyzed for 70 events. On arrival at the laboratory samples were processed immediately or refrigerated for less than 24 h; pH was measured before filtration. Approximately 300 mL was filtered through a 0.45-μm membrane filter and analyzed for ammonium Nitrogen (NH_4-N), Nitrate Nitrogen (NO_3-N), Total Phosphorous (TP), potassium (K), Calcium (Ca), Magnesium (Mg) and sodium (Na). pH was analyzed using an Orion pH meter with an 868 (9272BN) electrode. NH_4-N analysis was conducted using the indophenol-blue reaction and NO_3-N was determined using the phenol dilsulphonic acid chromophotometric method. TP was measured using the ammonium molybdate-stannous chloride method after perchloric acid digestion. K and Na were measured by flame photometry and Ca and Mg were determined by atomic absorption spectrophotometry.

Statistics and data analysis: Mean concentrations noted in figures and tables are volume weighted means. The differences between litter leachate and topsoil leachate were tested using one-way Analysis of Variance (ANOVA).

Pearson correlation analysis was applied to test for relationships between nutrients in litter leachate and topsoil leachate. Statistical analysis was performed with

Table 1: Basic soil properties of the study site

Layer (cm)	pH	Organic matter (g/kg)	Total nitrogen (g/kg)	Available P (mg/kg)	Available K (mg/kg)
0-5	6.3	32.2	1.6	16.8	140
5-10	6.3	25.6	1.3	10.5	100
10-70	6.4	19.6	0.9	6.7	90

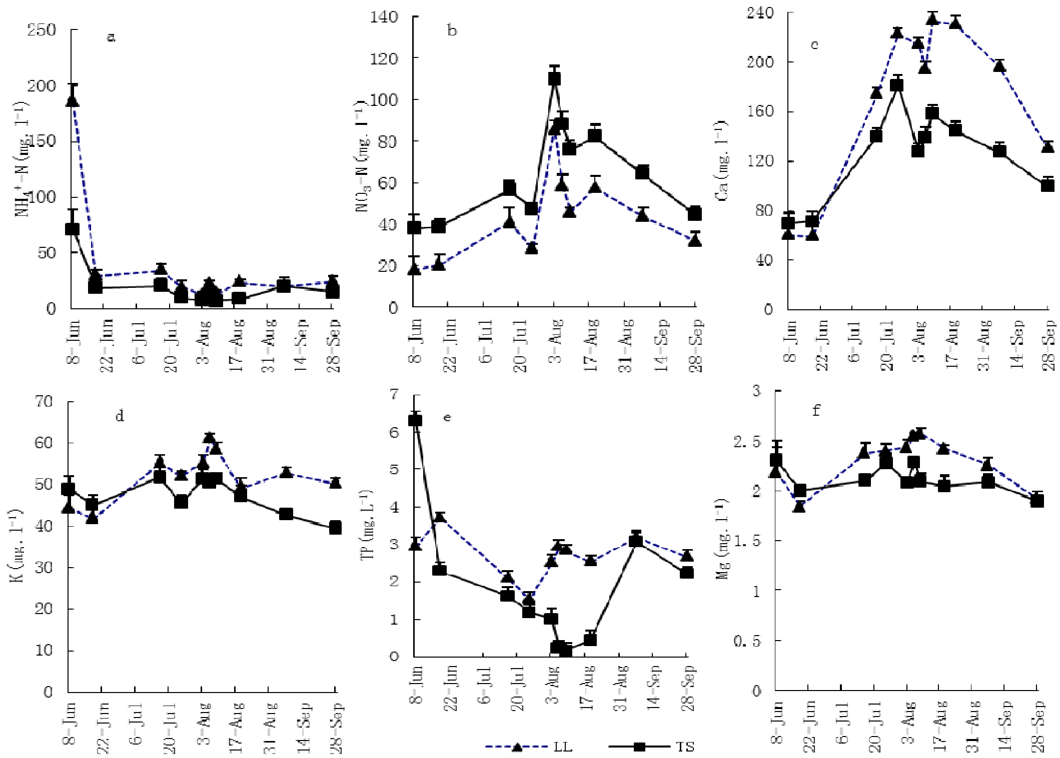

Fig. 1: Nutrient concentrations in litter leachate and topsoil leachate; (a): NH_4-N; (b): NO_3-N; (c): Ca; (d): K; (e): TP; (f): Mg

SPSS ver. 13.0 statistical software (SPSS Inc., Chicago, IL, USA).

RESULTS

Leachate concentrations: Concentrations of NH_4-N and NO_3-N of the litter and the topsoil leachates are shown in Fig. 1a and b, respectively. In the litter leachate, NH_4-N concentrations varied from 12.4 to 184.5 mg/L; the topsoil leachate showed a similar range, from 7.4 to 71.4 mg/L. The seasonal trends of NH_4-N concentrations in both the litter and the topsoil leachates were similar, with the highest concentrations occurring with the first precipitation event. Unlike NH_4-N, the trend of NO_3-N in both the litter and the topsoil leachates peaked in midseason, with ranges of 18.2 to 85.7 mg/L and 38.0 to 109.6 mg/L, respectively.

Trends in the Ca concentrations of both the litter and topsoil leachates were similar to those of NO_3-N, peaking in the summer and dropping in the spring and autumn (Fig. 1c). Calcium concentrations in the litter leachate, which ranged from 60.2 to 233.2 mg/L, had similar seasonal patterns as those in the topsoil leachate, which ranged from 69.9 to 180.9 mg/L.

Potassium concentrations in both leachates were similar and showed little variation over time (Fig. 1d). These ranged from 41.7 to 61.0 mg/L in the litter leachate and from 39.3 to 51.7 mg/L in the topsoil leachate.

Phosphorous concentrations in the litter and topsoil leachates are shown in Fig. 1e. TP concentrations in the litter leachate, which varied from 1.5 to 3.7 mg/L, exhibited different seasonal variation than that of the topsoil leachate, which had TP concentrations ranging from 0.2 to 6.3 mg/L.

Trends in the concentration of Mg were similar to those of K, remaining fairly constant in both the litter and topsoil leachates (Fig. 1f). For example, the Mg concentrations in the litter leachate ranged from 1.8 to 2.6 mg/L, while the topsoil concentrations ranged from 1.9 to 2.3 mg/L.

Volume-weighted monthly average concentrations for each of the nutrients are shown in Fig. 2.

Comparison of litter and topsoil leachates: Calcium had the highest proportion of any nutrient in both the litter and topsoil leachates, accounting for more than 50% of the total concentration. The concentrations of NH_4-N, NO_3-N, K accounted for 12.1, 13.6 and 16.3%, respectively in litter leachate and less than 10, 24.0 and 17.6%, respectively, in topsoil leachate. The lowest nutrient proportion in both leachates were for P and Mg, which accounted for less than 3%. Annual mean leachate concentrations for all parameters are shown in Table 2.

The topsoil leachate contained lower concentrations of NH_4-N, TP, Ca, Mg and K than the litter leachate. NH_4-N, TP and Ca concentrations in the

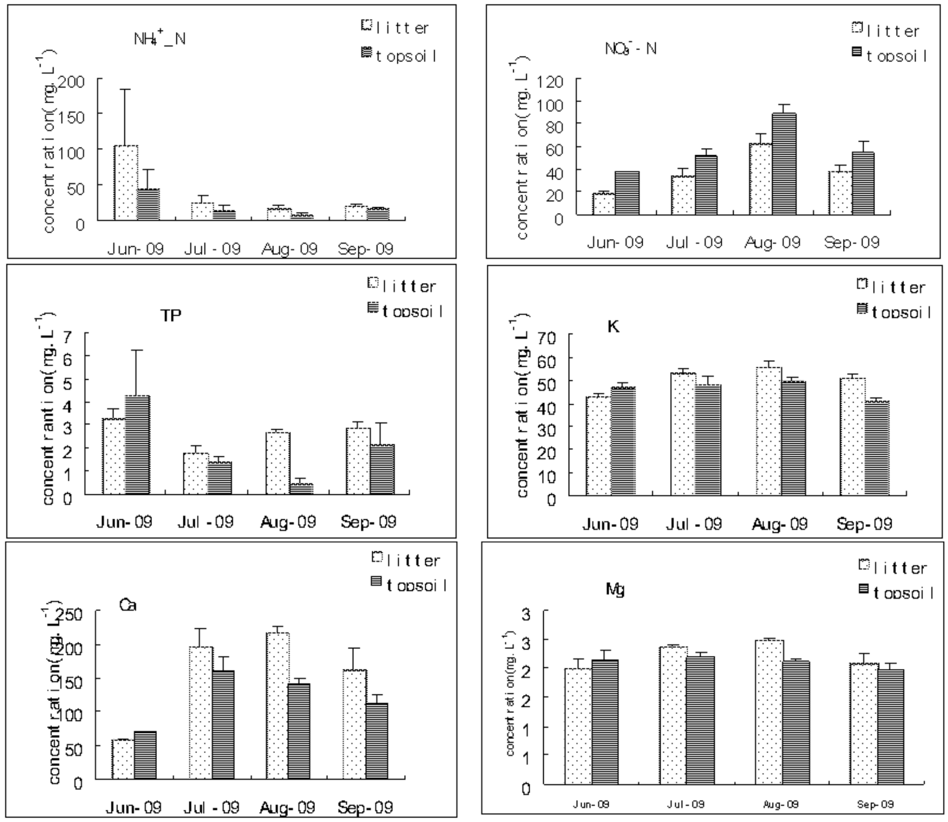

Fig. 2: Volume-weighted monthly average nutrient concentrations (mg/L) in litter and topsoil leachates

Table 2: Annual mean concentrations in litter leachate and topsoil leachate (mg/L)

Layer	NH_4-N	NO_3-N	NH_4-N/NO_3-N	TP	Mg	Ca	K
O horizon	38.5	43.2	0.9	2.7	2.30	171.3	51.9
Standard error[a]	(16.4)	(6.5)		(0.2)	(0.10)	(20.9)	(1.9)
A horizon	19.4	64.5	0.3	1.8	2.10	125.7	47.3
Standard error[a]	(6.0)	(7.6)		(0.6)	(0.04)	(11.3)	(1.3)

[a]: Standard error shown in parentheses (n = 4)

Table 3: Nutrient correlation coefficients between litter layer and topsoil layer, Pearson

NH_4-N	NO_3-N	TP	Ca	Mg	K
0.98**	0.98**	0.29	0.92**	0.51	0.46

n = 10; **: p<0.01

topsoil leachate are 50, 35 and 26% lower, respectively, than those in the litter leachate, while Mg and K are less than 16% lower. A t-test indicated there were no significant differences ($p<0.05$) between the two leachates. The concentrations of NO_3-N were higher than those of NH_4-N, both in the litter and the topsoil leachates. The concentrations of NH_4-N and NO_3-N were higher in August and September than in June and July. The ratios of NH_4-N to NO_3-N in the leachates were 0.9 and 0.3 for the litter and topsoil, respectively.

As shown in Table 3, positive correlations were noted between the two leachates for concentrations of NH_4-N, NO_3-N and Ca. There were no significant correlations in the concentrations of TP, Mg, or K for the two leachates (Table 3).

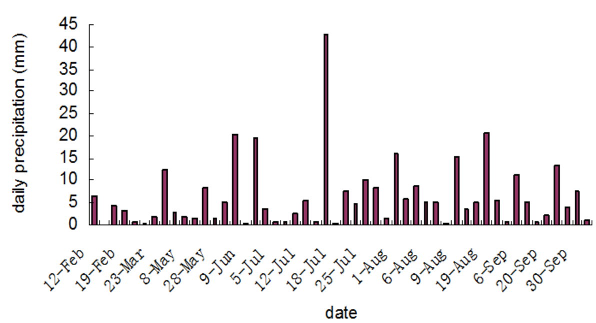

Fig. 3: Rainfall distribution (mm) in 2009

Nutrient fluxes: Precipitation carries nutrients downward from the litter layer to the soil below; the quantity of precipitation affects the concentrations of the nutrients in solution. Recorded rainfall in the study area was 316.6 mm, distributed as shown in Fig. 3.

Flux can be used to describe the quantity of nutrients passing through different layers. The 2009 field data were supplemented with data from 2005, who

Table 4: Nutrient fluxes in incident rainfall, throughfall, litter leachate and topsoil leachate in *Quercus variabilis*

	Nutrient flux (kg/ha/year)						
	NH_4-N	NO_3-N	TP	K	Ca	Mg	Na
Incident rainfall 2005	18.3	3.2		5.5	24.0	5.4	10.0
Throughfall 2005	16.0	4.7		18.6	47.5	6.6	2.2
Net nutrient flux from canopy[a]	-2.3	1.5		13.1	23.5	1.2	-7.8
Litter leachate 2005	10.9	2.8		32.1	79.1	16.1	5.8
Net nutrient flux from litter[a]	-5.1	-1.9		13.5	31.6	9.5	3.6
Litter leachate 2009	23.2	19.7	1.3	23.3	73.0	1.0	3.9
Net nutrient flux from litter	7.3	15.0		4.7	26.5	-5.5	1.7
Topsoil solution 2009	5.9	24.5	0.5	16.2	43.9	0.7	2.5
Net nutrient flux from topsoil	-17.3	4.8	-0.8	-7.1	-29.1	-0.3	-1.4

investigated the chemistry of precipitation in a *Quercus variabilis* forest (Table 4). The amounts of most nutrients, except that from NO_3-N, in litter leachate were substantially higher than the amounts in topsoil leachate. In 2009 the total litterfall amounted to 0.16 t N/ha and 0.01 t P/ha. Inorganic N (NH_4-N + NO_3-N) and TP leaching from litter amounted to 42 kg N/ha and 1 kg TP/ha, which was 13.9% of the TN and 13.7% of TP contained in the litterfall.

Net flux of Ca from the litter layer in 2005 (31 kg/ha) and 2009 (25 kg/ha) was greater than the other nutrients, representing 62 and 51%, respectively, of the net nutrient flux from litter leachate. The data from 2005 found inorganic N (NH_4-N + NO_3-N) was retained (i.e., negative leaching) in litter, whereas the 2009 field results indicate it was released (i.e., positive leaching). Less than 2.5% of TP, an important nutrient source for plants, was leached from litter. For K net flux, through fall contributed almost the same amount as the litter leachate in 2005. Potassium input was greater than Mg and Na input from litter in both 2005 and 2009.

In the topsoil leachate, the total NO_3-N stored was about 5 times greater than that of NH_4-N. Net leaching of NO_3-N from topsoil was 4 kg/ha.

DISCUSSION

Leachate concentrations:

Nitrogen: Concentrations of both NH_4-N and NO_3-N in the outflow from the litter layer were lower than that in throughfall in 2005, indicating that nitrogen in the form of NH_4^+ and NO_3^- was generally retained and adsorbed by organic colloidal material and/or transformed by nitrification. Loupe *et al*. (2007) found a cumulative release of NH_4-N from the litter layer. This is not surprising as NH_4-N, in particular, is easily immobilized during the first 6 months to 1 year of litter decomposition (Rustad and Cronan, 1988; Monleon and Cromack, 1996) or through a predominant mechanism of abiotic nitrogen immobilization involving the reaction of NH_4^+ with plant materials containing large amounts of lignin (Schimel and Firestone, 1989).

In the current study, the concentrations of NO_3-N were higher than those of NH_4-N in both leachates, which is consistent with the work of Madeira and Ribeiro (1995) related to *Quercus suber* in Portugal. Concentrations of NO_3-N (38.0-109.6 mg/L) in leachates collected from the topsoil below the litter were much higher than those in the leachate from the litter itself (18.2-85.7 mg/L), which is different from the work of Roda *et al*. (1990) in holm-oak (*Quercus ilex* L.) forest in the Montseny Mountains. Conversely, NH_4-N decreased with litter leachate percolating to the topsoil (Table 2). The decrease in NH_4-N could be due to uptake by root systems and nitrification in the soil. These results are similar to those reported by Solinger *et al*. (2001) in deciduous forests and by Boy *et al*. (2008) in an Andean tropical montane forest. The ratio of NH_4-N to NO_3-N was greater in litter leachate than that in topsoil leachate, which differs from the results reported by Williams *et al*. (1996).

The concentrations of NH_4-N and NO_3-N in litter and topsoil leachates found in the current study were 20 times higher than those reported for a tropical mountain forest (Goller *et al*., 2006) and a temperate mixed forest (Hafner *et al*., 2005). Differences between concentrations in the litter leachate and topsoil leachate in our study and other studies may be due to differences in N concentrations across decay classes, as well as differences in tree species or climate. In the current study, concentrations of NH_4-N in both leachates peaked in spring, while concentrations of NO_3-N were highest in fall. This differed from the concentrations of NH_4-N and NO_3-N in litter leachate in pine and hardwood forests reported by Currie *et al*. (1996).

Cations: The most concentrated cation in litter leachate was Ca; this was followed by K, the levels of which were similar to those reported in a temperate forest in southeastern New York State (Hafner *et al*., 2005) and in an Andean tropical montane forest (Boy *et al*., 2008). The high Ca concentrations in litter are mainly due to the accumulation of Ca in foliage up to the time of leaf fall and to a small amount of Ca from dust that is collected in the litter. In contrast, K and Na, in contrast, are readily leached and lost to throughfall. The role of litter in nutrient return is therefore more important for Ca than for other nutrients.

In the topsoil leachate, the concentrations of cations decreased relative to the litter leachates (Table 2 and Fig. 3). Cations in the soil solution are in dynamic equilibrium with cation exchange sites in the solid phase. At the same time, microbial and plant uptake of nutrients tend to lower their concentration in solution. Leaching characteristics of cations from the litter layer and topsoil were similar to those found by Xu *et al*. (2001) and Boy *et al*. (2008).

Phosphorous: The release of leachable TP in the topsoil layer did not reflect the changes observed in the litter layer (Fig. 2). The rapid depletion of leachable TP by early rainwater suggests that much of the topsoil TP, after a month of litter decomposition in dry, wet and hot weather, was readily soluble or mobilizable by rainwater. This is shown in the high concentrations of TP in the first leaching from topsoil (Fig. 2). Boy *et al*. (2008) found P was accumulated in the top soil but not detected in the litter leachate in an Andean tropical montane forest. This suggests that P was completely retained by the vegetation because the organic layer is densely rooted (Wilcke *et al*., 2002).

Total phosphorus released from litter leachate ranged from 1.5 to 3.7 mg/L; this differs from the findings of McComb *et al*. (2007), who reported a rapid decrease of leachable TP from litter and small amounts of TP in leachate later in the season.

Net input: Net flux of inorganic N (NH_4-N+NO_3-N) and calcium leached from litter was greater than through fall and topsoil leachate (Table 4), which indicates that the leaching litter layer is a significant source of inorganic nitrogen and Ca. This finding is similar to that of Loupe *et al*. (2007), who observed that the nutrients in the forest floor leachate are a potential source of inorganic N and similar to that of Cole and Rapp (1981), who found that nutrient return in the form of litter is more important for Ca than other nutrients. Different depletion patterns of phosphorous in litter and topsoil imply that litter is the source of P, similar to conclusions reached by Cole and Rapp (1981). Potassium is highly mobile and easily leached from canopy, it was however found much in litter leachate that would be probably for efficient capture of more mobile elements such as K.

CONCLUSION

The litter layer has been shown to not only have a higher sorption of nutrients, but to release nutrients to the soil as it decomposes. It can be found from data 2005 that the *Quercus variabilis* canopy was a large source of Ca and K. The statistical significance of the relationship between inorganic N and Ca in litter leachate and the topsoil leachate suggests that the forest litter is the largest source of dissolved inorganic N and Ca for the soil. In the litter layer, most dissolved inorganic N occurred as NH_4-N, whereas in topsoil it appeared as NO_3-N.

Leachate from litter and topsoil showed no seasonal variation, because there was no leachate in the dry season (April, May, September, October). This study shows that the amount of nutrients returned every year to the soil via litter varies and is influenced by the quantity, decomposition state and age of litter as well as the amount of rainfall. Long-term, on-site observations are needed to clarify the effects of these variables.

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