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NITROGEN FLUXES IN THROUGHFALL AND LITTERFALL IN TWO *NOTHOFAGUS* FORESTS IN SOUTHERN CHILE

APORTES DE NITROGENO POR LA PRECIPITACION DIRECTA Y LA CAIDA DE HOJARASCA EN DOS BOSQUES DE NOTHOFAGUS *EN EL SUR DE CHILE*

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ABSTRACT

Nitrogen return by leaf litterfall was compared with atmospheric nitrogen deposition for two deciduous *Nothofagus* stands in southern Chile, located in areas with contrasting land use. The litterfall return of nitrogen in a *Nothofagus alpina* (Poepp. et Endl.) Oerst. stand at San Pablo de Tregua, in the Cordillera de los Andes, was similar to the litterfall return in a *Nothofagus obliqua* (Mirb.) Oerst. stand at Paillaco, in the Central Depression. In contrast, the net throughfall and stemflow deposition differed significantly between the two stands. At San Pablo de Tregua, the annual bulk deposition of NH_4^+ and NO_3^- was significantly higher than the throughfall and stemflow deposition reaching the forest floor. This demonstrates an uptake of inorganic nitrogen by the aboveground biomass, which was correlated with month-to-month variation in the bulk inorganic nitrogen deposition by precipitation ($r^2 > 0.73$). At Paillaco, the canopy uptake of nitrogen was not directly detectable due to an estimated dry deposition input of 4-8 kg inorganic N ha^{-1} y^{-1}. In both stands, nitrogen return through leaf litterfall (~ 50 kg N ha^{-1} y^{-1}) was much higher than the atmospheric N deposition load (< 10 kg N ha^{-1} y^{-1}). The results consequently confirm the low level of atmospheric pollution in the forests of this region. However, the clear difference in net throughfall deposition of inorganic nitrogen between the two stands suggests that the external N input by dry deposition may be considerably higher in the Central depression than in Cordillera de los Andes. More emphasis on monitoring dry atmospheric N deposition is a necessary tool for evaluating the consequences of future emission changes.

Keywords: Ammonium, atmospheric deposition, canopy interactions, nitrate, nutrient cycling.

RESUMEN

El retorno de nitrógeno al suelo vía aporte de hojarasca fue comparado con la depositación de nitrógeno atmosférico para dos sitios con bosques deciduos de *Nothofagus* en el sur de Chile (39º - 40º S). En el bosque de *Nothofagus alpina* (Poepp. et Endl.) Oerst., en San Pablo de Tregua, Cordillera de los Andes, la depositación anual de nitrógeno vía precipitación indica que el flujo de NH_4^+ y NO_3^- que alcanzan el suelo del bosque, es significativamente alto respecto a la precipitación directa y escurrimiento fustal. Esto demuestra que existe una absorción de nitrógeno inorgánico en la biomasa del dosel del bosque, valor que es relacionado con la variación mensual en el aporte de depositación de nitrógeno vía precipitación ($r^2 > 0.73$). En el área experimental con *Nothofagus obliqua* (Mirb.) Oerst., en Paillaco, ubicado en la Depresión Intermedia del sur de Chile, la absorción de nitrógeno por el dosel arbóreo no es directamente detectable debido principalmente al aporte de la depositación seca de 4 - 8 kg ha^{-1} $año^{-1}$. En ambos sitios, el aporte de nitrógeno a través de la hojarasca (~ 50 kg N ha^{-1} y^{-1}) es mucho mayor que el aporte total de la depositación atmosférica (< 10 kg N ha^{-1} y^{-1}). Los resultados confirman el bajo nivel de contaminación atmosférica en la región. Sin embargo, la clara diferencia en la depositación neta vía precipitación directa entre los dos bosques investigados indica que el aporte externo de N vía depositación seca podría ser considerablemente mayor en la depresión intermedia comparado con la Cordillera de los Andes. Un monitoreo de la depositación atmosférica es una herramienta necesaria para evaluar la consecuencia de los cambios futuros de emisiones nitrogenadas.

Palabras claves: Amonio, ciclos de nutrientes, depositación atmosférica, interacciones del dosel, nitrato.

INTRODUCTION

The input of nutrients to forest ecosystems occurs by different processes, such as wet, dry, and occult atmospheric deposition (Lovett & Lindberg 1993), and mineral weathering (Zimmermann *et al*. 2002). Wet deposition is defined as the process by which atmospheric compounds are attached to and dissolved in cloud and precipitation droplets and delivered to the earth's surface by rain, hail or snow (Krupa 2002). A second important process is dry deposition of gaseous and particle phase components to the aboveground part of the ecosystem. Some fraction of dry-deposited nitrogen (N) is taken up by plants through stomata, the rest being adsorbed on plant surfaces and then leached down by precipitation (Horváth 2004). Thirdly, occult deposition of nutrients by fogs and clouds can be highly relevant, particularly in mountainous areas. For example, cloudwater input of N exceeded wet deposition at a coastal forest in southern Chile (Weathers *et al*. 2000). Dependent on the ecosystem and the site location, wet, dry, or cloud deposition can dominate the atmospheric deposition input (Lovett & Lindberg 1993). Fourthly, mineral weathering of nutrients is a critical process in nutrient cycling in natural ecosystems, but does not occur for nitrogen. Finally, for many nutrients, litterfall represents the most important source of element flux to the forest floor (Zimmermann *et al*. 2002). From the viewpoint of the ecosystem, however, litterfall has to be considered as an internal cycling mechanism.

The precipitation chemistry in southern Chile is among the cleanest in the world (Weathers & Likens 1997). Temperate forests in Chile are not yet affected by the elevated nitrogen deposition levels characteristic of forests in Europe and northeastern America (Perakis & Hedin 2002). However, anthropogenic activities such as transport, industry, and agriculture have been increasing in central and southern Chile (Godoy *et al*. 2003), and this may substantially alter the atmospheric N input to forest ecosystems in this region (Oyarzún *et al*. 2002, Van Breemen 2002). Within central and southern Chile, important differences in atmospheric deposition have been measured (Godoy *et al*. 2003). Regional differences are mainly related to the strong anthropogenic influence in the Central Depression, where roads, urban areas, and increasing agricultural activities are concentrated. Previous research demonstrates a significant influence of livestock farming on the precipitation deposition of ammonium in the Central Depression (Oyarzún *et al*. 2002). Dry, as well as wet deposition, can be expected to be important sources of nitrogen for forests in the Central Depression. However, there are few data on the importance of the different processes of atmospheric deposition onto pristine forest stands in Chile.

This paper examines the effect of regional land use on the aboveground nitrogen fluxes in two *Nothofagus* forests in southern Chile. Nitrogen fluxes in throughfall, stemflow, and litterfall were compared between two deciduous *Nothofagus* stands located in areas with contrasting land use. We expected that the atmospheric nitrogen deposition would be higher in a stand in the Central Depression, with anthropogenic influences, than in a stand located in the Cordillera de los Andes, removed from agricultural influences.

MATERIALS AND METHODS

STUDY AREAS

Two deciduous *Nothofagus* forest stands were selected in the province of Valdivia, in the lake district of southern Chile. The first site is a *N. obliqua* (Mirb.) Oerst. stand located near Paillaco, in the Central Depression (40°07'S, 72°51'W, 160 m a.s.l.). The climate is classified as temperate. The annual precipitation during the study period was 1658 mm and the mean annual temperature was 7°C. Soils of the area are denominated as typic dystrandepts (FAO classification) or "trumaos", originating from old volcanic ash (Tosso 1985). The overstorey is dominated by *N. obliqua* and has a mean tree height of 32 m, a density of 757 trees ha^{-1} and an average tree age of 120 years (Staelens *et al*. 2003). The stand has a subcanopy dominated by *Aextoxicon punctatum* Ruiz et Pav., and an understorey of the bamboo *Chusquea quila* Kunth and the small tree *Rhaphithamnus spinosus* (A.L.Juss) Molina. The aspect of the stand is southerly and the mean slope is 35-40%. The growing season lasts from September till April.

The second study site is a *N. alpina* (Poepp. et Endl.) Oerst. stand located at San Pablo de Tregua (39°30'S, 72°09'W, 620 m a.s.l.) in the foothills of the Cordillera de los Andes, near Panguipulli. The climate is classified as rainy temperate. The annual precipitation during the study period was 5308 mm, with a strong peak from May to August. The mean annual temperature was 11°C. Soils of the area are "trumaos", originating from volcanic ash of different ages. The first stratum of fine ash is 0.5-1.2 m deep and covers an older stratum of pumicitic material with larger particle sizes (Martínez 1981, Tosso 1985). The studied forest is a second-growth stand with an age of 50-55 years. The overstorey is dominated by *N. alpina*, with a negligible admixture of *N. obliqua* and *Laureliopsis philippiana* (Looser) Schodde in the small diameter classes. The stand has a mean tree height of 21 m (Reynaert 2004), a density of 1460 trees ha^{-1}, a canopy cover of 84%, and a basal area of 50 m^2 ha^{-1}. The understorey consists almost entirely of the bamboo *Chusquea culeou* E.Desv. The aspect of the stand is southerly and the mean slope is 35%. The growing season is from October till March.

DATA COLLECTION

Bulk precipitation was measured with three funnel collectors, each with a surface area of 200 cm^2, attached to a 2-l bottle. Throughfall was measured with 12 similar collectors systematically located on a 0.1 ha plot. Stemflow water was measured using plastic collars and 50-200 l containers for 12 trees that were representative of the tree diameter distribution. Water samples for chemical analysis were collected monthly during a period of one year. For each plot, the samples were pooled to one monthly sample of bulk precipitation, throughfall, and stemflow before chemical analysis. After filtration of the water samples through a orosilicate glass filter (Whatmann) of 0.45 μm, pH and electric conductivity were determined using specific electrodes. NO_3^--N was determined by a colorimetric method based on the reduction of cadmium (Clesceri *et al.* 1998). NH_4^+-N was measured by the phenate method (Clesceri *et al.* 1998). Organic N was calculated by subtracting NH_4^+-N concentration of total Kjeldahl nitrogen (sum of organic nitrogen and NH_4^+-N) measured by the Kjeldahl method. K^+, Ca^{2+}, and Mg^{2+} were measured by atomic emission spectrometry.

Litterfall was measured using 15 square litter traps, each with a surface area of 0.25 m^2, placed systematically in each plot. Litterfall was collected monthly during a period of one year. The litter was oven-dried (50°C for 48 h) and weighted. For San Pablo de Tregua, the litter was sorted into leaves, twigs, reproductive organs, and a miscellaneous fraction (moss, bark, etc), and each fraction was weighted separately. For each litterfall fraction, a composite annual sample was made. For the Paillaco study site, only the leaf litter fraction was weighted and analysed. Dried and milliground composite samples were analysed for N by Kjeldahl digestion. K^+, Ca^{2+}, and Mg^{2+} were measured by atomic emission spectrometry.

The water samples and litterfall were collected for one year, from May 2000 to April 2001 at Paillaco (Leiva & Godoy 2002) and from October 2002 till September 2003 at San Pablo de Tregua.

DATA ANALYSIS

Element fluxes in bulk precipitation, throughfall (TF), stemflow (SF) and leaf litterfall (LLF) were calculated by multiplying the water volume or litterfall amount with the element concentration. The concentrations of bulk precipitation, TF, and SF at San Pablo de Tregua were lacking for March 2003 due to logistic problems, and the deposition data of this month were omitted from all analyses and results. Net throughfall (NTF, kg ha^{-1} y^{-1}) was calculated by subtracting bulk deposition (BD) from TF + SF. For nitrogen compounds the following balance between the atmosphere and a forest ecosystem can be written (Horváth 2004):

$$[1] \qquad NTF = TF + SF - BD = DD - UP$$

where DD denotes dry deposition and UP canopy uptake. Monthly plot-average fluxes of BD, TF, SF, TF + SF, and NTF were compared between the two forest stands by a Mann-Whitney test. For each stand the monthly plot-average TF + SF was compared with the monthly BD by a Wilcoxon signed-rank test. Non-parametric tests were used because normality assumptions were not met.

Several methods have been suggested for estimating the contribution of DD and UP to net throughfall deposition. Two main methods are the empirical multiple regression model developed by Lovett & Lindberg (1984) and the canopy budget model proposed by Ulrich (1983) and adapted by Draaijers & Erisman (1995). However, none of these approaches was suitable for the present study. The regression model, on the one hand, requires TF data at the rain event level, which were not available due to the remoteness of the study sites. The canopy budget model, on the other hand, provides reasonable estimates of the DD of cations like K^+, Ca^{2+}, and Mg^{2+} (Draaijers & Erisman 1995, Staelens *et al*. 2003), but has never been validated for N compounds in regions with a low atmospheric deposition (Draaijers & Erisman 1995). Therefore, DD was inferred from NTF by estimating UP. The UP of inorganic nitrogen was estimated from the deposition of inorganic nitrogen to the forest floor by TF + SF (Lovett & Lindberg 1993, De Vries *et al*. 2003):

$$[2] \quad UP = 0.69 * (TF + SF) + 91.9 \quad (\text{eq N ha}^{-1}\ \text{y}^{-1})$$

Regression equation [2] is based on TF + SF depositions ranging from 100 to 1000 eq N ha^{-1} y^{-1} in several deciduous and coniferous forest stands of the Integrated Forest Study in the northeastern USA (Johnson & Lindberg 1992, Lovett & Lindberg 1993).

RESULTS

NITROGEN FLUXES IN PRECIPITATION, THROUGHFALL AND STEMFLOW

The annual amount of precipitation was significantly higher ($p < 0.001$) at San Pablo de Tregua during the study period 2002-2003 than at Paillaco during the period 2000-2001 (Table I). Nevertheless, the partitioning of precipitation into throughfall (TF), stemflow (SF), and interception loss was similar at the two studied sites (Table I), with a net precipitation (TF + SF) of about 70% of the incoming precipitation reaching the forest floor.

The average volume-weighted concentrations in precipitation were 76.0 mg N l^{-1} at Paillaco and 42.6 mg N l^{-1} at San Pablo de Tregua for ammonium, and 16.3 mg N l^{-1} at Paillaco and 29.5 mg N l^{-1} at San Pablo de Tregua for nitrate. Organic nitrogen had a rainfall concentration of 92.2 mg N l^{-1} at Paillaco and 45.7 N l^{-1} at San Pablo de Tregua. Due to the large difference in precipitation between the two sites, these differences in rainfall concentration were not reflected in bulk nitrogen depositions.

The bulk rainfall deposition of NH_4^+ and NO_3^- (Table II) was significantly ($p = 0.03$) lower at Paillaco during the study period 2000-2001 than at San Pablo de Tregua during the period 2002-2003 according to the Mann-Whitney test. However, the mineral and organic nitrogen deposition to the forest floor by TF and SF was about three times higher at Paillaco (10.0 kg N ha^{-1} y^{-1}, 2000-2001) than at San Pablo de Tregua (3.4 kg N ha^{-1} 11 $months^{-1}$, 2002-2003). Consequently, the N deposition in TF and SF was significantly ($p < 0.05$) higher at Paillaco than at San Pablo de Tregua for each considered N form (Table II). No clear seasonal trends in TF + SF depositions were observed (Fig. 1).

TABLE I. Precipitation (P) partitioning into throughfall, stemflow, and interception loss in a deciduous *Nothofagus* stand at Paillaco (2000-2001) and San Pablo de Tregua (2002-2003).

TABLA I. Precipitación directa, flujo fustal y pérdida por intercepción, en rodales de *Nothofagus* caducifolio en Paillaco (2000-2001) y San Pablo de Tregua (2002-2003).

	Paillaco		San Pablo de Tregua	
	mm y^{-1}	% of P	mm y^{-1}	% of P
Throughfall	1107.4	66.8	3490.4	65.8
Stemflow	16.4	1.0	197.2	3.7
Interception	533.8	32.2	1620.2	30.5
Precipitation	1657.6	100.0	5307.8	100.0

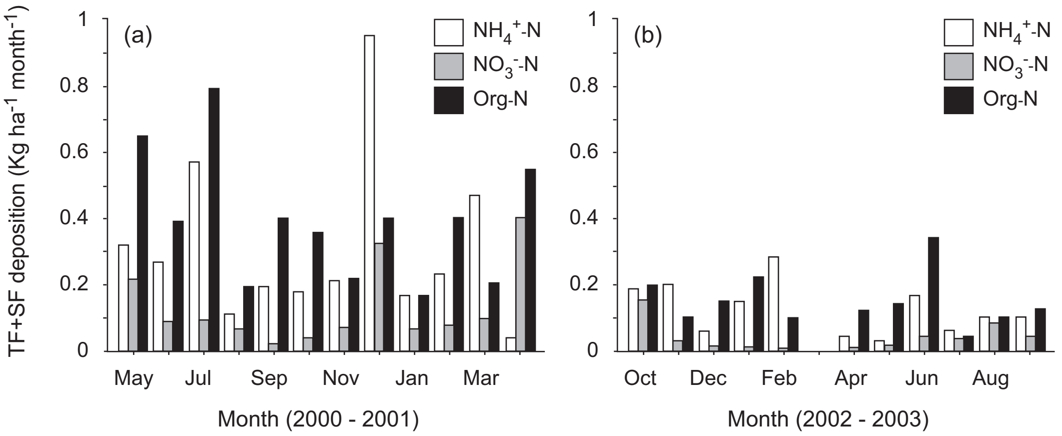

FIGURE 1. Throughfall plus stemflow deposition (TF+SF, kg N ha^{-1} month^{-1}) of different nitrogen compounds in a *Nothofagus* stand at (a) Paillaco and (b) San Pablo de Tregua (data of March 2003 were lacking).

FIGURA 1. Flujos de la precipitación directa y fustal (TF + SF, kg N ha^{-1} mes^{-1}) de distintas formas de compuestos nitrogenados en rodales de *Nothofagus* en (a) Paillaco y (b) San Pablo de Tregua (valores de marzo 2003 no registrados).

TABLE II. Bulk deposition (BD), throughfall (TF), stemflow (SF), net throughfall (NTF=TF+SF-BD), leaf litterfall (LLF), and total input to the forest floor (TF+SF+LLF) in a *Nothofagus* stand at Paillaco and San Pablo de Tregua (kg ha^{-1} y^{-1}). All data from San Pablo de Tregua, except for LLF, are given for 11 months instead of one year because of the loss of data on N concentrations for March 2003. Statistical differences between the two sites are indicated for BD, TF, SF, TF+SF, and NTF (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

TABLA II. Depositación total (BD), precipitación directa (TF), flujo fustal (SF), depositación neta (NTF), aporte de hojarasca (LLF), y aporte total al piso del bosque (LLF). Los datos de San Pablo de Tregua, excepto LLF, corresponden a un período de 11 meses, dada la ausencia de datos de marzo 2003. Las diferencias estadísticas entre los dos sitios se indican por asteriscos (* $p < 0,05$; ** $p < 0,01$; *** $p < 0,001$).

	Flux (kg ha^{-1} y^{-1})						
	BD	TF	SF	TF+SF	NTF	LLF	Total
Paillaco (2000-2001)							
NH_4^+-N	1.26*	3.65*	0.04	3.70*	2.44***	-	-
NO_3^--N	0.27**	1.48**	0.06**	1.54**	1.27***	-	-
Org-N	1.53	4.67***	0.06	4.73***	3.20***	-	-
Total N	3.06**	9.80***	0.17	9.97***	6.91***	49.6	59.6
San Pablo (2002-2003)							
NH_4^+-N	2.26*	1.33*	0.04	1.37*	-0.89***	-	-
NO_3^--N	1.57**	0.41**	0.01**	0.42**	-1.15***	-	-
Org-N	2.43	1.61***	0.03	1.64***	-0.79***	-	-
Total N	6.25**	3.35***	0.08	3.42***	-2.83***	56.3	59.7

NET THROUGHFALL WATER AND CANOPY INTERACTIONS

The net throughfall water (NTF=TF+SF-BD) of mineral nitrogen was positive at Paillaco (3.7 kg N ha^{-1} y^{-1}) and negative at San Pablo de Tregua (-2.0 kg N ha^{-1} 11 $months^{-1}$) (Table II). Consequently, the Wilcoxon signed-rank test showed that at Paillaco the TF + SF deposition of each N compound was significantly higher ($p < 0.01$) than the BD. At San Pablo de Tregua, in contrast, the TF + SF deposition of ammonium ($p = 0.07$) and nitrate ($p = 0.005$) was significantly lower than the BD.

The positive NTF at Paillaco is due to the unquantified amount of dry deposition (DD) of nitrogen on the forest canopy. The negative NTF at San Pablo de Tregua indicates that the amount of DD is smaller than the amount of canopy uptake (UP) (see Eq. [1]). Using eq. [2], the inorganic nitrogen uptake of the aboveground forest compartment was estimated to be 4.9 and 2.5 kg N ha^{-1} y^{-1} at Paillaco and San Pablo de Tregua, respectively. Consequently, the inorganic nitrogen DD was estimated to be 8.6 and 0.5 kg N ha^{-1} y^{-1} at Paillaco and San Pablo de Tregua, respectively.

Finally, the interactions between the canopy and inorganic nitrogen are illustrated by the relationship between the monthly BD and the monthly plot-average NTF. At San Pablo de Tregua, relatively strong relationships ($r^2 > 0.73$) were observed between the bulk deposition of nitrate and ammonium and the net throughfall deposition to the forest floor (Fig. 2). Such relationships were not found for Paillaco ($r^2 < 0.02$).

NITROGEN FLUXES IN LEAF LITTERFALL

The amount of litterfall in the studied stand of San Pablo de Tregua was 5776 kg ha^{-1} y^{-1}. Leaf litterfall accounted for 76.5% of the total litterfall, or 4419 kg ha^{-1} y^{-1}. Branches contributed 16.1% of total litterfall, reproductive organs 6.6% and the miscellaneous fraction (moss, bark, etc.) 0.8%. The amount of leaf litterfall at Paillaco was 5854 kg ha^{-1} y^{-1}. The annual nitrogen return by leaf litterfall was similar in the two studied stands (Table II).

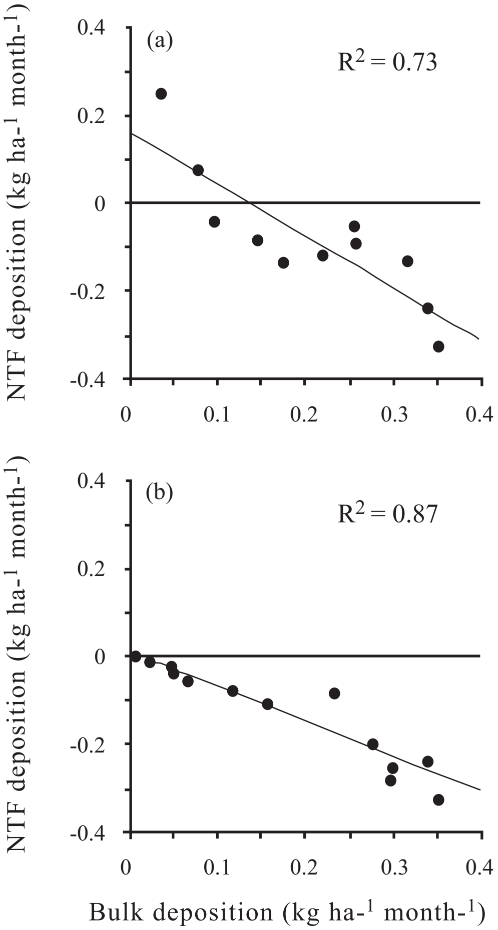

FIGURE 2. Net throughfall (NTF, kg N ha^{-1} $month^{-1}$) of (a) NH_4^+-N and (b) NO_3^--N as a function of bulk deposition (kg ha^{-1} $month^{-1}$) in a *Nothofagus* stand at San Pablo de Tregua. The best fitted line is indicated. Data of 11 months are shown because the data of march 2003 were lacking.

FIGURA 2. Depositación neta (NTF, kg N ha^{-1} mes^{-1}) de (a) N-NH_4 y (b) N-NO_3 en función de la depositación total (kg ha^{-1} mes^{-1}) en rodales de *Nothofagus* en San Pablo de Tregua. Se indica la línea de mejor ajuste. Valores de Marzo 2003 no registrados.

DISCUSSION

In both *Nothofagus* forests, N input through leaf litterfall (~ 50 kg N ha^{-1} y^{-1}) was much higher than the atmospheric N load (< 10 kg N ha^{-1} y^{-1}). This is in contrast with forests more polluted by atmospheric depositions, where input by atmospheric deposition can be the dominant N source (e.g. De Schrijver *et al*. 2004). Therefore, the results confirm the low degree of alteration by external pollution sources in the forests of the present study (Ukonmaanaho & Starr 2002). However, the clear difference in net throughfall deposition of inorganic N between the two studied stands (Table II) indicates that the external N input by dry deposition is higher in the Central depression than in the Cordillera de los Andes.

In the forest stand at San Pablo de Tregua, in the Cordillera de los Andes, the annual bulk deposition of NH_4^+ and NO_3^- was significantly higher than the throughfall and stemflow deposition reaching the forest floor (Table II). This demonstrates uptake of inorganic N in the canopy, in agreement with previous reports that significant amounts of inorganic N may be taken up by canopy foliage, stems and branches, as well as epiphytic lichens or other microflora in the forest canopy. Uyttendaele & Iroumé (2002) measured a bulk precipitation flux of 6.3 kg NO_3^--N ha^{-1} y^{-1} and throughfall fluxes of 1.3 kg NO_3^--N ha^{-1} y^{-1} in a pine stand (*Pinus radiata*) and a native evergreen forest site in southern Chile (39°44'S, 73°10'W), which indicates a retention of about 5 kg NO_3^--N ha^{-1} yr^{-1} by the aboveground biomass. Lovett & Lindberg (1993) reported that consumption of inorganic N in the canopy ranged from 1 to 12 kg N ha^{-1} y^{-1}.

While net throughfall of ammonium has often been found to be negative (Carleton & Kavanagh 1990; Lovett & Lindberg 1993; Hansen 1996; Lovett *et al.* 1996; Ukonmaanaho & Starr 2002; Zimmerman *et al.* 2002), NTF of nitrate has been described as positive (e.g. Balestrini & Tagliaferri 2001, Ferm & Hultberg 1999, Hansen 1996, Lovett *et al.* 1996, Zimmerman *et al.* 2002) or negative (e.g. Carleton & Kavanagh 1990, Lovett & Lindberg 1993, Lovett *et al.* 1996, Ukonmaanaho & Starr 2002, Uyttendaele & Iroumé 2002). Using ^{15}N labelled water solutions, it has been shown that spruce canopy uptake of NH_4^+ was about four times higher than of NO_3^- (Boyce *et al*. 1996). Also field studies of Potter (1991) and Stachurski & Zimka (2000) have demonstrated that tree canopies may absorb NH_4^+ more efficiently than NO_3^- ions. In the present study, in contrast, no clear difference between the canopy uptake of NH_4^+ and NO_3^- was found at San Pablo de Tregua. Furthermore, the net throughfall of both NO_3^- and NH_4^+ was significantly negatively correlated with the bulk deposition of inorganic N above the forest (Fig. 2). This relationship indicates that N uptake is enhanced proportionally with an increasing flux in precipitation. Similarly, Hansen (1996) found a strong negative relationship ($r^2 = 0.92$) between the net throughfall and the bulk deposition of NH_4^+ for a Norway spruce stand during the growing season. Also Lovett *et al*. (1996) found a significant effect of precipitation concentration on net throughfall for NH_4^+ ($r^2 = 0.65$), but not for NO_3^-.

At Paillaco, in the Central Depression of southern Chile, uptake of inorganic N was not directly detectable. However, uptake of NH_4^+ and NO_3^- is still possible when the net throughfall deposition is positive, but then it is obscured by dry deposition of nitrogen (see eq. [1]). In other words, a positive net throughfall of inorganic N indicates a greater dry deposition than aboveground uptake of inorganic N (Hansen 1996). The estimated canopy uptake at Paillaco of about 5 kg inorganic N ha^{-1} y^{-1} is in line with previous research (cf. supra). Therefore, the inferred dry deposition of about 8 kg inorganic N ha^{-1} y^{-1} on the *Nothofagus obliqua* stand at Paillaco seems reasonable. Furthermore, dry deposition of NH_3 gas and NH_4^+ aerosol onto surrogate surfaces in a grassland at Paillaco amounted to 12 kg NH_4^+-N ha^{-1} during six months (October 2003 - March 2004) (Godoy *et al*. submitted). Finally, even when the canopy uptake of N is assumed to be zero, the positive net throughfall deposition of 3.7 kg inorganic N ha^{-1} y^{-1} (Table II) can only be explained by a dry deposition of 3.7 kg inorganic N ha^{-1} y^{-1}. So, in conclusion, the minimum value of dry deposition onto the *Nothofagus* stand at Paillaco, obtained by neglecting canopy interactions, is still higher than the measured wet deposition. These findings stress the importance of including dry deposition estimates in nutrient cycling studies of forest ecosystems. Therefore, in order to assess the effect of future emission changes on natural ecosystems, monitoring of both the wet and dry deposition of nitrogen is important.

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