BULK PRECIPITATION, THROUGHFALL AND STEMFLOW DEPOSITION OF N-NH_4^+, N-NH_3 AND N-NO_3^- IN AN ANDEAN FOREST

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BURBANO-GARCÉS ML, FIGUEROA-CASAS A & PEÑA M. 2014. Bulk precipitation, throughfall and stemflow deposition of N-NH_4^+, N-NH_3 and N-NO_3^- in an Andean forest. This research evaluated the input flux of nitrogen (N) compounds, namely, NH_4^+, NH_3 and NO_3^- through an Andean forest canopy adjacent to a semi-natural wetland in south-western Colombia, South America. The concentrations of these compounds were determined in the hydrological processes of bulk precipitation, total throughfall and total stemflow. Other variables examined were catchment volume, pH and conductivity. The estimated entry for N compounds showed that throughfall was the process that recorded the highest weighted flux averages of N-NO_3^- (1.34 kg ha^{-1} month^{-1}), N-NH_4^+ (0.15 kg ha^{-1} month^{-1}) and N-NH_3 (< 0.001 kg ha^{-1} month^{-1}) over the sampling period. Results indicated that the forest canopy acted as a living barrier that retained emissions of man-made N compounds. This research contributed to the analysis of the transformation of nutrient input fluxes via bulk precipitation, throughfall and stemflow to provide better understanding of the biogeochemical functioning of tropical wetlands that are influenced by atmospheric inputs from natural and anthropic sources.

Keywords: Net precipitation, interception, nitrogen compounds, input flux, weighted flux

INTRODUCTION

Atmospheric deposition contributes to chemistry of plants, soils, surface water and nutrient cycling in the ecosystem and is the most important nutrient input into natural forests as well as adjacent ecosystems such as wetlands (Talkner et al. 2010). The canopy intercepts significant fraction of atmospheric deposition through precipitation (Bryant et al 2005). The temporal and spatial distribution of precipitation is modified before reaching the ground (Köhler et al. 2006).

Alterations in the chemical composition of precipitation water on coming into contact with plant tissues are due both to interactions in the canopy and dry deposition, which are determined through measurements of the hydrological processes of bulk precipitation, throughfall and stemflow. Through fluxes of these processes, nitrogen (N) compounds are transported to the ground but depending on their concentration, they can generate two conflicting results: (1) they assist the regeneration of degraded or long-lived ecosystems through their role as contributor of nutrients in the successional processes involved (Scheer 2011) or (2) they trigger a series of problems related to soil acidification and increase N concentration in soil water (Raat et al. 2002). Therefore, it is important to study the chemical composition of precipitation in order to detect changes in the balance of nutrients and contaminants at the spatial and temporal levels. Any recent changes in the balance of nutrients and pollutants enable determination of their source as either natural or man-made. Examples of N wetland inputs of anthropic origin include NO_x which is emitted primarily from stationary (industrial) and mobile (vehicle) sources and N-NH_3 from agricultural sources.

The primary objective of this research was to determine the total deposit (wet and dry) of N compounds (N-NO_3^-, N-NH_4^+ and N-NH_3) through the canopy of an Andean forest associated with a semi-natural wetland, through the processes of bulk precipitation, throughfall and stemflow. This research is useful for future research related to the biogeochemistry of Colombian Andean wetlands. The upper basin of the Cauca River is one of the most important

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watersheds in northern South America. A major concern of the Andean countries is the increasing fragmentation of natural forests due mainly to human agricultural practices and low resilience and slow recovery of the forest. The combination of these factors has influenced the loss of biodiversity and ecosystem services in high altitude wetlands.

MATERIALS AND METHODS

Study area

Samples of bulk precipitation, throughfall and stemflow were collected in an Andean forest adjacent to a semi-natural wetland located in El Manzanar, 10 km from the city of Popayan in south-western Colombia (Figure 1) at 2° 29' N and 76° 32' W and altitude of 1870 m above sea level. The study area is part of the Rio Blanco watershed, which belongs to the Rio Palacé subwatershed within the Cauca Basin. It is assumed that the origin of the wetland is due to the damming of the river, with the presence of a permanent lagoon (semi-natural lake), giving it importance as a water reservoir (Artunduaga 2007). This area forms part of the Premontane moist forest. The silted areas and the lagoon are 1.19 ha and 0.22 ha respectively. The adjoining wetland forest is relictual Andean type in an advanced successional stage, with an area of approximately 0.31 ha. The soils of the study site are deep to very deep with good natural drainage, whose parent material consists of volcanic ash deposited in layers of varying thickness from 1 to 8 m. In the immediate area most of the natural vegetation has been devastated by agricultural activities so that relict forests are observed only in the clefts between hillsides. Large areas of grassland are present where cattle ranching are practised extensively. Rainfall patterns over the study period (between July 2009 and January 2010) followed the bimodal pattern of quarterly change recorded historically for the Popayan plateau. The study site is located approximately 2.5 km of the Panamerican highway in the urban and the peri-urban area of the city of Popayan. It is located less than 200 m away from medium-scale tomato crop under greenhouses and it is surrounded mainly by areas devoted to cattle ranching.

Meteorological information

Meteorological information was obtained from the meteorological station at the Faculty of Engineering of the University of Cauca, located approximately 10 km away from the study site. The measuring instruments used corresponded to sensors for rainfall, temperature, relative

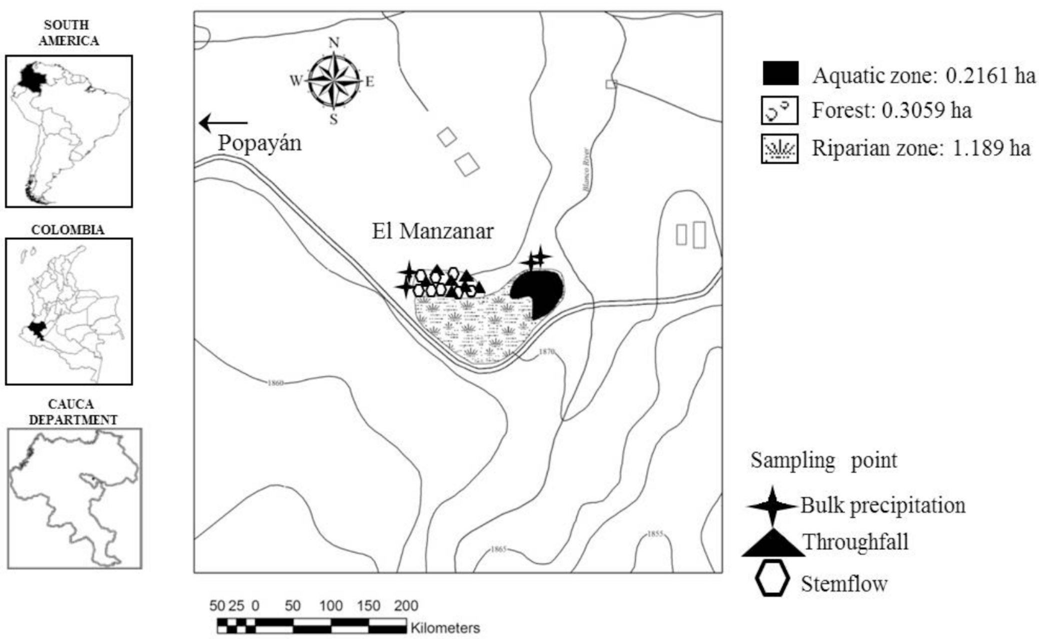

Figure 1 Geographic location of the study area in the municipality of Popayan

humidity, atmospheric pressure and wind speed and direction.

Temporal behaviour of the study site is presented in Figure 2. Rainfall recorded near the forest varied mainly in the wet months (October, November and December). Prevailing winds occurred between July and September (dry season) of 2009, most commonly from the south and west south-west (Figure 2), showing marked influence of warm currents coming from the Patía Valley and humid currents of the Pacific Coast. Less intense, but no less important, was the action of the south-east winds from the Coconucos chain of volcanoes that feature a row of 15 eruptive centres at the north-west end of which is located the Puracé volcano, 30 km to the south-east of Popayan and reaching a height of 4646 m above sea level (Arcila et al. 2002). It is important to note that in strong winds, the intensity of the precipitation generates lateral projections from neighbouring tree canopy. In theory this could lead to interception differentials between tree canopies at different heights (Herwitz & Slie 1995), also possibly affecting residence time of rainwater in the canopy.

Sampling procedure

The sampling of bulk precipitation, throughfall and stemflow was carried out in the morning every 10 days between July 2009 and January 2010. For the location of the throughfall and stemflow collectors, morphological characteristics of woody vegetation, predominantly *Alchornea* sp., *Heliocarpus americanus, Quercus humboldtii* and *Miconia caudate,* were taken into account (Table 1). For sampling in open air, bulk precipitation sampling technique (wet deposition as well as dry deposition) was used (Gutzler et al. 2010). Four rain collectors were installed bordering the forest (Figure 1). Each collector consisted of a polyethylene funnel (diameter 0.185 m) connected to a low density plastic reservoir (capacity 21 L) via a 0.02 m polyethylene hose. The same collectors were used for throughfall sampling (Figure 1). For this, 10 collectors were placed randomly under the woody forest vegetation adjacent to the wetland. Stemflow samples were collected using the spiral type stemflow collector (Clarke et al. 2010). Each collector was made using impermeable and chemically inactivated foam 5 mm thick × 0.20 m

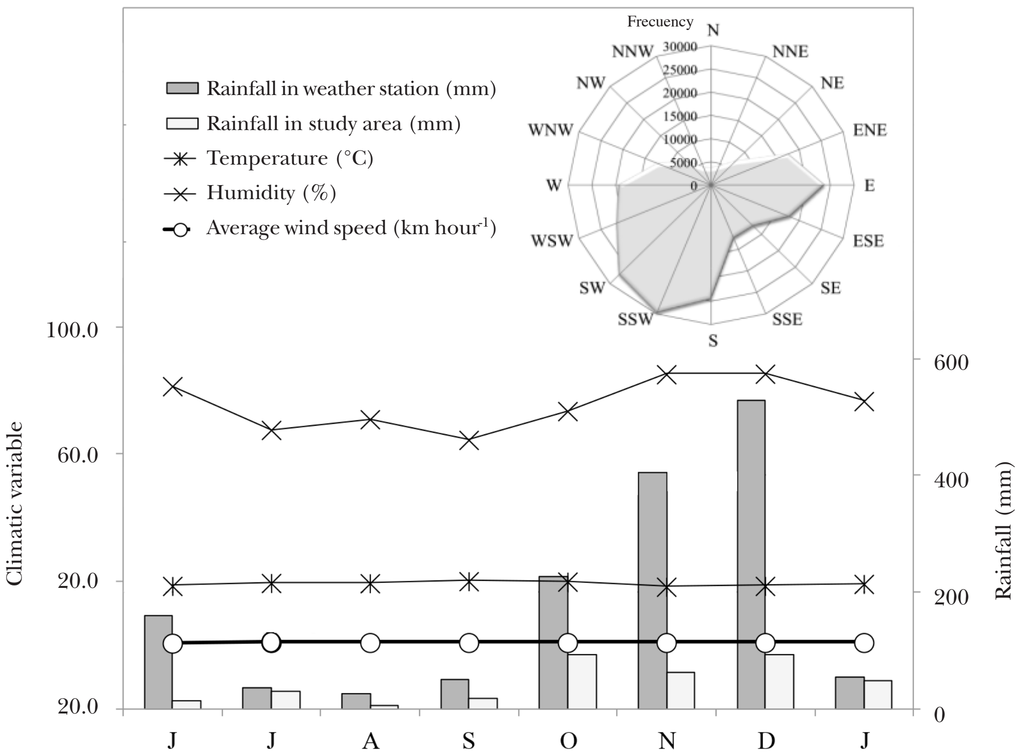

Figure 2 Climatic variables: temperature, relative humidity, average wind speed and direction, incident rain in the study area and in the monitoring station (June 2009–January 2010)

Table 1 Morphometric characteristics and epiphytism in trees sampled by the process

Process	Average height (m)	Total basal area (m^2 ha^{-1})	Average dbh (m)	Average bole height (from ground to first branch) (m)	Presence of epiphyte	Average area of the cup (m^2)
Throughfall	13.6	18.6	0.22	2.9	Abundant	28.1
Stemflow	15.0	18.6	0.22	3.1	Moderate	25.7

dbh = diameter at breast height

wide with length that varied depending on the tree diameter. The foam was attached spirally to the tree bark using inert glue. A funnel (diameter 0.05 m) and a hose (diameter 0.025 m) connected the collector to a reservoir of 21 L capacity. Only trees with diameter at breast height > 10 cm were considered in the sample.

Laboratory analysis

Sampling and transporting samples of bulk precipitation, throughfall and stemflow followed the chain of custody protocol as stipulated in the Colombian Technical Guide-100 (ICONTEC 2004). Determination of concentrations of N compounds ($N\text{-}NH_4^+$, $N\text{-}NH_3$ and $N\text{-}NO_3^-$) and complementary variables (pH and conductivity) were performed in the laboratory within a maximum of 6 hours after sampling. Nitrogen compounds were determined using a multiparameter sonde while pH and conductivity were determined using ion selective analyser (Eaton et al 1995). Detection limits for $N\text{-}NH_4^+$, $N\text{-}NH_3$ and $N\text{-}NO_3^-$ oscillated between 0.001 and 200 mg L^{-1} of N, with an accuracy of ± 10% on the reading mark, in accordance to the technical specifications of $N\text{-}NH_4^+$ sensor. The sensor used on the probe detected the $N\text{-}NH_4^+$ ions. However, considering that free ions of $N\text{-}NH_4^+$ and $N\text{-}NH_3$ were in equilibrium in any solution, the software could simultaneously use this information along with the values of pH, temperature and conductivity to automatically calculate the concentration of free ammonia ($N\text{-}NH_3$) in the sample. Samples of N compounds for analysis were filtered through 0.22 μm membrane filters and stored at a temperature of 5 °C until analysis. Separate standard curves were prepared for each analysis session of N ions. The results were acceptable when the r^2 values of the correlation between standards and peak areas were 0.99 or higher.

Analysis of the data

Fluxes were determined for N compounds deposited on the forest adjacent to the wetland via bulk precipitation, throughfall and stemflow. The fluxes were calculated by multiplying the concentration of the N compounds by the respective volumes obtained in the collectors (Veneklaas 1990). For bulk precipitation and throughfall, the area of the funnel was considered as the area of uptake for conversion of litres to mm. The stemflow was determined as the volume of water (L) of stemflow multiplied by collecting area or basal area of each tree (Germer et al. 2010). Total basal area of the four dominant species was 18.6 m^2 ha^{-1} comprising *Quercus humboldtii* (7.5 m^2 ha^{-1}), *Alchornea* sp. (7.2 m^2 ha^{-1}), *Heliocarpus american* (2.2 m^2 ha^{-1}) and *Miconia caudata* (1.7 m^2 ha^{-1}). Net precipitation was calculated, corresponding to the fraction of bulk precipitation reaching the forest floor, by aggregating total water volume of throughfall and stemflow collected in the reservoir of each one of these processes. Rainwater losses due to interception in the canopy were calculated as the difference between bulk precipitation and net precipitation (Valverde 2001, Gomez et al. 2008). The normality test showed that parameters determined in bulk precipitation, throughfall and stemflow are not significant (Shapiro–Wilk test for bulk precipitation: df = 41, $p < 0.05$, Kolmogorov–Smirnov test for throughfall and stemflow: df = 94, $p < 0.05$ and df = 58, $p < 0.05$ respectively). Considering these results, we used the Kruskal–Wallis non-parametric correlation analysis to demonstrate the degree of relationship between the variables involved for each hydrological process studied. Spearman correlation was calculated to determine the inter-correlation between pH, conductivity, concentrations and fluxes of N compounds.

RESULTS

Water balance

The volume of rain recorded in the nearest weather station was 1488 mm. Bulk precipitation was 82.8%, of which throughfall accounted for 81.3% and stemflow, 1.5%. The interception was 17.2%. Variation in bulk precipitation correlated consistently with throughfall and stemflow (Figure 3). All processes showed high values during the wet months, coinciding with the rainfall pattern (dry months: January–February and June–August while wet months: March–May and October–December) (Figure 3).

Concentration of N compounds in bulk precipitation, throughfall and stemflow

Weighted average concentrations of N compounds were highest in stemflow (9.82 mg L^{-1}) followed by throughfall (1.30 mg L^{-1}) and bulk precipitation (0.01 mg L^{-1}). The concentrations of N-NO_3^- were higher than N-NH_4^+ and N-NH_3 in all processes (Figure 4). Average concentrations of N-NH_3 were higher during the dry months (Figure 4), which could be explained by the fact that the means of entry of N-NH_3 into the forest were by deposition, volatilisation or absorption by external tissues of the plant, which occurred when weather is dry. However, during rain events, the slight acidity increased N-NH_3 solubility as N-NH_3 tended to be more soluble at low pH. The additional variables of pH and conductivity showed an increase during the dry months, mainly in August. This was observed in all processes (Figure 5). Therefore, considering that the natural pH value of rainwater was 5.6, pH values recorded in throughfall (6.3) and stemflow (6.5) were almost 10 times more basic than the pH found in bulk precipitation (5.4) throughout the study (Figure 5).

Input fluxes of N compounds by bulk precipitation, throughfall and stemflow

Average values of N fluxes in bulk precipitation followed the order N-NH_4^+ > N-NO_3^- > N-NH_3 and in throughfall and stemflow, N-NO_3^- > N-NH_4^+ > N-NH_3 (Figure 6). Variations were recorded in the monthly inflows of N compounds by bulk precipitation, throughfall and stemflow but especially in throughfall, in which the flow of N-NO_3^- was higher during the months of November 2009 and January 2010. Fluxes of N-NH_4^+ were higher in the months of December 2009 and January 2010, although there was an increase in the month of September 2009 (Figure 6). During the transition between the dry and rainy seasons, N-NH_3 fluxes were very low in all forest hydrological processes throughout the sampling period. Although there were monthly variations in the input of N compounds in all processes, there were no marked differences between the dry and wet months, particularly in the total fluxes for bulk precipitation and stemflow (Figure 6). Spearman correlation matrix showed an indirect relationship between volume and concentration of N-NO_3^-, N-NH_4^+ and N-NH_3 in bulk precipitation and throughfall.

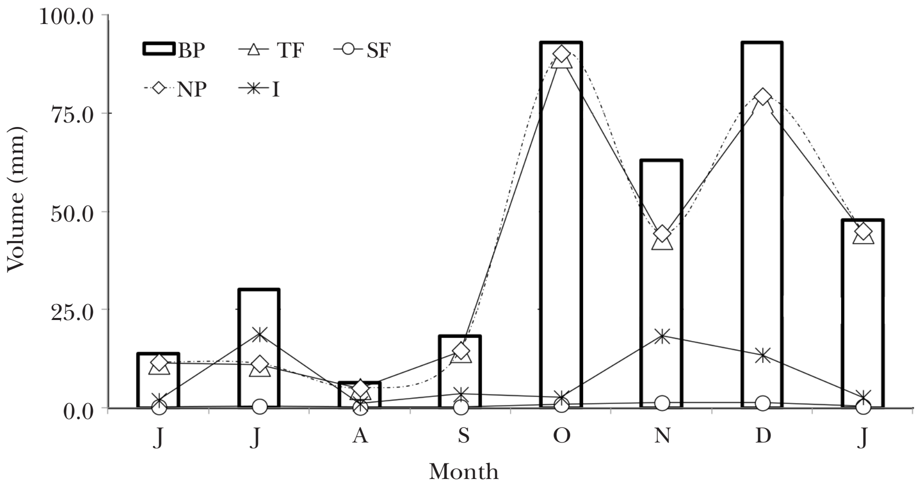

Figure 3 Seasonal variation of bulk precipitation (BP), throughfall (TF), stemflow (SF), net precipitation (NP) and interception (I) in the El Manzanar forest (June 2009–January 2010)

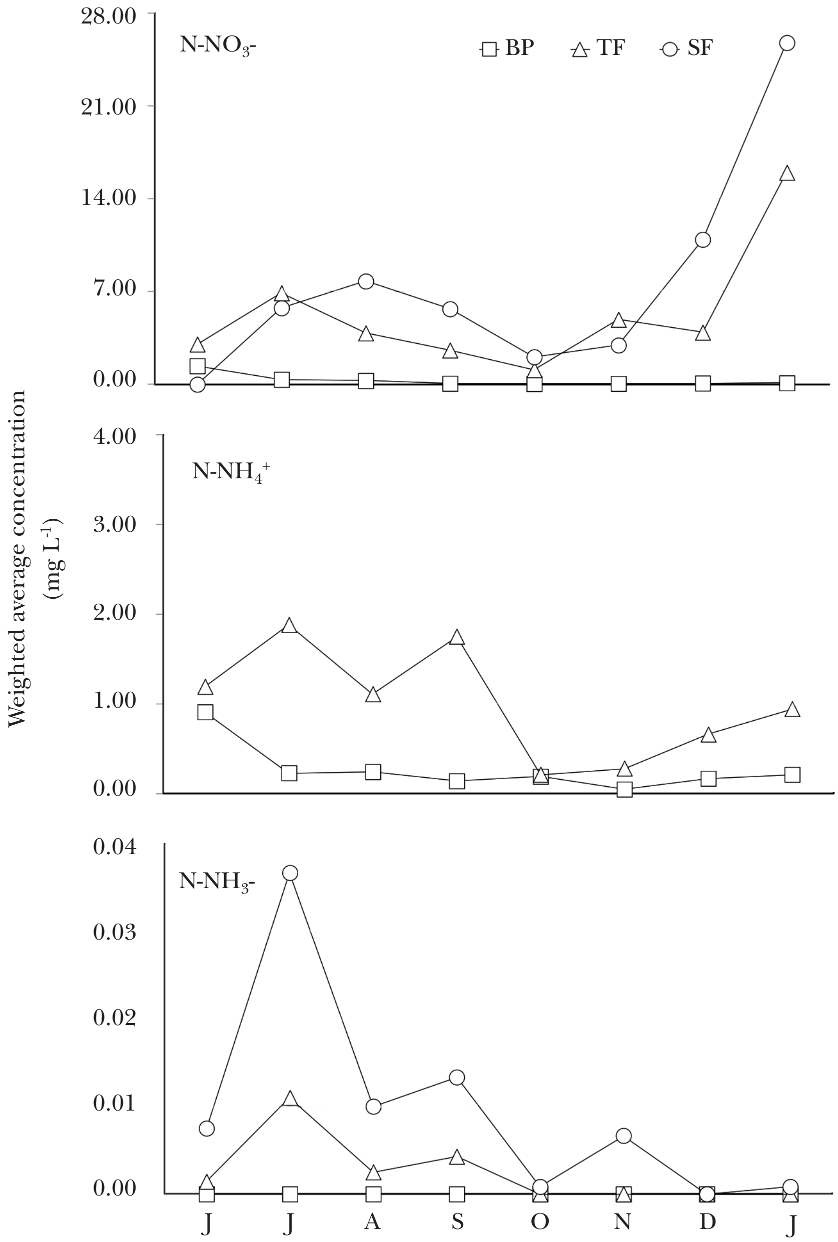

Figure 4 Seasonal behaviour of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$ concentrations in bulk precipitation (BP), throughfall (TF) and stemflow (SF) (June 2009–January 2010)

There is significantly positive correlation between volume of throughfall and fluxes of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ (Table 2). The strongest relationship between fluxes of $N\text{-}NO_3^-$ and their respective concentrations of $N\text{-}NO_3^-$ were found in bulk precipitation and stemflow. Based on fluxes calculated, it was possible to produce a diagram predictive of the average input fluxes of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$ by bulk precipitation, throughfall and stemflow through the canopy to the wetland (Figure 7) as a way of outlining how the exchange of energy operates between a wetland and its adjacent ecosystems, which in this case, was a forest area.

Net precipitation of nitrogen fluxes

The average net precipitation coming from the forest canopy (after direct interception of precipitation) to the soil was 1.04 kg ha^{-1} $month^{-1}$ of $N\text{-}NO_3^-$, 0.11 kg ha^{-1} $month^{-1}$ of $N\text{-}NH_4^+$ and 0 kg ha^{-1} $month^{-1}$ of $N\text{-}NH_3$. The net precipitation of $N\text{-}NH_4^+$ was relatively unchanged throughout the sampling period, whereas that of NH_3 was

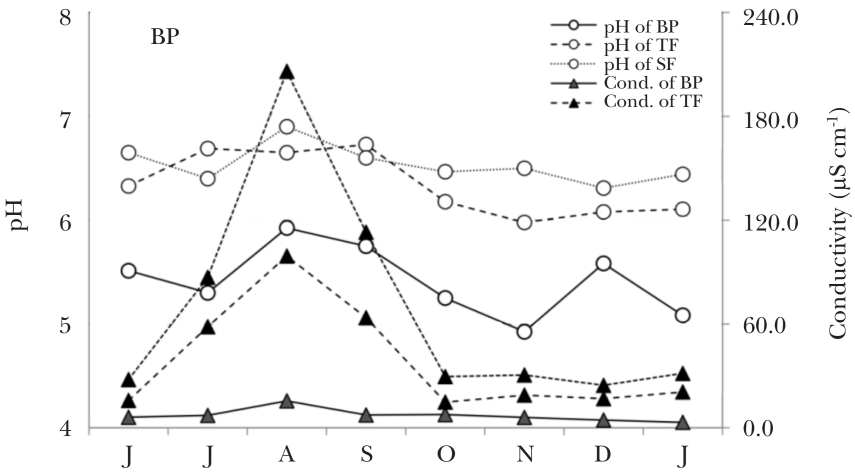

Figure 5 Temporal behaviour of pH and conductivity (cond.) in bulk precipitation (BP) , throughfall (TF) and stemflow (SF) (June 2009–January 2010)

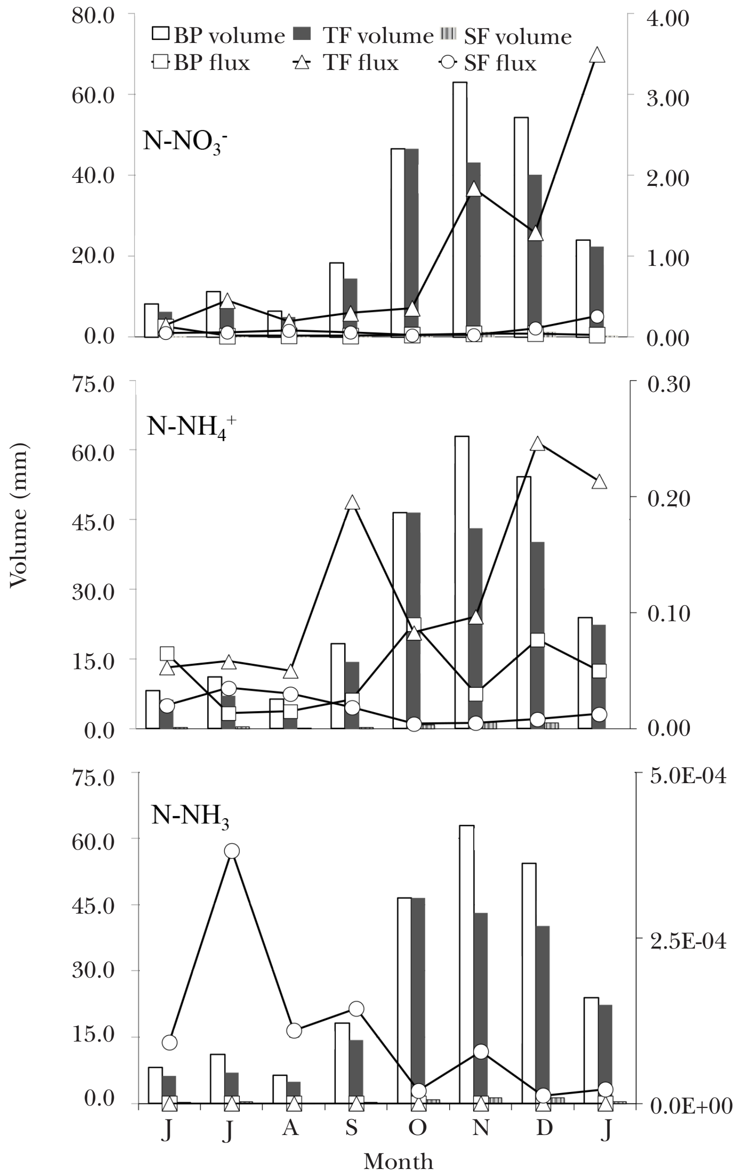

Figure 6 Monthly average flux of N-NO_3^-, N-NH_4^+ and N-NH_3 in the processes of bulk precipitation (BP), throughfall (TF) and stemflow (SF) (June 2009–January 2010)

Table 2 Spearman correlation coefficients for concentrations and fluxes of N compounds ($N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$), pH, conductivity and volume in bulk precipitation, throughfall and stemflow of a forest adjacent to a wetland, rural area in Popayan from July 2009 till January 2010

Parameter	Volume (mm)	pH	Conductivity ($\mu S\ cm^{-1}$)	$N\text{-}NH_4^+$ ($m\ L^{-1}$)	$N\text{-}NH_3$ ($m\ L^{-1}$)	$N\text{-}NO_3^-$ ($m\ L^{-1}$)	Flux of $N\text{-}NH_4^+$ ($kg\ ha^{-1}month^{-1}$)	Flux of $N\text{-}NO_3$ ($kg\ ha^{-1}month^{-1}$)
Bulk precipitation								
Volume (mm)	1.00	-0,471	-0.284	**-0.551**	-	**-0.568**	0.486	0.158
pH		1.00	0.153	0.333	-	0.521	-0.156	0.083
Conductivity ($\mu S\ cm^{-1}$)			1.00	0.331	-	-0.039	-0.02	-0.414
$N\text{-}NH_4^+$ ($m\ L^{-1}$)				1.00	-	0.323	0.387	-0.121
$N\text{-}NH_3$ ($m\ L^{-1}$)					1.00	-	-	-
$N\text{-}NO_3^-$ ($m\ L^{-1}$)						1.00	-0.238	**0.66**
Flux of $N\text{-}NH_4^+$ ($kg\ ha^{-1}month^{-1}$)							1.00	0.125
Flux of $N\text{-}NO_3^-$ ($kg\ ha^{-1}month^{-1}$)								1.00
Throughfall								
Volume (mm)	1.00	-0.5	-0.484		-0.365	-0.324	**0.614**	**0.594**
pH		1.00	**0.508**		0.487	0.184	-0.184	-0.272
Conductivity ($\mu S\ cm^{-1}$)			1.00		0.484	0.281	0.031	-0.197
$N\text{-}NH_4^+$ ($m\ L^{-1}$)					0.458	0.252	0.302	-0.252
$N\text{-}NH_3$ ($m\ L^{-1}$)					1.00	0.174	-0.029	-0.275
$N\text{-}NO_3^-$ ($m\ L^{-1}$)						1.00	-0.081	0.503
Flux of $N\text{-}NH_4^+$ ($kg\ ha^{-1}month^{-1}$)							1.00	0.476
Flux of $N\text{-}NO_3^-$ ($kg\ ha^{-1}month^{-1}$)								1.00
Stemflow								
Volume (mm)	1.00	-0.221	-0.281		-0.257	-0.092	**-0.358**	-0.073
pH		1.00	**0.519**		**0.644**	0.281	**0.570**	0.282
Conductivity ($\mu S\ cm^{-1}$)			1.00		**0.604**	0.334	**0.590**	0.317
$N\text{-}NH_4^+$ (mL^{-1})					**0.609**	0.435	**0.896**	0.425
$N\text{-}NH_3$ (mL^{-1})					1.00	0.203	**0.632**	0.201
$N\text{-}NO_3^-$ (mL^{-1})						1.00	0.461	**0.994**
Flux of $N\text{-}NH_4^+$ ($kg\ ha^{-1}month^{-1}$)							1.00	0,455
Flux of $N\text{-}NO_3^-$ ($kg\ ha^{-1}month^{-1}$)								1.00

The coefficients of significant statistic correlations are highlighted in bold

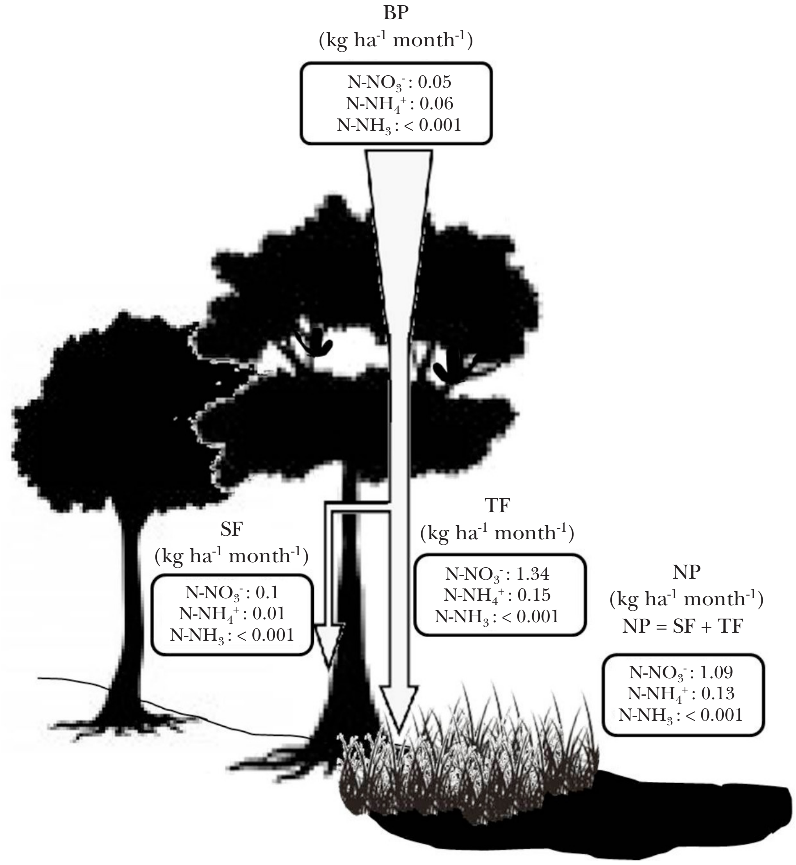

Figure 7 Balance of masses of the fluxes of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$and $N\text{-}NH_3$ in the hydrological processes from the tree canopy to the forest floor adjacent to the El Manzanar wetland; SF = stemflow, TF = throughflow, NP = net precipitation

very low (Figure 8). Net precipitation of $N\text{-}NO_3^-$ showed variability between dry and wet months, with an increase during the latter. However, net precipitation of $N\text{-}NO_3^-$ was higher during the month of January, the driest month (Figure 8).

DISCUSSION

Application of the linear regression model in the relationships between bulk precipitation with throughfall, stemflow and net precipitation allowed us to understand the influence of bulk precipitation on throughfall ($r^2 = 0.95$), stemflow ($r^2 = 0.75$) and net precipitation ($r^2 = 0.95$) as part of the water balance in the forest. Net precipitation (82.8%) indicated that water retention capacity of the canopy, from which fluxes of throughfall and stemflow were generated, was a mechanism used by forests to supply themselves with water and nutrients beneath the canopy and around the trunks respectively. This strategy is especially important in the dry months (Price 1982, Huber & Oyarzun 1983). The same relationship is not found between total rainfall and interception ($r^2 = 0.08$), as this process acted as barrier between rain and the forest floor and was responsible for redistributing the rain by evaporation, throughfall and stemflow. The amount of stemflow in the forest is 1.5% higher than in the tropical forests (Cavelier et al. 1997, Gomez et al. 2008). The Andean forests regularly receive additional inputs of water from interception of fog and rain carried by the wind. The amount of water in the foliage increases with increasing contact time between vegetation and fog. Fog density increases the contact surface with vegetation. Values of throughfall and interception in the El Manzanar forest were very similar to tropical forests in Colombia (Vis 1986, Veneklaas & Van 1990), Peru (Cavelier et al. 1997) and Panama (Gomez et al 2008). During the sampling period, concentrations of N compounds were higher in the stemflow process. Concentrations of $N\text{-}NH_4^+$ and $N\text{-}NH_3$ increased in the dry months,

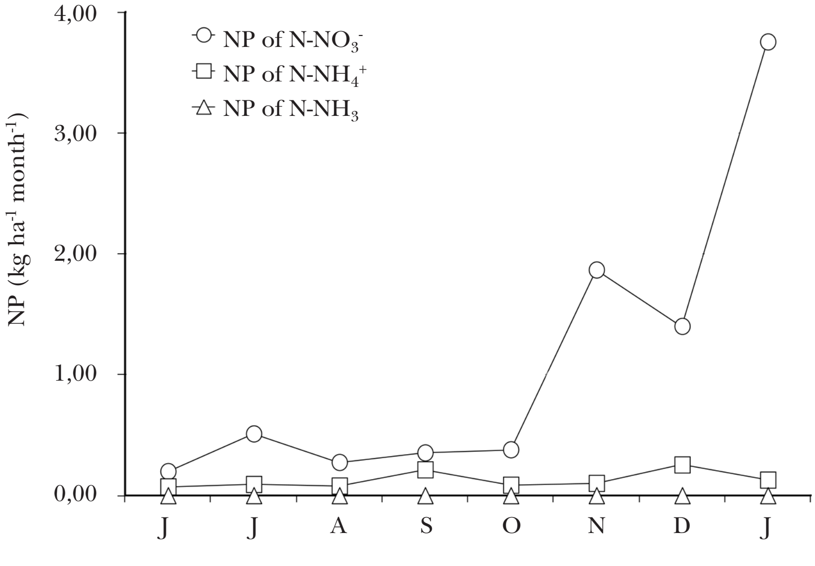

Figure 8 Net precipitation (NP) of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$ in the forest canopy

while concentrations of $N\text{-}NO_3^-$ were higher in the rainy months (Figure 4). The negative correlations of these compounds with respect to the uptake volume of each process (Table 2) reflected the enrichment of the canopy with N compounds via total deposition. Throughfall showed greater flow of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ ($p < 0.05$) compared with bulk precipitation and stemflow, which may be due to: (1) washing off of the dry deposit found on the foliage following evaporation of intercepted rainfall (Velthorst & Van Breeman 1989, Pryor & Barthelmie 2005), (2) washing off of plant exudates (Tóbon et al. 2004, Návar & Gonzalez 2009) and (3) chemical variability generated by the interaction between living biomass and rainwater as water passed through the foliage (Velthorst & Van Breeman 1989, Zimmermann & Elsenbeer 2007, Žaltauskaitė 2009). The presence of dead epiphytes during decomposition can supply N that has been broken down from the dead biomass. Comparing the three hydrological fluxes of nutrient inputs to the forest, it could be seen that the most important contributions of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$ were from throughfall and bulk precipitation, as reported in other tropical forests (Tóbon et al. 2004). High fluxes of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ in throughfall can be explained by the successional intermediate stage of the forest studied, whose canopy has moderate presence of live and senescent epiphytic biomass. On average, the forest has trees with average diameter at breast height of 0.29 m and height of 14.1 m. Morphological characteristics of the canopy, the intensity, duration and frequency of rain events can influence the retention time of water in the canopy, favouring interaction times of rainwater with the biomass. This means that there was retention of water in the forest before it began to pass through the canopy to the forest floor. The higher the retention time, the greater the chance of chemical interaction.

The $N\text{-}NH_3$ flux is not statistically significant between the three hydrological processes, and in some cases the concentration is below the detection limit (< 0.001). During the dry and hot months, concentration of $N\text{-}NH_3$ increased in stemflow. Low concentration values of stemflow are understandable given the atmospheric residence time for its dry deposit, i.e. about 2 hours. This depended on the flow patterns of air that was predominantly of high relative humidity (> 80%). This will make direct deposit unfavourable as $N\text{-}NH_3$ formes an equilibrium with the $N\text{-}NH_4^+$ once it is solubilised in the microparticles in the water vapour (Mitchell et al. 2004). Strong positive correlations between the concentrations of $N\text{-}NH_4^+$ and $N\text{-}NH_3$ in stemflow (Table 2) were expected because the two compounds were in chemical equilibrium in aqueous media and this equilibrium was governed by a reversible pH. Combined, $N\text{-}NH_4^+$ and $N\text{-}NH_3$ contribute to the acidification of the rainwater (Pearson 1993). In this study, $N\text{-}NH_4^+$ dominated the bulk precipitation fluxes (Figure 7). This higher value might be partly due to $N\text{-}NH_4^+$ which is released from livestock manure (Boxman et al. 2008), arising from ranching activities and the use of ammonia and its derivatives as N fertilisers (Sutton et al. 2008) in farming activities close to the study area. Throughfall deposition fluxes for $N\text{-}NO_3^-$ were high (1.34 kg^{-1} ha^{-1} $month^{-1}$), contributing to the increase in net precipitation (Figure 6). This was verified in the high net precipitation of $N\text{-}NO_3^-$ especially during rainy months. A large part of the $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ ions and $N\text{-}NH_3$ gas is absorbed by plants or reacted geochemically in the substrate of the wetland or is released into the atmosphere by volatilisation (White & Reddy 2009). Incident rain is not only a source of nutrient input in forest systems but constitutes an important means of transferring nutrients to the forest floor. This is reflected in how the fluxes of N compounds studied, $N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$, changed as they passed through the forest canopy. The increase in the statistical significance ($p < 0.05$) of the fluxes of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ in throughfall and stemflow relative to bulk precipitation show this. Throughfall comprised the main contributor of N to the wetland and dominated inputs of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$ and $N\text{-}NH_3$ to the forest floor by net precipitation. The contiguous vegetal cover in the wetland, viewed as an extension of the wetland, plays important roles as: (1) receptor, collector and supplier of limiting nutrients; (2) neutraliser of acidic compounds, (3) controller and protector against contaminants via wet and dry precipitation and (4) controller of the hydrological fluxes towards the drainage channels that make up a river basin. The results allow the generation of local and regional focus on the management of wetlands as ecosystems that are interrelated and linked to the river basins, watersheds and microwatersheds. The focus should take account of the fact that the biogeochemical processes inherent in the functioning of the wetlands play a heavy part in the quality of water that reached the lotic systems. Quality water in the lotic systems in turn ensures not only the survival of important aquatic fauna but the availability of water resources for the different community needs. The forest as a terrestrial ecosystem with clear functions of interception, biogeochemical and hydrological nutrient regulation and protection against contaminants via wet and dry precipitation operate in harmony with the wetland as an aquatic ecosystem that receives water load and nutrient cycle. Together they create a better, more biodiverse and more resilient ecosystem. Finally, the forest offers a buffer function. The morphology of the forest canopy and retention time of rainwater provided the ecosystemic service of hydrological and biogeochemical regulations.

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