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COMPARISON OF DRY DEPOSITION AND CANOPY EXCHANGE OF BASE CATIONS IN TEMPERATE HARDWOOD FORESTS IN FLANDERS AND CHILE

ESTUDIO COMPARATIVO DE LA DEPOSITACION SECA E INTERCAMBIO EN EL DOSEL DE LOS CATIONES DE BASE EN BOSQUES TEMPLADOS DE FLANDERS Y CHILE

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ABSTRACT

Bulk precipitation, throughfall and stemflow of base cations Na^+, K^+, Mg^{2+} and Ca^{2+} were measured in two deciduous beech forests, located in regions with different air pollution characteristics and strongly differing in soil acidity and soil base saturation. The contribution of dry deposition and canopy leaching to net throughfall flux was estimated using Na^+ as a tracer ion. The input of base cations via bulk precipitation was not significantly different between *Nothofagus obliqua* (Mirb.) Bl. in southern Chile and *Fagus sylvatica* L. in Flanders. However, net throughfall input of Ca^{2+} and Mg^{2+} to the forest floor was significantly higher in Chile than in Flanders. Potassium fluxes were similar in both studied stands. Dry deposition of Ca^{2+} was higher in Chile, in absolute value as well as in relative contribution to net throughfall flux. A strong difference between the two Fagaceae-dominated forests was found for magnesium. In Chile, canopy leaching of Mg^{2+} (8.9 kg ha^{-1} y^{-1}) was the major input source to the forest floor, while Mg^{2+} canopy leaching was close to zero in Flanders. As the availability of base cations in the soil solution determines the possibility of trees to exchange cations, we hypothesize that the lower Mg^{2+} canopy leaching in Flanders is mainly due to magnesium deficiency in the Flemish forest soil.

KEYWORDS: Atmospheric deposition, base cations, Fagaceae, forest canopy, throughfall.

RESUMEN

Se midieron las concentraciones de los cationes de base Na^+, K^+, Mg^{2+} y Ca^{2+} en la precipitación incidente, precipitación directa y escurrimiento fustal en dos bosques deciduos, localizados en regiones con diferente contaminación atmosférica, acidez del suelo y saturación de bases. La contribución de la depositación seca y el lavado del dosel en la precipitación efectiva se estimó utilizando el Na^+ como un ion trazador. El ingreso de cationes de base vía precipitación incidente no fue significativamente diferente entre *Nothofagus obliqua* (Mirb.) Bl. en el sur de Chile y *Fagus sylvatica* L. en Flanders. Sin embargo, las entradas netas de Ca^{2+} y Mg^{2+} hacia el suelo del bosque fue significativamente mayor en Chile que en Flanders. Los flujos de potasio fueron similares en ambos bosques. La depositación seca de Ca^{2+} fue mayor en Chile, tanto en valores absolutos como en su contribución relativa en el agua que ingresa al bosque. Se encontró una fuerta diferencia en el magnesio entre los dos bosques de Fagaceae. En Chile, el lavado del dosel de Mg^{2+} (8,9 kg ha^{-1} a^{-1}) constituyó el principal ingreso al suelo del bosque, mientras que en Flanders fue cercano a cero. Así como la disponibilidad de cationes de base en la solución del suelo determina la posibilidad de los árboles de intercambiar cationes, nosotros hipotetizamos que el lavado menor de Mg^{2+} en el dosel de los bosques en Flanders se debería principalmente a las deficiencias de magnesio en el suelo de los bosques de Flanders.

PALABRAS CLAVES: Cationes de base, depositación atmosférica, dosel, Fagaceae, precipitación directa.

INTRODUCTION

The chemistry of precipitation that reaches the forest floor is influenced by chemical and hydrological characteristics of the incident

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precipitation, washoff of dry-deposited materials from canopy surfaces, washoff of material transported from within canopy tissues prior to the precipitation event, and absorption or release of substances by the plants and their associated microflora during the precipitation event (Parker 1983; Lovett *et al*. 1989). Throughfall water is generally enriched in most chemical elements compared to bulk precipitation, and it is widely acknowledged that this enrichment results from (i) dry deposition of aerosols and gases as well as (ii) canopy leaching, i.e. release of ions from plant tissues. To separate these individual processes of deposition and chemical exchange, several approaches have been developed. Two main methodologies based on throughfall measurements are (i) the empirical multiple regression model developed by Lovett & Lindberg (1984), and (ii) the canopy budget model (Ulrich 1983), used in this paper.

Forest canopies buffer part of the incoming acid deposition by exchanging K^+, Ca^{2+} and Mg^{2+} for H^+ and NH_4^+ (Potter 1991). These exchange processes are dependent on the forest canopy composition and the local ecological conditions (Van Ek & Draaijers 1994). The availability of base cations in the soil solution strongly influences the cation exchange potential of trees canopies. For example, fertilization has been found to enhance canopy leaching considerably (Matzner *et al*. 1983). There is growing evidence that various anthropogenic factors such as atmospheric depositions and harvesting activities may now be disrupting natural cycles and depleting Ca^{2+} and Mg^{2+} from forest soils (Likens *et al*. 1998; Adams 1999). Factors influencing the base cation pools of soils include declines in atmospheric base cation deposition (Hedin *et al*. 1994; Matzner & Meiwes 1994), soil acidification resulting in soil aluminium mobilisation (Falkengren-Grerup & Tyler 1991), and nitrogen saturation (Aber *et al*. 1995). Base cation status of soils is changing more rapidly than previously anticipated (Schaberg *et al*. 2001), and the input of Mg^{2+} and Ca^{2+} becomes crucial for the overall cycling of these elements in forest ecosystems (Armbruster *et al*. 2002).

The present study is part of a project comparing biogeochemical cycling in temperate deciduous hardwood forests in Chile and Flanders. The forest stands studied in this paper both consist of tree species of the Fagaceae family, but are located in regions with different air pollution characteristics, soil acidity and soil base saturation. While N and S deposition in Flanders results in an exceedance of the critical load for acidification in the majority of forest stands (Craenen *et al*. 2000), nutrient cycling in the pristine temperate forests of southern Chile is largely undisturbed by atmospheric contamination (Hedin *et al*. 1995). In order to estimate and evaluate the input of nitrogen to forest ecosystems in both regions, it is necessary to gain a better understanding in the atmospheric input of base cations to these forests. Studies of unpolluted areas can provide important baseline information about natural patterns of element cycling, against which disturbed cycles can be compared (Hedin *et al*. 1995).

The purpose of this study is therefore (i) to compare throughfall and stemflow fluxes of base cations between two deciduous *Fagaceae* forests in Flanders and Chile, and (ii) to estimate and compare the dry deposition and canopy leaching of base cations in both forests.

MATERIALS AND METHODS

STUDY AREAS

The *Nothofagus obliqua* (Mirb.) Bl. forest is located in the Central Valley of Chile (40°07'S, 72°51'W, 160 m a.s.l.). The climate is classified as temperate and the annual precipitation during the study period (May 2000 - April 2001) was 1657 mm. Soils of the area are denominated as typic dystrandepts (FAO 1988) or "trumaos", originating from volcanic ash. The overstorey is dominated by *Nothofagus obliqua* and has a mean tree height of 32 m, a stand density of 757 trees ha^{-1} and an average tree age of 120 years (C. Oyarzún & R. Godoy, unpublished data). The stand has a subcanopy dominated by *Aextoxicon punctatum* Ruiz *et* Pavon, and a shrub layer of *Chusquea quila* Kunth and *Rhaphithamnus spinosus* (A. L. Juss) Mol.

The *Fagus sylvatica* L. forest is located in Torhout (51°05'N, 3°02'O, 10 m a.s.l.), in the northern part of Belgium (Flanders). The climate is also temperate and the annual precipitation during the study period (Jan 2000 - Dec 2000) was 1007 mm. The forest soil is characterised as a gleyic, dystric cambisol (FAO 1988). Mean tree height of the stand is 25 m, stand density is 292 trees ha^{-1} and the stand age is 79 years. There is no understorey in this planted, monospecific stand that had a basal area of 39.2 m^2ha^{-1} in 1999.

The growing period of the year, in which trees had leaves, was from October till April in Chile and from May till November in Flanders.

Data collection

Bulk precipitation and throughfall water were collected with funnel collectors attached to a 2-l bottle. For the collection of bulk precipitation 3 funnels were used in Chile (surface area of 200 cm^2) and 4 in Flanders (surface area of 154 cm^2); for throughfall water, 12 and 10 collectors were used respectively. Stemflow water was measured using plastic collars and 50-200 Containers for 12 trees in Chile and 5 trees in Flanders.

Water samples for chemical analysis were collected monthly in Chile and biweekly in Flanders. The pH and electronic conductivity were determined using specific electrodes. Base cations were measured by atomic emission spectrometry in Chile, and by atomic absorption spectrophotometry in Flanders. The Flemish data were collected as a part of the UN/ECE intensive monitoring of the forest ecosystems in Europe (Level II-plot).

Data analysis

To allow easy comparison of the two forest stands, biweekly data of Flanders were combined into monthly data. The sum of throughfall and stemflow water is the total amount of water reaching the forest floor, and is called net precipitation. The nutrient flux in net precipitation is the actual input to the forest floor. The total effect of the canopy on nutrient fluxes is calculated by subtracting bulk precipitation from net precipitation, designated as net throughfall water (NTF, kg ha^{-1} yr^{-1}):

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

where BD = bulk deposition, TF = throughfall, SF = stemflow, DD = dry deposition, and CL = canopy leaching.

Independent samples t-tests were used to compare bulk precipitation, net precipitation as well as net throughfall between Chile and Flanders, after lognormal transformation to meet normality assumptions.

To estimate the contribution of dry deposition and canopy leaching to net throughfall water, the canopy budget method was used (Ulrich 1983; Draaijers & Erisman 1995, De Vries *et al*. 1998) on a seasonal basis. In this method, Na$^+$ in throughfall is assumed to be inert with respect to the canopy, i.e. neither uptake nor leakage occurs. Furthermore, particles containing Ca^{2+}, Mg^{2+} and K$^+$ are assumed to have the same deposition velocity as Na$^+$, as expressed by a dry deposition factor (DDF):

$$DDF = \frac{(TF + SF - BD)_{Na}}{BD_{Na}} \qquad [2]$$

Dry deposition of Ca^{2+}, Mg^{2+} and K$^+$ is then calculated as the bulk deposition flux multiplied with the dry deposition factor:

$$DD_X = BD_X \cdot DDF \qquad [3]$$

Canopy leaching of each ion is calculated by subtracting the estimated dry deposition flux from the net throughfall flux.

RESULTS

Water fluxes

Although annual precipitation in Flanders was 40% less than in Chile, growing season precipitation was

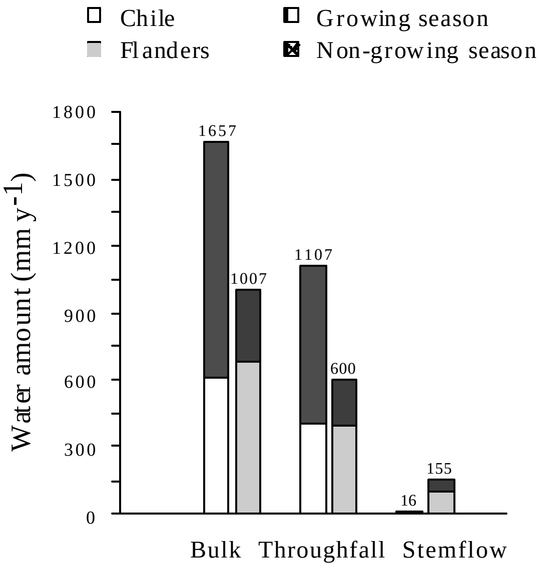

Figure 1. Annual bulk precipitation, throughfall and stemflow amount (mm y^{-1}) in a *Nothofagus obliqua* stand (Chile) and a *Fagus sylvatica* stand (Flanders).

comparable: 610 mm in Chile vs. 676 mm in Flanders (Fig. 1). Monthly precipitation in the growing season was not significantly different between the two countries ($p = 0.765$), in contrast to monthly precipitation in the non-growing season ($p = 0.034$). Rain interception, i.e. the fraction of the bulk precipitation that never reached forest soil, was 32% in Chile and 25% in Flanders. In Chile nearly all net precipitation (TF+SF) came as throughfall (98.5%), while stemflow accounted for 21% of net precipitation input in Flanders (Fig. 1). The amounts of net precipitation and net throughfall (TF+SF-BP) were not significantly different between Chile and Flanders during the growing season and over the year, but were significantly higher in Chile during the non-growing season (Table II). In Chile, the amount of net throughfall water was significantly different between the growing and non-growing season ($p = 0.010$), in contrast to Flanders ($p = 0.168$).

TABLE I. Bulk deposition (BD), throughfall (TF), stemflow (SF) and input to the forest floor (TF+SF) in a *Nothofagus obliqua* stand (Chile) and a *Fagus sylvatica* stand (Flanders) (kg ha^{-1} y^{-1}).

Element	Chile				Flanders			
(kg ha^{-1}y^{-1})	BD	TF	SF	TF+SF	BD	TF	SF	TF+SF
Na^+	14.8	31.6	0.6	32.2	20.2	20.9	6.0	26.9
K^+	3.6	49.8	1.5	51.3	6.7	32.1	7.3	39.4
Ca^{2+}	9.2	21.5	1.0	22.5	8.3	9.6	3.3	12.9
Mg^{2+}	1.5	11.9	0.3	12.2	2.8	3.0	0.7	3.7

TABLE II. Difference between *Nothofagus obliqua* (Chile) and *Fagus sylvatica* (Flanders) in the water flux (mm month^{-1}) and base cation flux (kg ha^{-1} month^{-1}) in (i) net precipitation and (ii) net throughfall: significance of two-tailed t-statistic (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

	Net precipitation (TF+SF)			Net throughfall(TF+SF-BD)		
Element	Year	Growing	Non-grow	Year	Growing	Non-grow.
Water	0.467	0.559	0.050 *	0.018 *	0.692	0.002 **
Na^+	0.800	0.427	0.300	0.015 *	0.009 **	0.519
K^+	0.767	0.722	0.115	0.621	0.767	0.062
Ca^{2+}	0.315	0.271	0.926	0.004 **	0.006 **	0.296
Mg^{2+}	0.012 *	0.014 *	0.515	0.000 ***	0.001 ***	0.032 *

NUTRIENT FLUXES IN CHILE AND FLANDERS

Bulk deposition of base cations Na^+, K^+, Ca^{2+} and Mg^{2+} was generally of the same magnitude in the two regions (Table I). On an annual basis as well as during the growing and non-growing seasons, bulk deposition of base cations was not significantly different between Chile and Flanders. For all base cations, the input to the forest floor in net precipitation (TF+SF) was higher in Chile than in Flanders (Table I), but this difference was only significant for Mg^{2+} annually and in the growing season (Table II). Net throughfall (TF+SF-BD) was significantly different between Chile and Flanders for Na^+, Ca^{2+} and Mg^{2+} on annual basis and during the growing season (Table II). During the non-growing season, only net throughfall of Mg^{2+} differed significantly between both countries.

The evolution of TF concentrations over the year is illustrated in Fig. 2. In Chile, TF concentrations of all base cations were much higher in the growing season than in the non-growing season. In Flanders, K^+ concentrations were higher during the growing season, while Na^+ concentrations were highest in the non-growing season. In Flanders, sodium was characterized by especially high TF concentrations during the first four months of 2000 (Fig. 2), because of increased atmospheric sea aerosol levels due to high storm activity.

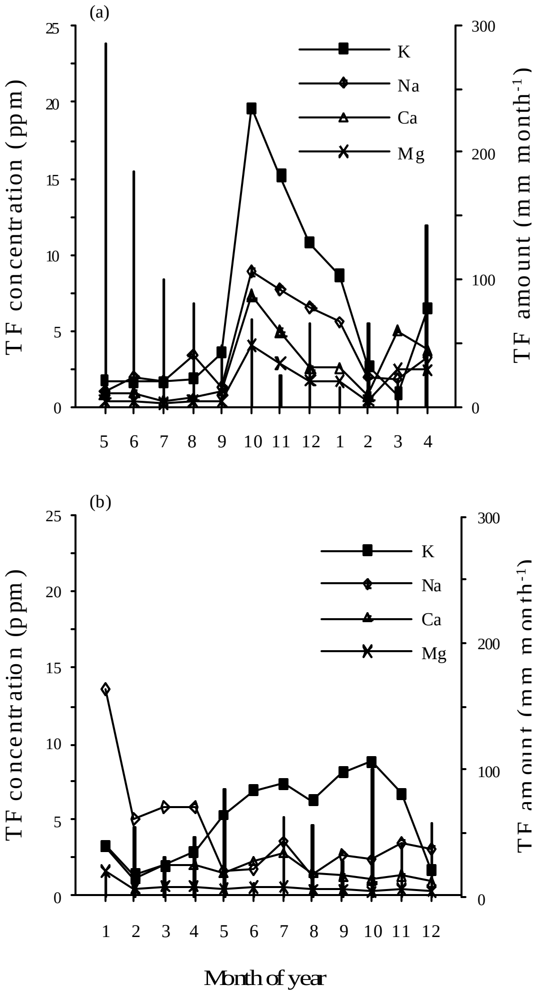

Figure 2. Monthly variation in throughfall amount (shown by bars) and base cation concentration (shown by symbols and lines) under stands of (a) *Nothofagus obliqua* (Chile) and (b) *Fagus sylvatica* (Flanders).

Dry deposition and canopy leaching

The contribution of bulk deposition, dry deposition and canopy leaching to the forest floor input was cation-dependent (Fig. 3). Stand deposition of K^+ was much higher during the growing season due to increased canopy leaching (Fig. 2). The contribution of dry deposition (<10%) and canopy leaching (>90%) to net throughfall of K^+ was comparable between Flanders and Chile (Table III). For Ca^{2+}, bulk deposition was an important input source in both countries (Fig. 3). Dry deposition of Ca^{2+} was much higher in Chile than in Flanders, in absolute values (Fig. 3) as well as in relative contribution to net throughfall deposition (Table III). The principal source of calcium in Flanders was bulk deposition, while dry deposition was more important in Chile (Fig. 3). The amount of Ca^{2+} canopy leaching was comparable in both countries.

For Mg^{2+}, a strong difference between the two Fagaceae forests was found. In Chile, the input of Mg^{2+} was mainly originating from canopy leaching, contributing 8.9 kg ha^{-1} yr^{-1} on a total input to the forest floor of 12.2 kg $ha^{-1}y^{-1}$. In Flanders, canopy leaching of Mg^{2+} was close to zero, indicating no effect of the canopy on Mg^{2+} in rain water. Bulk deposition was consequently the most important source of Mg^{2+} in Flanders (Fig. 3).

The total amount of wet and dry deposited base cations was of the same magnitude in both countries, except for Ca^{2+} (Fig. 3). The sum of wet and dry deposition of Ca^{2+} was twice as high in Chile (21.2 kg ha^{-1} yr^{-1}) as in Flanders (10.7 kg ha^{-1} yr^{-1}).

Table III. Estimated contribution (%) of dry deposition (DD) and canopy leaching (CL) to annual net throughfall deposition of base cations for *Nothofagus obliqua* (Chile) and *Fagus sylvatica* (Flanders).

Element	Chile		Flanders	
	DD (%)	CL (%)	DD (%)	CL (%-)
Na+	100	0	100	0
K+	9	91	5	95
Ca^{2+}	91	9	53	47
Mg^{2+}	16	84	98	2

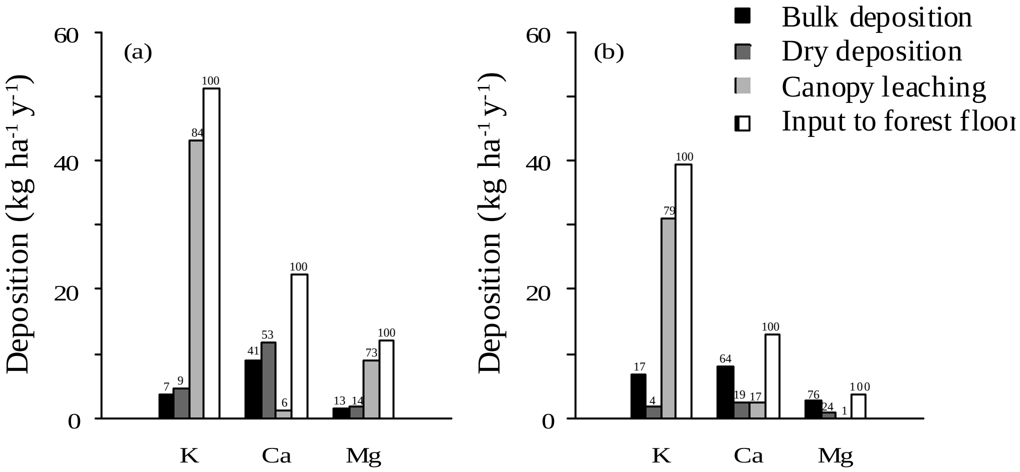

FIGURE 3. Deposition of base cations (kg ha^{-1} y^{-1}) in (a) *Nothofagus obliqua* (Chile) and (b) *Fagus sylvatica* (Flanders). Numbers above bars indicate contribution (%) of each source to cation input to the forest floor.

DISCUSSION

Throughfall and stemflow measurements showed a higher input of base cations in Chile than in Flanders, which was significant for Mg^{2+} (Table II). Subtracting bulk deposition revealed significant differences between the two forests for Ca^{2+} and Mg^{2+} in net throughfall water (Table II). To find a probable reason of the higher input of base cations to the *Nothofagus* forest, three underlying processes can be discussed: bulk deposition, dry deposition and canopy leaching.

There are slight differences in bulk deposition of base cations between the two forests. However, the higher throughfall deposition of base cations in Chile was not determined by a different input *via* precipitation, as bulk deposition of K^+ and Mg^{2+} was even higher in Flanders (Table I). Overall, we found no significant differences in monthly bulk deposition of base cations between the two countries. The input of base cations *via* precipitation was measured by bulk precipitation samplers instead of wet-only samplers, but no attempt was made to correct bulk deposition for the probable contribution of dry deposition onto the funnels of bulk samplers.

A second factor contributing to the input of base cations to the forest floor is dry deposition. The estimated dry deposition was higher for the *Nothofagus* forest in Chile than for the *Fagus* stand in Flanders, especially for Ca^{2+} (Fig. 3). The amount of dry deposition depends on ambient air concentrations and the collection efficiency of the surface, which is increased by wet surface conditions and a high ambient relative humidity (Draaijers *et al*. 1997b). Consequently the difference between the two forests may be due to differing deposition velocities as influenced by the temporal precipitation distribution, as well as to differing air concentrations. Air concentrations of Ca^{2+} are related to (amongst other things) dust emissions associated with traffic on unpaved roads or agricultural tillage practices, and natural particle emissions (Hedin *et al*. 1994). Cloud and fog deposition were not measured or estimated, as both forest stands were low elevation plots without frequent fog events.

Canopy leaching results generally agree with previous studies (Reiners & Olson 1984; Lovett & Schaefer 1992). Potassium is in both countries found to be more susceptible to canopy leaching than Mg^{2+} and Ca^{2+} (Fig. 3), because it is not so tightly bound in structural tissues or enzyme complexes (Draaijers *et al.* 1997a). Calcium is derived primarily from the wash off of dry deposition or the depletion of readily accessible ionic pools on canopy surfaces, but is regarded as highly immobile (Lovett & Schaefer 1992). Magnesium seems to take an intermediate position between K^+ and Ca^{2+} (Table III). Generally, leaching of base cations is higher in Chile than in Flanders, but the difference is most pronounced for Mg^{2+} (Fig. 3). Possible factors that regulate canopy leaching of base cations are (i) precipitation characteristics, such as duration, amount and acidity of rain events, (ii) canopy characteristics, such as aboveground biomass and amount and concentration in tree leaves, and (iii) forest soil characteristics, such as extractable amount of base cations and soil solution concentrations (Lovett & Schaefer 1992). Canopy interactions with acidic precipitation are for instance influenced by the phenological status of trees (Cronan & Reiners 1983). Since the effect of precipitation characteristics is more important as rain-pH decreases, canopy exchange in the studied forest stands will to a large extent be determined by tree and soil characteristics. Although both forests types differ in structural characteristics, phenology and morphology are comparable. Thus, we suggest that the observed difference in Mg^{2+} leaching may be related to soil nutrient status.

In Flanders, pH-value and base saturation of the soil are much lower than in Chile, because of differing soil types and as a result of historical differences in acid loadings. Nitrogen deposition in the range of 10-40 kg N $ha^{-1}y^{-1}$ is common in much of Europe (MacDonald *et al*. 2002), and substantial amounts are deposited as NH_4^+ (Meiwes *et al*. 1998). In regions with intensive agricultural activities, like Flanders, forest soils have been subjected to high atmospheric deposition for several decades (Craenen *et al*. 2000), which has resulted in a significant acidification of forest soils over the past 50 years (Ronse *et al*. 1988). At the Flemish forest site, soil pH(H_2O) of the top 30 cm is 3.7, compared to 6.0 for the Chilean soil of volcanic origin. Aluminium is consequently the dominant cation in the Flemish forest soil solution, probably hampering Mg^{2+} uptake by roots (Evers & Hüttl 1991; Falkengren-Grerup & Tyler 1991). Magnesium deficiency is indeed a widespread phenomenon in European forests (Armbuster *et al*. 2002). No difference in canopy leaching of e.g. K^+ was observed, in agreement with the fact that potassium ions are strong competitors with other cations (Mengel & Kirkby 2001).

Comparing forest ecosystems in Chile and Flanders is not straightforward because of the differences in tree species, climate and air pollution characteristics. Furthermore, data quality can be influenced by dissimilarities in sampling protocol and analytical techniques. To our knowledge, all reported studies that used the model of Ulrich (1983) were based on seasonal or annual data, although the method theoretically also works on e.g. monthly basis. Estimating dry deposition and canopy leaching over long time periods has the disadvantage that the fluxes cannot be compared statistically when only one year's data are available. As we also used the method of Ulrich (1983) on a seasonal basis, it was not possible to determine the significance of the difference in canopy leaching between Flanders and Chile. However, the contrast between the canopy leaching of Mg^{2+} in Chile and Flanders is so large that the suggested hypothesis on the influence of Mg^{2+} soil deficiency in Flanders certainly warrants further research.

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