

Nutrient cycling in a poplar plantation (*Populus trichocarpa* x *Populus deltoïdes* 'Beaupré') on former agricultural land in northern Belgium

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Abstract: Hydrological fluxes, atmospheric deposition, litterfall, and soil percolation of the most important nutrients were measured in an 18-year-old poplar plantation on a well-drained silt loam soil during 2 consecutive years. Downward soil water flux and transpiration are the most important factors in the water balance. Around 80% of the total nitrogen input (6.6 - 6.5 kmol ha^{-1} in both years 1 and 2, respectively) originates from litterfall. After nitrification only a negligible amount of nitrate leaches during the growing season. Yearly uptake of nitrogen by the poplar ecosystem (woody biomass, leaves, and ground vegetation) approximately equals the input, of which more than 50% is accounted for by the leaves. This indicates a very efficient nitrogen cycling. Total deposition of base cations originates from two processes, dry deposition (Mg^{2+} and Ca^{2+}) and canopy leaching (K^+ and Ca^{2+}). Litter input of Ca^{2+} represents about 83% of the total input (stand deposition + litterfall), Mg^{2+} about 61%, and K^+ less than 50%. Percolation of base cations at 1 m depth is very limited. Rather high Ca^{2+} and K^+ contents of the woody biomass can lead to high exports at harvesting. Nutrient cycling in the poplar stand proved to be very efficient, with no significant nutrient losses.

Résumé : Durant 2 années successives, les flux hydrologiques, la déposition atmosphérique, la litière et la percolation de nutriments dans le sol ont été étudiés dans une plantation de peupliers de 18 ans, installée sur un sol argile sableux bien drainé. Le flux descendant dans le sol et la transpiration sont les termes les plus importants du bilan hydrique. Presque 80 % du input total en azote (6.6 - 6.5 kmol ha^{-1} , an 1 et an 2, respectivement) est d'origine litière. Après nitrification, seulement une quantité négligeable d'azote lessive pendant la saison de croissance. L'assimilation annuelle d'azote par l'écosystème peuplier (bois, feuilles et couverture végétale) équivaut pratiquement l'input, dont plus que 50 % dans les feuilles, indiquant l'efficacité du cycle d'azote. La déposition totale de cations basiques est élevée et enrichie par les processus de la déposition sèche (Mg^{2+} et Ca^{2+}) et l'échange de nutriments au niveau de la cime (K^+ and Ca^{2+}). Input par la litière de Ca^{2+} représente environ 83 % de l'apport total, de Mg^{2+} environ 61 % et de K^+ moins que 50 %. La percolation de cations de base à un mètre de profondeur est très limitée. Mais à cause de concentrations assez élevées en Ca^{2+} et K^+ dans la biomasse ligneuse, des quantités considérables peuvent être exportés lors de l'abattage. Le cycle nutritif dans la plantation de peupliers se manifeste comme très efficace, sans pertes en nutriments significatives.

Introduction

The Flemish region is a sparsely forested area. With only 10.8% of the surface covered by woodland, Flanders is one of the least forested regions of Europe and has forest indexes comparable to those of Ireland, the Netherlands, Denmark, and the United Kingdom (FAO 2001). Nearly half of the forested area consists of deciduous stands. The Flemish Government has decided to actively promote land-use changes to increase the forest area. The objective is an increase of 10 000 ha by 2007. Afforestation of agricultural land will play an important role in achieving this goal, which is being encouraged via a grant system. This also fits the objectives of the Kyoto Protocol, as carbon sequestration by afforestation can be accounted as a sink in national CO₂ budgets. Fast-growing tree species are eligible for this purpose, as they quickly create a forest microclimate.

Afforestation has a considerable impact on the nutrient status of the soil (Ritter et al. 2003). Management of agricultural soils has intensified considerably over the past few decades. This intensification is characterized by a high input of mineral or organic fertilizers, frequent interference through site preparation using heavy agricultural machinery, and repeated application of pesticides (Matson 1997). A change in land use from agriculture to forestry implies that this high level of human interference is replaced by a much longer forest cycle characterized by less interference (Makeschin 1997). The forest soil remains more or less undisturbed, apart from possible soil preparation at the beginning of the rotation period and harvesting impacts at the end.

Trees have a particular and intensive influence on the forest ecosystem that is due to the effects of tree root development and canopy cover (Augusto 2002). The tree species, with its characteristic traits of light requirement and growth, determines the litter quality, rates of nutrient uptake, the degree of interception of atmospheric deposition, and eventually the uptake or leaching of water and nutrients. Hybrid poplars (*Populus* spp.), are fast-growing trees that rapidly produce a forest microclimate. Poplars generally exhibit a high level of uptake of nutrients, particularly nitrate, and produce leaf litterfall rich in base cations. This results in a quick decomposition, forming a mull-type form of humus and active soil bioturbation by macroinvertebrates. The hybrid poplar has been widely planted in stream and river valleys and on (sand) loam plateaus. Because of its fast growth and high wood production, it is appropriate for rotation cycles of 15-20 years. Fifteen percent of the Flemish forest area is covered by poplar and it provides 50% of the deciduous timber felled each year,

Since studies on nutrient cycling in poplar plantations are very scarce, this study aims to (i) assess the-nutrient cycling in an 18-year-old monoclonal poplar stand and (ii) quantify the seasonal water and nutrient budgets of the plantation over a 2 year period.

Materials and methods

Site description and soil characteristics

The poplar plantation is located at Balegem (50°55'N, 3°47'E), in northern Belgium, at an altitude of 45 m above sea level. Mean annual precipitation is 750 mm and precipitation during the growing season (1 April to 31 October) is 465 mm. The site is a former meadow with an orchard of about 1.5 ha. The relief is flat. The parent material of the soil is Pleistocene loess with a silt-loam texture. The soil is classified as a Glossaqualf according to *Keys to Soil Taxonomy* (Soil Survey Staff 2003) or a Gleyic-Anthic Albeluvisol according to the World Reference Base for Soil Resources (FAO, ISRIC, ISSS 1998).

The humus is a typical Eumull (Brethes et al. 1995). The site was not fertilized at the time of planting or after afforestation. Evidence of anthropogenic activity was observed in the topsoil (cultivation) and from by-traces of historical artificial drainage showing brick tubes at 90 cm depth, which were blocked and out of use at the time of profile description. A degraded Argic B (Bt) horizon with albeluvic tonguing was the main diagnostic feature. The physical and chemical characteristics of the soil are given in Table 1. Prior to analysis, oven-dried mineral soil was crushed and sieved to pass a 2 mm mesh screen.

Texture was determined using a laser diffraction method on a Coulter laser diffractometer (Coulter LS200, Beckman Coulter, Fullerton, California). Sampling for bulk density was done by the core method using standard sharpened steel cylinders of 100 ml, cc-volume. Bulk density was measured after the soil moisture retention curve was determined at eight matric potentials. The samples were oven-dried (105 °C) to constant mass (>24 h). Macroporosity was calculated as the difference between total porosity and moisture content at -10 kPa. Available water capacity estimated as the difference between the moisture content at field capacity (-33 kPa) and the permanent wilting point (-1.5 MPa).

Soil acidity ($\text{pH}_{\text{H}_2\text{O}}$) was measured in a 1:5 v/v suspension and carbonates were determined by titration. Total organic carbon in the mineral soil was measured with a total organic carbon analyser (Shimadzu 5050A with SSM-5000A Solid Sample Module, Shimadzu, Kyoto, Japan) after correction for inorganic carbon. The standard Kjeldahl nitrogen content of the mineral soil was determined using a Gerhardt Vapodest 60 distillation system (Gerhardt, Königswinter, Germany). Total phosphorus was determined by inductively coupled plasma atomic emission spectrometry in an aqua regia extract following microwave digestion. Exchangeable cations were determined using 0.01 M BaCl_2 as extradant according to ISO 11260.

In 1984, approximately 1 ha was planted with 2-year-old sets of the poplar clone *Populus trichocarpa* x *Populus deltoides* 'Beaupré'. The spacing in the entire plantation is approximately 7 m

x 7.5 m. Stand characteristics are given in Table 2. The plantation shows a good yield, reaching an average annual circumference increment of 8.2 cm and an annual volume increment of 22.9 m³.

Meteorological conditions and hydrological fluxes

The experimental setup for measuring the climatic conditions is extensively described in Meiresonne et al. (1999). Precipitation, wind speed, wind direction, air temperature, relative humidity, and incoming short-wave radiation at 2 m height were continuously measured by an automatic weather station installed in a nearby meadow. A second weather station was placed in the stand. Net precipitation was measured by flowmeters to determine the canopy interception. The flowmeters recorded the throughfall collected by plastic gutters with 3 m² surface area placed between the trees and the stemflow collected by spirals along the stem of two modal trees. The fluctuation of the groundwater table was continuously monitored to a depth of 4.4 m using a Didcot DWL-10 water-level sensor. Soil moisture content was measured by time domain reflectometry (TDR) sensors (Tektronix 1502B, Redmond, Wash.) installed in duplicate horizontally at intervals of 25 cm to a depth of 3 m.

Water balance and hydrological fluxes were simulated by means of the WAVE (water and agrochemicals in soil, crop, and vadose environment) model, which describes the transport and transformations of matter and energy in the soil, crop, and vadose environment (Vanclooster et al. 1994). Although the water-transport module of WAVE was originally developed for agricultural crops, it has also been calibrated and validated for forest conditions (Meiresonne et al. 1999, 2003; Verstraeten et al. 2005). This model describes one-dimensional soil water transport using Richards' equation (1931), which is based on the soil hydraulic properties. These include soil moisture retention, described by the power function of van Genuchten (1980), and the hydraulic conductivity relationship, for which Gardner's (1958) model performed well under Belgian conditions (Vereecken et al. 1990). The soil profile is divided into a number of compartments and the total time period into discrete time increments of unequal lengths (time steps smaller than 1 day) for the numerical calculation of the soil water fluxes. Conductivity and differential moisture capacity are linearized. Daily precipitation, interception, and groundwater-table data are input values. Transpiration is calculated as the integral of root water uptake over the entire profile. For each compartment, maximal root uptake (optimal conditions) is reduced, based on the soil water pressure head; water uptake is reduced at high pressures associated with anaerobiosis (near saturation) and at low pressures due to soil moisture stress. The initial soil moisture content is required. The soil moisture profile is used to calibrate the model, based on data collected during the first years after installation of the water balance experimental setup (1995 and subsequent years).

Atmospheric deposition

Bulk deposition was collected using four bulk collectors placed in a meadow near the forest. Ten throughfall collectors were systematically distributed over the poplar plantation. Bulk and

throughfall collectors consisted of a polyethylene funnel (15 cm diameter) placed at a standard height of 1 m, which was attached to a 2 L polyethylene bottle. The bottles were placed below ground level to prevent the growth of algae and keep the samples cool. Nylon mesh was placed in the funnel to avoid contamination by large particles. Stemflow water was collected from at-two representative trees using spirals along the stem. Water fractions were collected and measured fortnightly from 19 April 2000 to 2 April 2002. On each sampling occasion, the volume of water in every collector was measured in the field, and the collector was then replaced with a bottle rinsed with distilled waters. For each water fraction, samples were pooled for the chemical analyses. All water samples were transported and stored at a maximum temperature of 5 °C. After the samples had been analysed for pH (ion-specific electrode), they were filtered through a 0.45 µm membrane filter. Samples were analysed within a month for Cl^- , SO_4^- , NO_3^- , and NH_4^+ by ion chromatography, for K^+ , Ca^{2+} , Mg^{2+} and Na^+ after acidifying to pH <2 (with HNO_3) by flame atomic absorption spectrophotometry, and for alkalinity by titration with HCl to pH 4.2. Element input by bulk deposition, throughfall, and stemflow was calculated by multiplying the water volume by the concentration of the element in that volume.

Unlike that of bulk precipitation, the chemical composition of throughfall water is generally altered, and it is widely acknowledged that this transformation results from (i) washing of dry deposition of aerosols and gases as well as (ii) canopy leaching, i.e., release of ions from plant tissues or canopy uptake (Parker 1983). The canopy budget method was used (Ulrich 1983; de Vries et al. 1998) to estimate the contribution of dry deposition and canopy leaching or uptake. Following Parker (1983), we calculated net stand deposition (NSD, $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$) to obtain the total effect of the canopy on deposition in the forest:

$$[1] \quad NSD = TF + SF - BD = DD + CE$$

where BD is bulk deposition, TF is throughfall, SF is stemflow, DD is dry deposition, and CE is canopy exchange.

In the canopy budget method, Na^+ is assumed to be inert with respect to the canopy, i.e., neither uptake nor leakage occurs. Furthermore, particles containing K^+ , Ca^{2+} , and Mg^{2+} are assumed to have the same deposition velocity as those containing Na^+ as expressed by a dry-deposition factor (DDF):

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

Dry deposition of K^+ , Ca^{2+} , and Mg^{2+} is then calculated as bulk deposition multiplied by this dry-deposition factor:

$$[3] \quad DD_x = BD_x \cdot DDF$$

where x is K^+ , Ca^{2+} , or Mg^{2+} ,

Canopy exchange of each base cation is calculated by subtracting the estimated dry deposition from net throughfall water.

In this paper, total deposition is defined as the sum of bulk deposition and calculated dry deposition, while total stand deposition is the measured throughfall flux.

Litter sampling and litter analyses

Fifteen circular litterfall collectors (surface area 0.29 m²) were randomly distributed over the plot. Litterfall was collected fortnightly between 20 April 2000 and 2 April 2002. The litter was separated into leaves, branches, catkins, and bud scales. These were dried in a ventilated oven at 40 °C, mechanically ground (Pulverizette 14, Fritsch, Idar-Oberstein, Germany), and stored in dark glass vials before analysis. Total litter nitrogen was measured by the Kjeldahl method. Total litter element concentrations were extracted with HNO₃ (p.a. 65%) and H₂O₂ (ultrapure) in a 3:1 ratio using microwave digestion and measured with an inductively coupled plasma atomic emission spectrometer (Varian Liberty Series II, Varian, Palo Alto, California). Digestion was performed using a microwave system (1200 MS Mega Milestone, Bergamo, Italy). Element input by litterfall was calculated for each fraction by multiplying the oven-dry mass by the element concentration,

Solute fluxes

Soil solution was collected using three suction lysimeter candles with ceramic cups at four depths (0.05, 0.2, 0.5, and 1 m). The suction cups were systematically distributed over the poplar plantation in a triangular design with about 80 m spacing. They covered a significant part of the site and were in the vicinity of the throughfall and stemflow water collectors. The water fractions of the three suction lysimeter candles at each respective depth were pooled. The element concentrations of the water in single cups were not analysed.

Water fractions were collected and measured fortnightly from 19 April 2000 to 2 April 2002. The applied suction was -50 kPa and was applied for 2 days. The element concentration in the soil water solution was used as the average concentration for the previous 14 days.

After the samples had been analysed for pH (ion-specific electrode), they were filtered through a 0.45 µm membrane filter. Samples were analysed within a month for Cl⁻, SO₄⁻, NO₃⁻ and NH₄⁺ by ion chromatography, for K⁺, Ca²⁺, Mg²⁺ and Na⁺ after acidifying to pH <2 (with HNO₃) by flame atomic absorption spectrophotometry, and for alkalinity by titration with HCl to pH 4.2.

Element percolation flux was calculated by multiplying the element concentration of the soil solution with the water fluxes calculated using the WAVE model.

Quality control

The results of the analysis of the water fractions were subjected to quality control using an ion balance. Differences in concentration ($\text{mmol}\cdot\text{L}^{-1}$) between the total charge of cations and anions are caused by the non-measurement of ions that are present in significant amounts or by inaccurate measurements.

The accuracy of the foliar and litter element analysis was checked using international reference material (CRM 100; beech leaves) for calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), and sulphur (S). Values obtained ($\text{mg}\cdot\text{kg}^{-1}$ dry mass) were for Ca 5443 (certified value 5300), Mg 878 (certified value 878), K 9814 (certified value 9600), P 1599 (certified value 1550), and S 2683 (certified value 2690).

Results

Hydrological fluxes

High rainfall inputs occurred during both study years (978 mm in year 1, 1081 mm in year 2) (Table 3). During the growing season (1 April to 31 October), precipitation was 16% higher than the long-term average in year 1 and 31 % higher in year 2. During the dormant season (1 November to 31 March) rainfall also exceeded the long-term average by 54% in year 1 and 65% in year 2. The precipitation pattern through the year differed clearly between years 1 and 2. During year 1, precipitation was more or less equally distributed over the year, while during year 2 the precipitation pattern was irregular, with more dry periods at the end of April and the beginning of May and high rainfall concentration in the second half of July and the first half of September. The portions of rainfall intercepted by the vegetation were comparable in the 2 years (14% and 17%), but were markedly higher during the growing season (16% and 20%) than in the dormant season (11% and 12%). Stemflow was of only minor importance in the total stand deposition (2% in year 1 and 1% in year 2). The higher precipitation in year 2 led to greater soil evaporation and runoff. During the growing season in both years, about 50% of root water uptake occurred in the top 5 cm of the soil profile. Another 30% was taken up between 5 and 30 cm depth.

The hydrological model WAVE was used to calculate the soil water fluxes and it also provides the soil water content at different depths. These can be tested against the measured values to validate the model, as illustrated in Fig. 1.

The groundwater table was permanently above - 50 cm during the dormant season (Fig. 2). From the beginning of April in year 1 and the beginning of May in year 2 it dropped below -50 cm to attain its deepest level in August (-366 cm in year 1 and -446 cm in year 2).

Atmospheric deposition

Nitrogen

Total inorganic nitrogen for bulk deposition and total stand deposition was 1.27 and 1.33 kmol·ha⁻¹, respectively, in year 1 and 1.06 and 1.41 kmol·ha⁻¹, respectively, in year 2. The inorganic nitrogen in both bulk deposition and total stand deposition consisted mainly of NH⁴⁺ : in year 1 only 32% of bulk deposition and 32% of total stand deposition consisted of nitrate, and in year 2 these values were 36% and 35%, respectively (Tables 4 and 5). Total stand deposition of nitrate and NH⁴⁺ were both 1.1 times higher than bulk deposition in year 1 and 1.3 and 1.4 times higher in year 2, respectively. These enrichments were not significant, however. Stemflow deposition made only a minor contribution to total stand deposition of nitrogen (Table 5).

The net stand deposition flux of ammonium was negative in the first half of May, from mid-June to mid-July, and from the end of September to mid-October in year 1, and from mid-May to mid-June

and from mid-September to the end of October in year 2 (Fig. 3). These negative net stand deposition fluxes suggest uptake of ammonium-N in the canopy.

The Kjeldahl nitrogen pool (nitrates not included) in the mineral soil down to 1 m depth is estimated at 932 kmol ha^{-1} . Hence, total stand deposition represents only a small fraction of total nitrogen (0.15%).

Base cations and H^+

Total deposition, the sum of bulk deposition and dry deposition, of Mg^{2+} was equal for the 2 years, while total deposition of Ca^{2+} and K^+ was 2.0 and 1.6 times higher, respectively, in year 1 and total deposition of Na^+ was 1.5 times higher in year 2 (Table 4). Total deposition of all base cations was higher than hulk deposition in both years. Ca^{2+} and Na^+ were the most important base cations in bulk deposition. Relative to bulk deposition, Na^+ , Ca^{2+} , Mg^{2+} , and K^+ in total stand depositions, which is the sum of throughfall and stemflow flux, were significantly enriched by a factor of 2.4, 2.6, 3.2, and 12.4 in year 1 and by 2.1, 3.9, 2.8, and 14.9 in year 2, respectively. K^+ predominates in the throughfall during the growing season, while Na^+ is the most important element during the dormant season (Table 5). For all base cations, stemflow deposition made a minor contribution to total stand deposition (Table 5). Only for K^+ in the dormant season did stemflow deposition account for more than 5% of total stand deposition.

The chemical composition of throughfall and stemflow water differs from that of bulk precipitation because of (i) dry deposition of aerosols and gases in the canopy and (ii) canopy exchange, i.e., release or uptake of ions from plant tissues or canopy uptake. Canopy leaching is the most important source of potassium in throughfall and stemflow water and is responsible for 87% of K^+ in net stand deposition in year 1 and 93% in year 2 (Table 6). Sources of net stand deposition of Mg^{2+} were spread more or less equally over canopy leaching and dry deposition in both years. The composition of net stand deposition of Ca^{2+} in both years was more diverse: 91.5% of net stand deposition originated from dry deposition in year 1, while canopy leaching accounted for 63% in year 2.

Total stand deposition of protons was significantly lower than bulk deposition. On an annual basis, the forest canopy and stems neutralized 50% of the incoming protons in year 1 and 33% in year 2.

The exchangeable pool of base cations in the mineral soil (Table 1) was estimated at 655 kmol ha^{-1} for Ca^{2+} , 13 kmol ha^{-1} for Mg^{2+} , 39 kmol ha^{-1} for K^+ , and 16 kmol ha^{-1} for Na^+ . Relative to these pools, total stand deposition represents, on average, 0.1 %, 2.4%, 4.1 %, and 9.6% of Ca, Mg, K, and Na, respectively, for both years.

Sulphate and chloride

Bulk deposition of sulphate-S and chloride was significantly enriched during canopy passage by a factor of 2.2 and 3.5 in year 1 and 2.3 and 2.7 in year 2, respectively. Assuming conservative behaviour of sulphate and chloride, this enrichment has to be attributed to the dry deposition of both

elements. The bulk deposition input of chloride was twice as high in year 2 as in year 1, while total stand deposition was 1.6 times higher in year 2. Stemflow deposition was of minor importance for both elements.

The total S pool in the mineral soil is quantified as 64 kmol ha^{-1} (Table 1), while about 1 kmol ha^{-1} (1.6%) of sulphate-S is added each year by total stand deposition.

Litterfall

The total amount of litter biomass in the poplar stand was 4724 kg ha^{-1} in year 1 and 5650 kg ha^{-1} in year 2. Leaves were the main constituents of total litter biomass (72% in year 1 and 67% in year 2). The corresponding amounts of other litter fractions were 4% and 3% for bud scales, 11% and 25% for branches, and 13% and 5% for fruits, respectively. Although more biomass was returned by leaves (377 kg surplus) in year 2, the amount of leaves relative to total litter was lower than in year 1. The higher amount of litter biomass during year 2 can be attributed to the enormous quantity of branches that fell, mainly during the winter of year 2 (Table 6). There were considerably more fruits in year 1 than in year 2. The allocation of assimilates to reproductive parts in year 1 reduced the leaf litterfall (-10%).

Nitrogen return by litterfall was considerably higher than total stand deposition. The total nitrogen input (total stand deposition + litterfall) amounted to 6.6 kmol in year 1 and 6.5 kmol in year 2, of which 80% and 78%, respectively, came from litter. Also, the return of Ca^{2+} and Mg^{2+} by litter was higher than the stand deposition in both years. Total Ca^{2+} and Mg^{2+} input (stand deposition + litter) was 5.3 and 0.8 kmol in year 1 and 4.8 and 0.8 kmol in year 2, respectively. Input of Ca^{2+} by litter amounted to 83% of the total input for both years, and input of Mg^{2+} was about 60% and 65% in years 1 and 2, respectively. Total K^+ input amounted to 2.97 kmol in year 1 and 2.28 kmol in year 2, most being attributable to stand deposition.

Input of phosphorus by litter is calculated to be about 0.4 kmol ha^{-1} for both years. Concentrations of PO_4^{2-} -P in bulk deposition, throughfall, and stemflow water were not measured, since they were negligible and below detection level. The input of sulphur by litter is calculated to be 27% of total sulphur input for both years.

Relative to the soil nutrient pools down to 1 m depth, litterfall cycled, on average, 0.6% of the total nitrogen, 0.2% of the phosphorus, 2.6% of the potassium, 0.6% of the calcium, 3.8% of the magnesium, and 0.6% of the sulphur pool.

Element percolation

During the dormant season the groundwater table rose to enter the sphere of influence of the lysimeters. Therefore, the evolution of element percolation could only be studied during the growing season, based on the one-dimensional soil water fluxes provided by the WAVE model.

At 5 cm depth, small amounts of nitrate-N percolated: 50 and 10 mol ha⁻¹ in growing seasons 1 and 2, respectively (Table 7). Percolation of nitrate-N was already strongly reduced in the subsoil levels, dropping to 20-30 mol ha⁻¹ at 1 m depth during the growing season. Table 8 shows the 2 year average nitrate concentration in the soil water at four depths during the growing and dormant seasons. During the dormant season, subsoil nitrate concentrations are 1.5-5 times higher than during the growing season. This can largely be explained by the lower uptake by the poplar trees, understorey vegetation, and microorganisms.

Even in the dormant season, absolute nitrate concentrations are more than 10 times lower than the European standard for drinking water (50 mg L⁻¹ or 806 µmol L⁻¹) and may be considered very low.

Almost no ammonium-N was present in the percolation water at any depth. (Fig. 4).

The pH of the percolation water in the upper soil averaged around 7.0 during the growing season. Deeper soil layers were characterized by neutral pH values (Table 7).

Calcium percolation at 5 cm depth amounted to 2.67 and 2.17 kmol ha⁻¹ for years 1 and 2, respectively, and decreased with greater depth. At 50 cm depth, 4% of the total Ca²⁺ input in year 1 and 32% in year 2 is still leaching (2.42 and 1.53 kmol ha⁻¹, respectively) (Fig. 4). Percolation of Mg²⁺ showed the same pattern. At 50 cm depth, 31% and 20% (0.25 and 0.16 kmol ha⁻¹ yr⁻¹) of the total input of Mg²⁺ in years 1 and 2, respectively, is still present. At 5 cm depth, percolation of K⁺ had already dropped to 13% and 9% of the total input for years 1 and 2, respectively (Fig. 4). At 1 m depth, percolation of K⁺, Ca²⁺, and Mg²⁺ amounted to 3%, 7%, and 13%, respectively, of their total input in year 1. In year 2, these percentages were comparable: 4%, 9%, and 15%, respectively. These data indicate that the losses of potassium, calcium, and magnesium are small and are offset by inputs through precipitation.

The percolation pattern of sulphur differed strongly between the 2 years. In year 1, 88% of the total input of sulphur was still present in the percolation water at 50 cm depth; in year 2 this had dropped to 50%. At 5 cm depth, Na⁺ percolation quickly dropped from 1.24 and 1.26 kmol ha⁻¹ to 0.58 (47%) and 0.53 kmol ha⁻¹ (42%) in years 1 and 2, respectively. Percolation of Cl⁻ did not drop as quickly in year 2 (64%), and it even accumulated at 50 cm depth in year 1 (by a factor of 2).

The leaching of nitrates from soil at 1 m depth was less than 0,003% of the soil nitrogen pool and 0.5% of the annual litterfall input. Sodium showed the highest percolation beyond the rooting zone (100 cm), amounting to 1.6% of its total stock, while K⁺, Ca²⁺, Mg²⁺, and sulphur all leached less than 0.8% of their total soil pool.

Relative to their litterfall input, the leaching of potassium, calcium, magnesium, and sulphur beyond 100 cm was estimated to be, on average, 8.7%, 9%, 20%, and 55%, respectively.

Discussion

Plants are an integral part of ecosystem element cycling because they take up nutrients and produce biomass, which subsequently decomposes and releases nutrients (Knops et al. 2002). Plant species vary in their rates of nutrient uptake, litter quality, and efficiency in producing biomass (Knops et al. 2002). Hybrid poplars (*Populus* spp.) are fast-growing trees characterized by high biomass production (Laureysens et al. 2004) and high litter quality (Lopez et al. 2001; Perez-Corona et al. 2006). This nutrient-rich litter feeds an important earthworm population and stimulates microbial activity, resulting in a mull-type humus and good physicochemical topsoil properties (Dunger and Voigtlander 2005).

A large number of studies have monitored input and output fluxes of nitrogen and other major elements in forest ecosystems (e.g., de Vries et al. 2003; Dise and Wright 1995; Macdonald et al. 2002). Other European studies have investigated the effect of tree species on soils, and recent evidence suggests that trees can alter soils relatively rapidly (e.g., Berendse 1998; Muys et al. 1992; Reich et al. 2005). However, few studies have investigated nutrient cycling in poplar plantations under Western European conditions. This limits comparison of our results with literature data. Bulk precipitation, throughfall, and soil-solution data were collected according to the methods of the EU-UNECE (1998) sampling and analysis program for intensive monitoring. This manual was of major importance for quality control, as it provided uniform, detailed methodologies for sampling, sample treatment, and analysis.

Nitrogen input and output

Forests across Europe receive a wide range of nitrogen inputs from the atmosphere in the form of wet and dry deposition. Nitrogen input in throughfall ranges from less than $0.1 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ in northern Norway and Finland to $4.3 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ in the Netherlands and the Czech Republic (Macdonald et al. 2002), with an average input across Europe of $1.2 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$. Erisman and de Vries (2000) found that 50% of 163 investigated forest plots all over Europe received nitrogen inputs, dominated by ammonium, above $1 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$.

Although total net stand deposition of ammonium was positive in both years, the poplar canopy retained ammonium during parts of the growing season, thus diminishing total stand deposition. The aboveground uptake of wet-deposited inorganic nitrogen by forests may be in the range $1\text{-}10 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ (Harrison et al. 2000). The estimated canopy uptake ranges between $<5\%$ (Boyce et al. 1996; Wilson and Tiley 1998) and $>40\%$ of the nitrogen required for annual wood production by a deciduous forest (Lindberg et al. 1986). During the growing season, canopy uptake of ammonium-N in the poplar plantation is accompanied by the release of protons from the canopy, indicating canopy exchange of ammonium for H^+ (Neary and Gizyn 1994). This is also suggested by the negative correlation coefficient between ammonium and H^+ deposition ($r = 0.759$, $p = 0.01$).

Nitrogen input by litterfall was considerably higher than total stand deposition of inorganic nitrogen, representing 80%-83% of the total nitrogen input (sum of total inorganic stand deposition and litterfall) in years 1 and 2, respectively. Berthelot et al. (2000) found comparable nitrogen input from litterfall in a short-rotation poplar coppice.

Of the considerable total input of nitrogen (litterfall + stand deposition), only a negligible amount is percolating at 1 m depth under the poplar plantation: 0.02-0.03 kmol N-NO₃·ha⁻¹ and no N-NH₄ during the 7-month growing season. During the growing season the nitrate concentration in the soil solution never exceeded 80 μmol·L⁻¹ at 5 cm depth and 35 μmol·L⁻¹ at 50 cm depth. The average nitrate concentration in the groundwater is a factor of 1.5-5 higher in the subsoil in the dormant season than in the growing season, but absolute levels remain 10 times lower than the European standard for drinking water. Because of the restrictions imposed by the WAVE model, we cannot calculate correct seepage water fluxes during the dormant season, but the low nitrate concentrations most likely indicate no substantial nitrate leaching. These results are remarkable for Flanders, since most other studies of forest ecosystems report high percolation fluxes of nitrate to the groundwater (e.g., De Schrijver et al. 2004; Neiryck et al. 2002). Moreover, the low C/N ratio of the mineral topsoil may indicate nitrogen saturation at the site, nitrification can be stimulated, and nitrate output is strongly related to input (Macdonald et al. 2002).

What are the major sinks for nitrogen input in this poplar plantation? Most of the nitrogen from atmospheric deposition remains in the soil rather than being taken up by plants (Nadelhoffer et al. 1999), therefore the soil is considered to be the greatest sink (Davidson et al. 1992; Nadelhoffer et al. 1999). The soil organic nitrogen pool at the Balegem site is quite large relative to the total stand deposition and litterfall inputs. Vejre et al. (2003) reported nitrogen N-pools in the range 0.16-1.53 kg·m⁻² for 97 Danish forest soils. For the 102 plots of the French RENECOFOR forest soil network the median nitrogen N-stock in the upper 40 cm was 321 kmol·ha⁻¹, with a 90th percentile value of 628 kmol·ha⁻¹ (Ponette et al. 1997). The top 40 cm at the Balegem site contains 607 kmol N·ha⁻¹, which illustrates its rather large nitrogen pool.

Storage of nitrogen in a forest soil is mainly regulated by the activity of microorganisms and mycorrhizal fungi in the soil (Persson et al. 2000). According to Knops et al. (2002), nitrogen cycling within ecosystems is dominated by a microbial nitrogen loop, and soil microbes are the dominant factor structuring ecosystem nitrogen cycling. The low C/N ratio in the soil can reflect a high nitrification rate and, consequently, nitrogen storage in the soil. Owing to the rapid turnover of the poplar litter, nitrogen can become less sequestered in the forest floor and can be rapidly incorporated into the mineral soil. This nutrient-rich organic matter probably supports large populations of nitrogen-rich microorganisms, which contribute to an increase in soil nitrogen. The presence of a well-developed bacterial community in conjunction with a large earthworm biomass is probably an important factor in nitrogen storage in this poplar plantation.

No ammonium was found in the percolating water, although it was dominant in the deposition. Nitrogen sinks include nitrogen reuptake by the vegetation, microbial nitrogen immobilization, and adsorption to the soil exchange complex (in the case of ammonium). Nitrogen may also be lost in gaseous form, that is, through denitrification or ammonia volatilization, but these output fluxes are expected to play a minor role in most common forest soils (Van Miegroet et al. 1992). Even for systems with seemingly favourable conditions for denitrification, the contribution to nitrogen cycling seems to be limited (Persson et al. 2000). We have not measured the denitrification rate. However, during the dormant period several requirements for significant denitrification are present (Brady and Weil 1996): the availability of nitrate, availability of organic compounds, less than 10% oxygen because of water saturation, and soil pH >5. The temperature should range between 2 and 50 °C, with optimum temperatures between 25 and 35 °C. Average denitrification rates for forests were estimated to be 0.28 kg N·ha⁻¹·year⁻¹ (*N* = 21) for coniferous forests and 2.10 kg N·ha⁻¹·year⁻¹ (*N* = 24) for deciduous forests (Persson et al. 2000). Assuming that these average values are valid for the poplar plantation, denitrification may account for up to 17% of bulk deposition. Further research is obviously necessary.

Once ammonium is nitrified, nitrate must be quickly immobilized by the microorganisms or efficiently taken up by the trees and ground vegetation. Consequently, leaching of nitrates is negligible, since it is less than 0.0027% of the nitrogen pool.

Nutrient storage in tree biomass depends on the tree species, its biomass production, and local soil conditions. Analysis of one tree at the experimental site yielded an indicative value of 0.11% nitrogen content for the total bole (wood plus bark) (unpublished results). This is comparable to an 8-year-old, wide-spaced plantation of the same clone in the Garonne valley (Valadon and Breton 1998). With a growth rate of 23 m³·ha⁻¹·year⁻¹ and a wood density of 383 kg·m⁻³ (unpublished data), the immobilization of nitrogen in the woody biomass of the poplars amounted to 0.69 kmol·ha⁻¹·year⁻¹. This immobilization rate is, in spite of the high growth rate of poplar trees, low in comparison with calculations for other deciduous trees (e.g., 0.89 kmol·ha⁻¹·year⁻¹ for oak with a wood density of 517 kg·m⁻³, average nitrogen content of 0.30%, and growth rate of 8 m³·ha⁻¹·year⁻¹ (Van der Salm and De Vries 2000). Of the total nitrogen input, only 11% is stored in the woody biomass of the poplars. Nitrogen is stored more efficiently in foliar biomass. Analysis of leaf samples at the experimental site indicates a nitrogen content of 1.31% (unpublished data). Nitrogen storage in the leaves during the growing season is therefore approximately 3.18 kmol·ha⁻¹ in year 1 and 3.53 kmol·ha⁻¹ in year 2, or 4.6 and 5.2 times the amount immobilized in the woody biomass, respectively. We estimated that yearly understorey vegetation biomass production under a poplar canopy can vary between 1 and 2 t dry matter·ha⁻¹. Sampling and analysis of the present understorey vegetation reveals a nitrogen content of 1.79% (unpublished data), which brings the nitrogen contribution of the understorey vegetation to between 1.28 and 2.56 kmol·ha⁻¹ on a yearly basis. Yearly uptake of nitrogen by the poplar ecosystem therefore amounts to 5.15-6.78 kmol·ha⁻¹, which is very close to the total annual nitrogen input. This indicates that this poplar plantation has a very efficient nitrogen cycle, during

which very little nitrogen is leached to the groundwater.

Base cation input and output

Total deposition of K^+ and Ca^{2+} in the poplar stand was high in comparison with the average total deposition flux in the West/Atlantic plots of the pan-European programme for intensive and continuous monitoring of forest ecosystems (1997 data) (de Vries et al. 2003). For Mg^{2+} the deposition value for the poplar plot was considerably lower than reported by De Vries et al. (2003). The poplar canopy influences the composition of stand deposition through the process of dry deposition and leaching from inside the leaves or branches. The process of canopy exchange strongly depends on the season and was particularly high during the growing period. According to the canopy budget method, element leaching of K^+ from the leaves accounted for 87% of total net stand deposition in year 1 and 93% in year 2, typically with a peak in autumn, when leaves are senescent. Houle et al. (1999), Vanek and Draaijers (1994), Parker (1983), and Ragsdale et al. (1992) also reported that the leaching of K^+ is very important, and is generally over 70% on a yearly basis.

For Ca^{2+} , dry deposition is more important than canopy leaching in net stand deposition in year 1 (92%), while canopy leaching (62%) is greater than dry deposition in year 2. According to the canopy budget model, Ca^{2+} was taken up by the poplar canopy during the dormant season in year 1. This is a probable bias of the filtering approach, since in most of the literature only leaching of Ca^{2+} is reported (Houle et al. 1999; Lovett and Schaefer 1992). The major assumptions and weaknesses of the canopy budget model of Ulrich (1983) are summarized in De Schrijver et al. (2004).

For Mg^{2+} , dry deposition (57% in both years) is more important than canopy leaching. The calculated contribution of canopy leaching to net stand deposition of Mg^{2+} was higher than that of Ca^{2+} in year 1, in contrast to the results of previous research (Houle et al. 1999; Ragsdale et al., 1992; Vanek and Draaijers 1994).

Litter input of Ca^{2+} and Mg^{2+} was much higher than stand deposition in both years. The input of K^+ from litterfall represented only 42% and 35% of the total input for years 1 and 2, respectively. The K^+ input via litter decreased by 36% in year 2, mainly because of reduced fruit fall. Cole and Rapp (1981) calculated the average nutrient return in litterfall for different climatic regions. For a temperate deciduous forest a litterfall of $5399 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ was reported and a nutrient return of phosphorus, potassium, calcium, and magnesium of 0.13, 1.06, 1.69, and $0.45 \text{ kmol}\cdot\text{ha}^{-1}$, respectively. Potassium and magnesium inputs are comparable, but our data for phosphorus and calcium are higher by a factor of 3 and 2.5, respectively. Since the chemical composition of foliage depends on tree species and site (Augusto et al. 2002), the high phosphorus and calcium concentrations may be due in part to the high contents in this former agricultural soil, especially in the B_{2t} horizon (Table 1).

Few data are available in the literature concerning poplar stands, so comparisons are difficult. The K^+ input of the 4-year-old high-density poplar plantations of Lodhiyal and Lodhiyal (1997) was almost twice that of the poplar plantation in our study. Average input via litter under a 7-year-old short-rotation poplar coppice (Berthelot et al, 2000) was recorded as slightly lower for Ca^{2+} (by a factor of 0.9) and slightly higher for Mg^{2+} (by a factor of 1.1) compared with our results.

Comparison of our data with calcium concentrations in the foliage litter from the 14 tree species reported by Reich et al, (2005) shows that the poplar leaves in our plot contain much higher concentrations (not shown) and deliver an amount of calcium double the highest reported values for the small-leaved lime, *Tilia cordata* Mill., and sycamore maple, *Acer pseudoplatanus* L. This conclusion can be attributed to both the tree species and the fertility of the site (Augusto et al. 2002). Reich et al. (2005) put forward evidence that the variation in calcium concentration in green foliage, and hence in litter, is the key driver of decadal-scale change in soil properties. We did not study the earthworm community of our plot, but based on the known relationship between litter chemistry and earthworms (Hendriksen 1990; Hendrix et al. 1999; Reich et al. 2005) and our own observations, we can assume a high abundance and biomass of earthworms, with consequently positive effects on forest-floor turnover and exchangeable soil calcium (Reich et al. 2005) in the long term.

Nutrient percolation generally decreased with increasing depth. However, at 50 cm depth, all nutrients except nitrogen and potassium show relatively high percolation rates, especially in year 1. We assume that this phenomenon is related to the underlying Argic B horizon, which is quite dense and makes nutrient percolation rather difficult. Furthermore, with an increased clay content below 50 cm, more exchange sites are available to capture cations, which also results in lower percolation losses for most elements at 100 cm depth.

Indicative analysis of one tree at the experimental site revealed high base cation contents of woody biomass, 0.38% for Ca^{2+} and 0.37% for K^+ , amounting to 3 times those found by Valadon and Breton (1998). This reflects the availability of the exchangeable base cations in the soil of the former agricultural land. This brings the average yearly immobilization to $0.83 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ for both Ca^{2+} and K^+ , corresponding to 16% and 32% of the total Ca^{2+} and K^+ input, respectively (i.e., $5.1 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ for Ca^{2+} and $2.6 \text{ kmol} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ for K^+). Assuming a rotation length of 20 years for this fast-growing poplar clone, standing biomass at harvest represents $16.6 \text{ kmol} \text{ Ca}^{2+}$ and K^+ on a per-hectare basis. Losses of Ca^{2+} and K^+ as a result of torn-harvesting are greater than losses from leaching. To avoid high exports of base cations by harvesting (Huntington 2000; Likens et al. 1998; Merino et al. 2005), we recommend that the economically less valuable parts of the tree, such as the crown, be left in situ.

Sodium, chloride and sulphate input and output

Sodium, chloride, and sulphate are generally believed to behave conservatively in forest canopies. Sodium, chloride, and sulphate deposition in stand deposition is double to triple that in bulk

deposition, indicating the importance of dry deposition of these elements. Furthermore, chloride, and to a lesser degree sodium, are considered to be biologically inert in the soil, i.e., not preferentially taken up or excluded by roots. Moreover, chloride concentrations are not affected by mineral weathering (Thomas and Buttner 1998). The ability of a soil to retain sulphate by means of inorganic adsorption mechanisms has long been recognised, and adsorption of sulphate may regulate leaching of sulphur. The exact nature of sulphate adsorption in soils is, however, chemically complex. Several factors enhance sulphate adsorption, including (i) decreasing soil pH, (ii) an increase in increasing-clay content or the quantity of aluminum and iron oxides, and (iii) a decrease in organic matter (Harrison and Johnson. 1992). The relative importance of each of these factors seems to vary with soil type, and most research has been conducted on only one factor. Since it is very difficult to interpret our data set in terms of this, we do not discuss it extensively in this paper. Furthermore, our results confirm the generally accepted idea that sulphur cycling through litterfall fluxes is small compared with the total deposition flux.

Phosphorus input and output

Input by litterfall is the major input pool for phosphorus. Phosphorus concentrations in bulk, throughfall, and stemflow water were negligible and below detection level, input of phosphorus by litter in the poplar stand ($0.4 \text{ kmol} \cdot \text{ha}^{-1}$ for both years) was comparable to that in the short-rotation poplar coppice of Berthelot et al. (2000), where the phosphorus litterfall flux amounted to $0.3 \text{ kmol} \cdot \text{ha}^{-1}$. Cole and Rapp (1981) mentioned that phosphorus return in temperate deciduous forests was $0.13 \text{ kmol} \cdot \text{ha}^{-1}$. Litterfall input is about 0.2% of the total phosphorus pool in the mineral soil

Conclusions

Nutrient cycling in an 18-year-old monoclonal poplar stand on a well-drained silt-loam soil was studied. Analysis of the water budget revealed that the stemflow water flux was of minor importance and consequently also the associated nutrient load. Deposition fluxes were mainly determined by throughfall. Model calculations showed that 80% of water uptake occurred in the upper 30 cm of the soil. Ammonium-N was dominant in the bulk deposition and was partly taken up in the canopy. However, no ammonium was detected in the percolation water, which can probably be largely explained by a high nitrification rate followed by an immediate uptake and immobilization of nitrates. Evidence of leaching of potassium from the canopy during the growing season was found.

For all elements studied, nutrient return by litterfall was greater than inputs by total stand deposition. However, litterfall inputs often represent only a small portion of the soil nutrient pool at 1 m depth.

Nutrient losses below 1 m soil depth were very small compared with nutrient inputs and were easily offset by annual inputs by total stand deposition for all elements studied.

It was concluded that the poplar stand on that site was able to utilize nutrient resources, especially nitrogen, very efficiently. No evidence of significant nutrient losses was found. The

low rate of nitrate leaching suggests the potential of poplar stands for nitrogen retention and thus for preserving groundwater quality.

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Table 1. Physical and chemical characteristics of the soil at the poplar plantation site at Balegem, Belgium, in 2002.

Physical characteristics										
Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g.cm ⁻³)	Total porosity (cm ³ .cm ⁻³)	Macroporosity (cm ³ .cm ⁻³)	AWC* (cm ³ .cm ⁻³)	K _{sat} (cm.day ⁻¹)	
Ap	0-27	15	71	14	1.28	0.51	0.10	0.24	1.460	
E	27-49	13	73	14	1.57	0.42	0.02	0.27	1.460	
B ₁	49-69	11	73	16	1.51	0.46	0.09	0.24	5.476	
B _{2t}	69-81	11	71	18	1.68	0.40	0.02	0.22	5.476	
B _{3g}	81-100	12	72	17	1.72	0.41	0.04	0.13	0.903	
Chemical characteristics										
Concentration (cmol(+).kg ⁻¹)										
pH _{H2O}	Carbonates (%)	TOC ^r (%)	Nitrogen (Kjeldahl) (%)	C/N ratio	Total phosphorus (µg.g ⁻¹)	Total sulphur (µg.g ⁻¹)	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺
5.99	0.62	2.63	0.203	13	593	307	8.79	0.26	0.41	0.08
63.72	0.48	0.59	0.072	8	307	96	6.55	0.09	0.20	0.07
6.80	0.64	0.28	0.053	5	300	72	7.50	0.07	0.18	0.10
6.90	0.96	0.22	0.046	5	428	78	11.30	0.27	0.27	0.14
7.00	0.94	0.12	0.031	4	521	85	9.98	0.21	0.22	0.16

*Available water capacity (AWC) = $\theta_{FC} - \theta_{PWP}$, where FC is field capacity (pF 2.5) and PWP is plant wilting point (pF 4.2).

^r Total organic carbon

Table 2. Stand characteristics of the poplar plantation at Balegem in 2001.

Stand age (years)	18
Stocking density (number.ha-1)	189
Basal area (m ² .ha-1)	34.2
Mean DBH (cm)*	47.1
Mean tree height (m)	35.1
Volume (m ³ .ha-1)	412
Leaf area index (m.m-2)	3.6

*Diameter at breast height (1.30 m)

Table 3. Components of water balance and percolation flux (mm) in the poplar stand at Balegem.

	<u>April 2000 - March 2001</u>			<u>April 2001 - March 2002</u>		
	Growing season	Dormant season	Total	Growing season	Dormant season	Total
Bulk deposition	538	440	978	610	471	1081
Throughfall	445	382	827	483	407	890
Stemflow	9	8	17	3	7	10
Total stand precipitation	454	390	844	486	414	900
Interception evaporation	84	50	134	124	57	181
Calculated transpiration	369.5	21.5	391	372.9	21.2	374.1
Calculated soil evaporation	56.9	19.2	76.1	65.8	89.8	155.6
Calculated runoff	1.9	54.5	56.4	26.7	108.4	135.1
Total fux						
At surface level	395.2	316.3	711.5	393.5	215.8	609.3
At 5 cm depth	205.8	302	507.8	222.4	204.2	426.6
At 20 cm depth	94.2	294.6	388.8	115.7	193.5	309.2
At 50 cm depth	63	285.7	348.7	98.3	181.8	280.1
At 100 cm depth	46.1	274.7	320.8	93.1	167.2	260.3

Note : The growing season is 1 April to 31 October and the dormant season is 1 November to 31 March.

Table 4. Bulk deposition, dry deposition, and total deposition at the poplar stand at Balegem.

	Season	mm	H ⁺	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	HCO ₃ ⁻	SO ₄ ²⁻ -S	Cl ⁻	NO ₃ ⁻ -N	NH ₄ ⁺ -N	ΣN
Bulk deposition (kmol.ha-1)													
Year 1	Growing	538	0.10	0.23	0.06	0.11	0.26	0.80	0.26	0.24	0.26	0.64	0.90
	Dormant	440	0.30	0.14	0.03	0.03	0.26	0.20	0.17	0.21	0.14	0.23	0.37
	Total	978	0.40	0.37	0.10	0.14	0.52	1.00	0.43	0.45	0.40	0.87	1.27
Year 2	Growing	610	0.20	0.12	0.05	0.07	0.40	0.40	0.22	0.39	0.22	0.38	0.60
	Dormant	471	0.10	0.09	0.06	0.03	0.48	0.40	0.22	0.53	0.16	0.30	0.46
	Total	1081	0.30	0.21	0.11	0.10	0.88	0.80	0.44	0.92	0.38	0.68	1.06
Dry deposition (kmol.ha-1)													
Year 1	Growing			0.30	0.08	0.14	0.32		0.36	0.65			
	Dormant			0.24	0.08	0.06	0.43		0.17	0.46			
	Total			0.54	0.13	0.20	0.75		0.53	1.11			
Year 2	Growing			0.12	0.05	0.07	0.40		0.34	0.65			
	Dormant			0.10	0.07	0.04	0.57		0.23	0.69			
	Total			0.23	0.12	0.11	0.98		0.57	1.34			
Total deposition (kmol.ha-1)													
Year 1	Growing			0.53	0.14	0.25	0.58		0.62	0.89			
	Dormant			0.38	0.08	0.09	0.69		0.34	0.67			
	Total			0.91	0.23	0.34	1.27		0.96	1.56			
Year 2	Growing			0.24	0.10	0.14	0.80		0.56	1.04			
	Dormant			0.19	0.13	0.07	1.05		0.45	1.22			
	Total			0.44	0.23	0.21	1.86		1.01	2.26			

Note : The growing season is 1 April to 31 October and the dormant season is 1 November to 31 March.

Table 5. Canopy exchange, throughfall, and stemflow deposition, total stand, and net stand deposition (H^+ in 10^{-4} kmol.ha $^{-1}$) in the poplar stand at Balegem.

Season		mm	H^+	Ca^{2+}	Mg^{2+}	K^+	Na^+	HCO_3^-	SO_4^{2-} -S	Cl $^-$	NO_3^- -N	NH_4^+ -N	ΣN
Canopy exchange (kmol.ha $^{-1}$)													
Year 1	Growing			0.11	0.09	1.32	0.00						
	Dormant			-0.06	0.01	0.06	0.00						
	Total			0.05	0.10	1.38	0.00						
Year 2	Growing			0.26	0.07	1.17	0.00						
	Dormant			0.12	0.02	0.12	0.00						
	Total			0.38	0.09	1.29	0.00						
Throughfall (kmol.ha $^{-1}$)													
Year 1	Growing	445	0.10	0.62	0.22	1.53	0.56	1.80	0.60	0.87	0.22	0.50	0.72
	Dormant	382	0.10	0.31	0.09	0.14	0.67	0.40	0.33	0.65	0.19	0.39	0.58
	Total	827	0.20	0.93	0.31	1.67	1.23	2.20	0.93	1.52	0.41	0.89	1.30
Year 2	Growing	483	0.10	0.50	0.17	1.29	0.79	1.20	0.56	1.03	0.26	0.44	0.70
	Dormant	407	0.10	0.30	0.14	0.18	1.04	0.30	0.44	1.21	0.22	0.46	0.68
	Total	890	0.20	0.80	0.31	1.47	1.83	1.50	1.00	2.24	0.48	0.90	1.38
Stemflow deposition (kmol.ha $^{-1}$)													
Year 1	Growing	9	0.00	0.02	0.01	0.05	0.02	0.05	0.02	0.02	0.01	0.01	0.02
	Dormant	8	0.00	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.00	0.01	0.01
	Total	17	0.00	0.03	0.01	0.06	0.04	0.06	0.03	0.04	0.01	0.02	0.03
Year 2	Growing	3	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.01
	Dormant	7	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.02
	Total	10	0.00	0.01	0.00	0.02	0.02	0.00	0.01	0.02	0.01	0.02	0.03
Total stand deposition (kmol.ha $^{-1}$)													
Year 1	Growing	454	0.10	0.64	0.23	1.58	0.58	1.85	0.62	0.89	0.23	0.51	0.74
	Dormant	390	0.10	0.32	0.09	0.15	0.69	0.41	0.34	0.67	0.19	0.40	0.59
	Total	844	0.20	0.96	0.32	1.73	1.27	2.26	0.96	1.56	0.42	0.91	1.33
Year 2	Growing	486	0.10	0.50	0.17	1.30	0.80	1.20	0.56	1.04	0.26	0.45	0.71
	Dormant	414	0.10	0.31	0.14	0.19	1.05	0.30	0.45	1.22	0.23	0.47	0.70
	Total	900	0.20	0.81	0.31	1.49	1.85	1.50	1.01	2.26	0.49	0.92	1.41

Net stand deposition (kmol.ha⁻¹)

Year 1	Growing	0.00	0.41	0.17	1.47	0.32	1.05	0.36	0.65	-0.03	-0.13	-0.16
	Dormant	-0.20	0.18	0.06	0.12	0.43	0.21	0.17	0.46	0.05	0.17	0.22
	Total	-0.20	0.59	0.22	1.59	0.75	1.26	0.53	1.11	0.02	0.04	0.06
Year 2	Growing	-0.10	0.38	0.12	1.23	0.40	0.80	0.34	0.65	0.04	0.07	0.11
	Dormant	0.00	0.22	0.08	0.16	0.57	-0.10	0.23	0.69	0.07	0.17	0.24
	Total	-0.10	0.60	0.20	1.39	0.97	0.70	0.57	1.34	0.11	0.24	0.35

Note : The growing season is 1 April to 31 October and the dormant season is 1 November to 31 March.

Table 6. Litterfall fractions in the poplar stand at Balegem.

Litterfall fraction and period	Dry mass (kg.ha ⁻¹)	Ca ²⁺ (kmol.ha ⁻¹)	Mg ²⁺ (kmol.ha ⁻¹)	K ⁺ (kmol.ha ⁻¹)	S (kmol.ha ⁻¹)	N (kmol.ha ⁻¹)	P (kmol.ha ⁻¹)
Leaves							
Year 1	3401	3.70	0.37	0.83	0.28	3.80	0.26
Year 2	3777	3.14	0.42	0.57	0.30	3.59	0.31
Bud scales							
Year 1	201	0.07	0.02	0.03	0.01	0.16	0.01
Year 2	186	0.06	0.02	0.02	0.01	0.14	0.01
Branches							
Year 1	527	0.43	0.02	0.05	0.02	0.26	0.01
Year 2	1410	0.74	0.05	0.11	0.04	0.86	0.04
Fruits							
Year 1	596	0.19	0.07	0.33	0.05	1.04	0.10
Year 2	277	0.08	0.03	0.09	0.03	0.54	0.05
Total							
Year 1	4724	4.38	0.48	1.24	0.35	5.26	0.38
Year 2	5650	4.02	0.52	0.79	0.37	5.12	0.40

Table 7. Percolation during the growing season (1 April to 31 October) in the poplar stand at Balegem.

	mm	pH	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	HCO ₃ ⁻	SO ₄ ²⁻ -S	Cl ⁻	NO ₃ -N	NH ₄ ⁺ -N	ΣN
Percolation (kmol.ha ⁻¹)												
At 5 cm												
Year 1	-205.8	7.4	-2.67	-0.69	-0.37	-1.24	-5.46	-1.02	-1.04	-0.05	0.00	-0.05
Year 2	-222.4	7.3	-2.17	-0.55	-0.21	-1.26	-2.70	-1.33	-1.33	-0.01	0.00	-0.01
At 20 cm												
Year 1	-94.2	7.5	-1.57	-0.24	-0.14	-0.62	-1.95	-0.66	-0.89	-0.01	0.00	-0.01
Year 2	-115.7	7.4	-1.22	-0.18	-0.07	-0.56	-1.76	-0.46	-0.68	0.00	0.00	0.00
At 50 cm												
Year 1	-63	7.4	-2.42	-0.25	-0.01	-0.58	-1.71	-1.15	-2.05	0.00	0.00	0.00
Year 2	-98.3	7.4	-1.53	-0.16	-0.01	-0.53	-1.85	-0.58	-0.85	-0.01	0.03	-0.04
At 100 cm												
Year 1	-46.1	6.9	-0.34	-0.09	-0.09	-0.23	-0.37	-0.16	-0.33	-0.02	0.00	-0.02
Year 2	-93.1	7.1	-0.41	-0.11	-0.08	-0.28	-0.29	-0.24	-0.52	-0.03	0.00	-0.03

Table 8. Average nitrate concentrations ($\mu\text{mol}\cdot\text{L}^{-1}$) in soil water at the poplar stand at Balegem during the growing and dormant seasons (average of measurements in years 1 and 2).

Soil depth (cm)	Growing season	Dormant season
5	28.2	28.6
20	12.9	61.0
50	7.3	22.6
100	9.7	13.4

Fig. 1. Measured and simulated soil water content at 25 cm depth beneath the popLar plantation at Balegem, Belgium, during measuring year 2 (1 April 2001 to 31 March 2002).

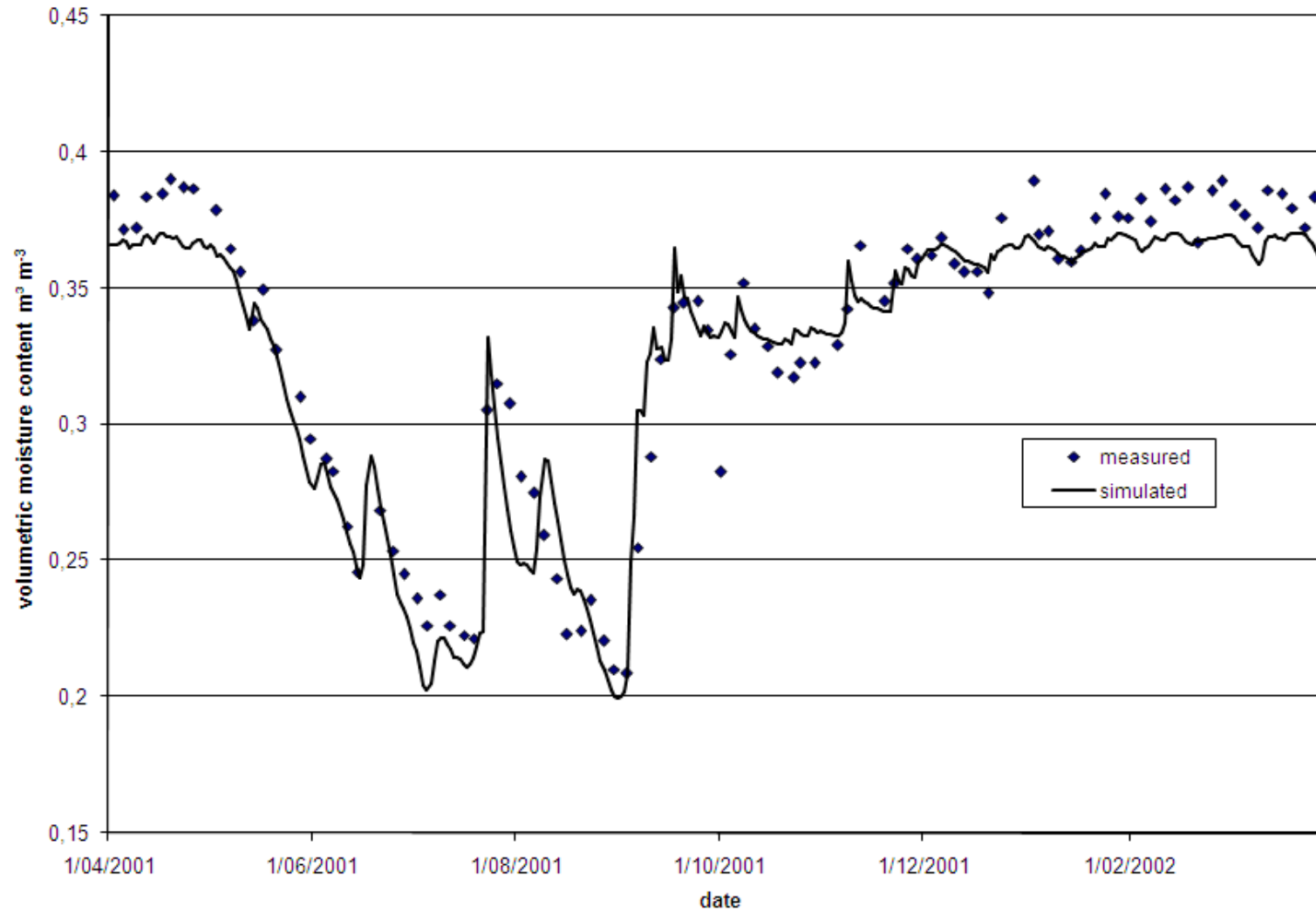


Fig. 2. Change in depth of the groundwater level beneath the poplar plantation at Balegem during the measuring period (April 2000 to March 2002).

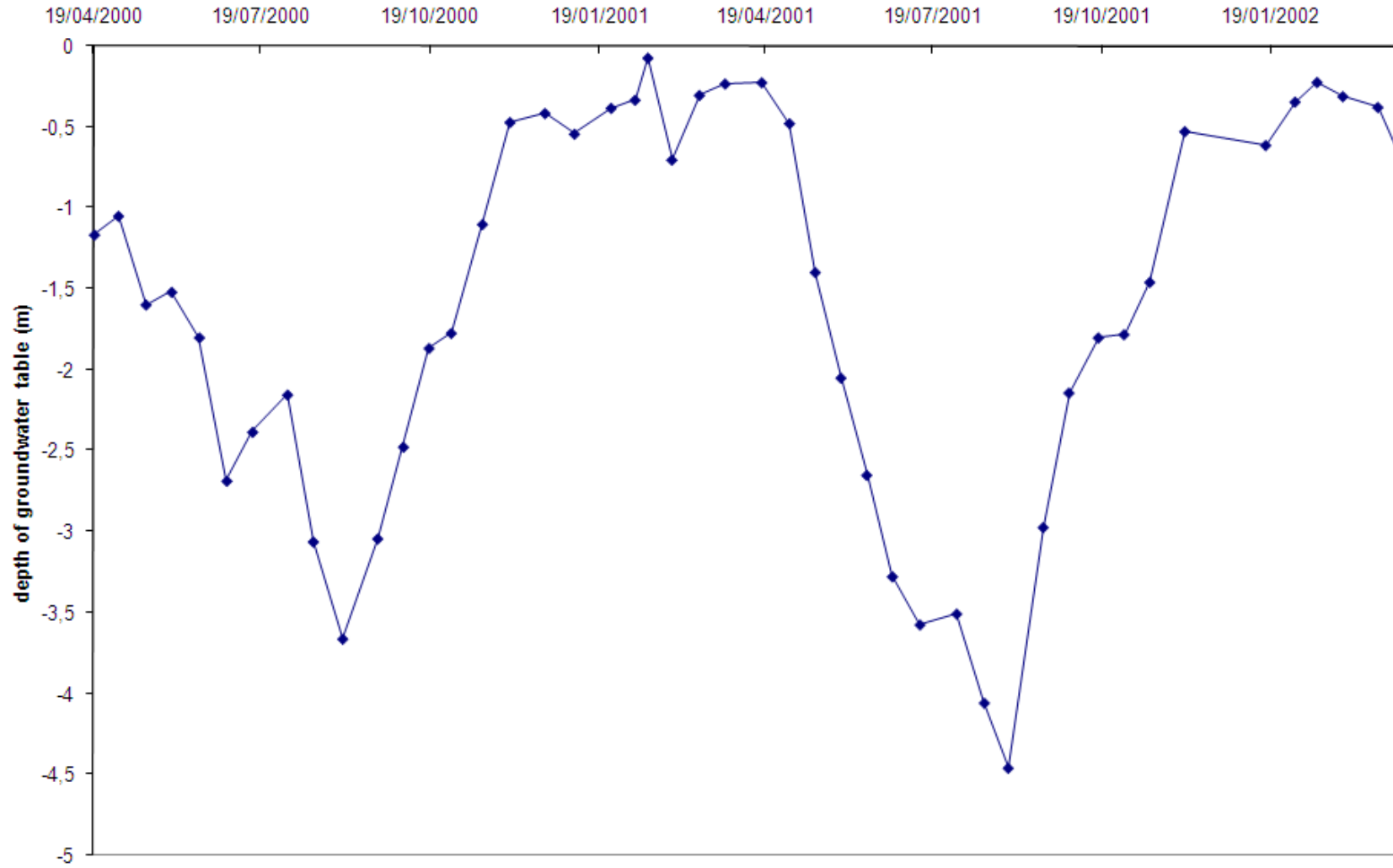


Fig. 3, Net throughfall fluxes of ammonium-N ($\text{kmol}\cdot\text{ha}^{-1}$) and protons ($\text{kmol}\cdot\text{ha}^{-1} \times 10^4$) in the poplar plantation at Balegem during the measuring period (April 2000 to March 2002).

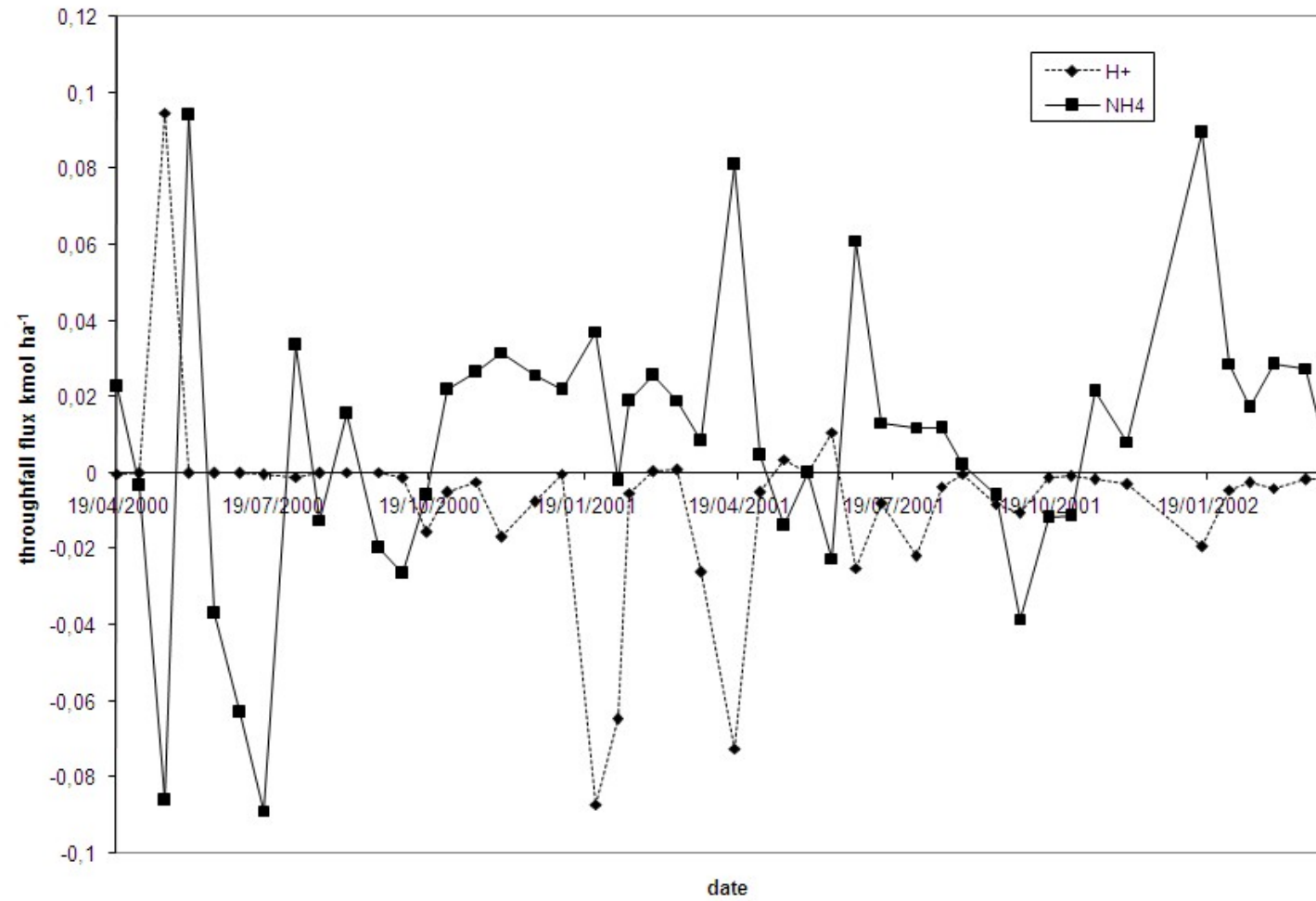


Fig. 4, Input-output fluxes of nitrogen, calcium, magnesium, potassium, and sulphur for measuring years 1 (April 2000 to March 2001) (a) and 2 (April 2001 to March 2002) (b).

