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Modelling water balance and nitrate leaching in temperate Norway spruce and beech forests located on the same soil type with the CoupModel

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Abstract

Two contrasting forest ecosystems located in close proximity to each other were selected for evaluating the importance of tree species and afforestation in relation to the water balance and the quality of the water leaving the forest root zone. Measurements included soil water content and the collection of precipitation, canopy throughfall, stem flow and soil solution on a weekly basis during 15 months (1999–2000). Soil solutions were extracted using suction probes installed at all major horizons within the upper 120 cm of a Norway spruce (N. spruce) stand (Picea Abies [L.] Karst.) and a European beech stand (Fagus Sylvatica L.) located on the same soil type. Soil solutions were analyzed for the content of all major ions, including nitrate. A water balance model (CoupModel) was used to estimate percolation rates beneath the root zone. Percolation at the beech stand was 292 mm and only 41 mm at the N. spruce stand mainly due to differences in the interception loss. The highest annual leaching of Mg, K, Na, Al, Cl, SO_4-S was noted in the N. spruce stand while leaching of NO_3-N was highest in the beech stand, corresponding to 39 kg ha^{-1} y^{-1}. By contrast, the annual leaching of NO_3-N in the N. spruce stand was only 0.5 kg ha^{-1} y^{-1}. The larger amount of NO_3-N was leaving the beech forest soil despite the fact that the N. spruce stand had the highest atmospheric N-deposition. Thus, differences in NO_3-N leaching between the stands must be related to differences in uptake and accumulation of N in the vegetation and within the upper 120 cm of the soil. Differences in the water balance and NO_3-N leaching between beech and N. spruce stands call for further attention to the selection of tree-species on a soil type basis when planning future afforestation projects, particularly when such projects aim to improve the quality of water infiltrating to the groundwater zone.

Keywords: CoupModel, European beech, forest, nitrate, Norway spruce, water balance

1. Introduction

The number of afforestation projects is increasing due to the fact that forests can accumulate and store atmospheric carbon in biomass and due to reduced leaching of nitrate as forest ecosystems are often less fertilized as compared to conventional farming. In Denmark, the aim of afforestation of former agricultural land is mainly to protect groundwater resources, create recreational areas and establish green corridors for wildlife (Skov og Naturstyrelsen, 1999).

Input and turnover of nutrients in forests control the quality of percolating water. Nitrogen (N) has been intensely studied due to its dual role as a vital nutrient for vegetation and as a contaminant in groundwater. N circulation in particular is closely related to the cycling of carbon, due to the fact that almost all N in the forest ecosystem is stored in organic form and in the same pools as carbon. Anthropogenic inputs of atmospheric N over the last 30-40 years in European temperate forests may have led to a decline in forest growth and elevated levels of NO_3-N leaching from forests caused by N-saturation of the ecosystem (Aber, 1992; Aber et al., 1998; Callesen et al., 1999; Dise & Wright, 1995; Gundersen, 1991; Nihlgård, 1985).

Groundwater recharge is controlled by the combination of atmospheric, soil and plant related processes. Deciduous forest ecosystems generally yield more water and of better quality as groundwater than coniferous forest ecosystems due to the smaller atmospheric deposition in the canopy (Hansen, 2003). But factors such as stand age and plot can have an adverse effect on the composition of soil water (Callesen et al., 1999). Despite the fact that afforestation of former agricultural land will alter the hydrological cycle and water balance, knowledge about changes of the amount of percolation and the quality of the soil water in forests due to afforestation is scarce. This is partly due to the fact that quantitative estimates of evapotranspiration is technically complicated and associated with uncertainty in measurement procedure (Wilson et al., 2001).

One way to quantify the constituents of the water balance in forest ecosystems is to use water balance models based on soil, vegetation and atmosphere characteristics (SVAT-models). These models consider the interaction between meteorology, vegetation and the soil and may after acceptable calibration and validation produce outputs regarding evapotranspiration, percolation and other variables difficult to measure in the field. Another advantage of SVATs is that different types of vegetation can be compared under the same climatic conditions. The CoupModel is a well-established SVAT-model (Jansson & Halldin, 1979), which has been revised several times since (Jansson & Karlberg, 2004). The CoupModel was originally developed for Swedish forest ecosystems, and has been developed to encompass most types of ecosystems. For a comprehensive list of works including usage or descriptions of the CoupModel, see Jansson Karlberg (2004). Recently, Ladekarl et al. (2005) used the CoupModel to calculate the water balance in oak, heath and agricultural ecosystems. Measurements of the water content of the soil provide a basis for evaluating the performance of the model and estimating the water balance of different ecosystems that have well defined boundary conditions (Alvenäs & Jansson, 1997; Bouten & Jansson, 1995; Eckersten et al.; 1995, Jansson et al.; 1999a Ladekarl et al.; 2005).

The main aims of this paper are firstly to quantify the water balance, using the CoupModel, in two contrasting forest ecosystems, N. spruce (Picea Abies [L.] Karst.) and European beech (Fagus Sylvatica L.) located on the same soil type, and secondly, to quantify and discuss the total and seasonal trends of the leaching of cations and anions with a focus on NO_3-N from the two forest ecosystems.

2. Materials & Methods

2.1. Site description

The study site is located near Nødebo in the northern part of Zealand (55°N, 12°E), Denmark, and is described in detail by Elberling & Ladegaard-Pedersen (2005). Two contrasting forest stands located within 2 ha of each other were selected: deciduous beech (Fagus Sylvatica L.) and coniferous common or N. spruce (Picea Abies [L.] Karst.) (Fig. 1). The beech forest stand was planted in 1977 and has been growing at a rate of 8 – 9 m^3 ha^{-1} yr^{-1} to an average height of 9 m (in 2003). The N. spruce stand was planted in 1959 and has been growing at a rate of 16 – 17 m^3 ha^{-1} yr^{-1} to an average height of 23 m (in 2003). The number of trees and current live aboveground volume of beech and N. spruce wood has been estimated to be approx. 600 trees ha^{-1} and 145 m^3 ha^{-1} and approx. 300 trees ha^{-1} and 387 m^3 ha^{-1}, respectively (personal comm. with forest ranger S. Løw, 2003). The forest is a production forest where 10 – 20% of the above ground biomass is cut every 4 – 5 years. Under-storey vegetation is scarce in both forest stands. No fertilizer has been used.

The forest stands are situated on ice marginal hills and sandy ground till from the Weichsel ice age with very low or no slope in the study area. Soils have been classified as Typic Udorthents according to Soil Taxonomy (Soil Survey Staff, 1997), the texture is predominantly loamy sand, and stones of varying sizes are present in the soil. The main soil characteristics are presented in table 1.

The climate is temperate humid with a mean annual temperature of 8.2 °C (1961-1990). The mean annual precipitation was approx. 657 mm with an annual potential evapotranspiration of approx. 571 mm (DMI, 2000). Values were calculated by DMI using interpolation algorithms established for 10 km x 10 km grids covering the whole country. Algorithms were based on measurements (1961 – 1990) for meteorological stations distributed evenly in Denmark. Meteorological measurements at the study site were conducted from the beginning of November 1999 until the beginning of February 2001.

2.2. Measurements of precipitation, throughfall and stemflow

Precipitation was collected in a plastic funnel with an area of 213 cm^2 placed 35 cm above the ground in a clearing. The sampling containers were placed in pits to limit biological activity. Throughfall (TF) was collected in two plastic funnels in each stand with an area of 213 cm^2 and connected to an open plastic container by a tube. The TF containers were also placed in a pit. Filters were put over the top of the containers to avoid leaves and animals contaminating the sample. The stemflow (SF) was collected through a 1 m long PVC tube wrapped 1.5 times around the trunks of two separate trees in each stand and sealed with silicone along the trunk to avoid water running beneath the tube. Holes of 5 mm were drilled at 8 cm intervals in each tube and equipped with water filters at the beginning. The tubes were connected to a closed bucket on the ground. Water sampling occurred weekly, but every second week in January and February 2000. The sampling frequency was changed to every third week from June 2000.

2.3. Measurements of soil water content

Soil water content was measured using TDR (Time Domain Reflectometry) using the approach suggested by Topp et al. (1980). In November 1999 three sets of TDR-probes, 20, 40, 60, 80 and 120 cm in length and

5 mm in diameter, were installed in each tree stand vertically in the mineral soil after removal of the O-horizon. After installation of the probes, the O-horizon material was carefully put back into place. Thus, soil water content measurements represented integrated measurements in the intervals 0-20, 0-40, 0-60, 0-80 and 0-120 cm. Measurements were made with a Tektronix 1502C cable tester (Tektronix, 1999). Subsequently, data was processed with AUTOTDR (Prenart Equipment Aps, Denmark) to estimate water content in volume percentage. Water content was measured at least weekly in both stands from November 6, 1999 to February 16, 2001. Afterwards, the water content measurement was converted to depth-specific water storage in mm.

2.4. Collection of soil samples and soil solution

Intact depth-specific and volume-specific (100 cm^3) soil samples (3 replicates) were collected in October 2000 at 5 cm depth intervals within each horizon to a depth of 1 m. Soil samples were kept cold and dark until analyzed.

Soil solution was extracted using teflon lysimeters of the type PRENART SUPER QUARTS (Prenart Equipment Aps, Denmark) with a pore size of 2 μm. One lysimeter in each horizon was installed using slurry of the horizon specific soil and double ion-exchanged water in November 1999. In the beech stand the lysimeter was installed at the following depths: 8, 17, 30, 48 and 70 cm. In the N. spruce stand the lysimeter was installed at depths of 6, 20, 35 and 76 cm. Water collected at depths 70 and 76 cm is assumed to reflect the amount and quality of water leaving the root zone and will be used in the calculation of leaching. Field observations (Elberling & Ladegaard-Petersen, 2005) suggested that root densities below 70-80 cm in both stands were very low, supporting the assumption that lysimeter installed at this depth sampled water lost from the root zone. A suction of –35 kPa was used to extract soil solution at 20 second intervals with a period of 60 seconds in between extractions. The sampling containers were placed inside a wooden box, buried in the forest floor in order to limit the suction required to extract water, avoid freezing and suppress biological activity. Water samples were placed in a dark room at 5 ºC shortly after extraction and sub-samples for analysis were taken within 24 hours of sampling. Sampling of the accumulated amounts of soil water followed the time schedule of TF with the exception that sampling of soil solution in the N. spruce stand terminated in July 2000.

2.5. Laboratory analyses

Soil pH was measured in distilled water (1:2.5). All other chemical soil analyses were made using only the soil fraction finer than 2 mm. Total organic carbon (TOC) was measured after acidification using the dry combustion method at 1250 °C on an Eltra SC-500 analyzer, with an accuracy of ± 0.2%. Total N was analyzed using dry combustion and infrared detection of N using a LECO FP-428, version 2.03 apparatus. The grain size distribution was analyzed after samples were oxidized with 4M H_2O_2 to remove organic matter. After drying, samples were sieved through meshes of 63, 125, 250, 500, 1000 and 2000 µm. The fraction finer than 20 µm was analyzed using a hydrometer (Gee & Bauder, 1986). Soil water retention curves were obtained using a pressure membrane apparatus at pressures equivalent to 10, 100, 1000 and 15,000 cm of water corresponding to pF 1.0, pF 2.0, pF 3.0 and pF 4.2 (Klute, 1986).

Conductivity and pH of the recovered water was determined upon return to the laboratory the same day. This was also the case for the alkalinity, which was determined by titration of HCl. The rest of the water was kept at 5°C and dark until analyzed. Total dissolved Fe, Mn, Mg, Ca, K, and Na were determined on acidified water samples using atomic absorption spectroscopy and Cl, NO_3 and SO_4 were determined on water samples of non-preserved water using ion chromatography.

2.6. Meteorological variables

Measurements of meteorological data were collected in a nearby forest, Stenholt Vang, located 2 km from the Nødebo site. At Stenholt Vang a 10 m mast was installed in a clearing and measurements were made at 15 minute intervals (described by Hansen, 2003) and used as input values in the modelling for both stands. The meteorological variables include: precipitation at 2 m wind speed at 10 m, relative humidity at 2 m, global radiation at 2 m in and air temperature at 2 m. In this study the meteorological variables have been modified to represent daily means of wind speed, relative humidity, global radiation and temperature.

Precipitation is represented as daily accumulation in mm. Fig. 2C shows the temporal variation of precipitation (mm) from 1999 – 2001 measured at Stenholt Vang (see Hansen, 2003). Annual observed precipitation in 2000 was 798 mm. The maximum input of daily precipitation (53 mm) occurred on September 2. The pattern of precipitation showed no distinct trend during the year, but daily inputs of precipitation exceeding 30 mm all occurred from June – September.

2.7. Model description and setup

The CoupModel is a one-dimensional numerical model that takes the vegetation, soil and atmosphere into account. Evapotranspiration forms a central part of the model governing the input of water to the soil. Evapotranspiration can be divided into three parts: evaporation from the soil surface, evaporation of intercepted water in the canopy and transpiration from the plants. The actual evapotranspiration is calculated as the sum of evaporation from intercepted water, soil evaporation and transpiration. The forest canopy is represented by a single leaf concept as given by Monteith (1965), for calculation of both direct evaporation losses from intercepted water and transpiration from the leaf originating from the water uptake from the soil (Jansson & Karlberg, 2004). The actual transpiration is calculated on the basis of the potential transpiration given by the Penman-Monteith formulation and response functions for soil and meteorological factors (Jansson & Karlberg, 2004). Soil evaporation is considered by using an energy balance approach (Alvenäs & Jansson, 1997). When modelling water balance of forest ecosystems, key input parameters include: LAI, surface resistance of canopy, vertical root distribution and soil hydraulic properties such as unsaturated and saturated hydraulic conductivity (Jansson et al., 1999b).

Input variables included air temperature, wind speed, global radiation, relative humidity and precipitation. The flow of water in the soil is calculated on the basis of Richard's equation using an explicit numerical solution using finite differences either with a forward or a central difference scheme (Jansson & Karlberg, 2004). In the CoupModel the soil was divided into eight layers, 0 – 0.2, 0.2 – 0.4, 0.4 – 0.6, 0.6 – 0.8, 0.8 – 1.2, 1.2 – 1.6, 1.6 – 2.0 and 2.0 – 2.5 m for each stand. The grain size distribution and retention curve observed for each of the horizons provided the basis for estimating the hydraulic properties. Hydraulic properties (lambda [shape parameter of the water retention curve], air entry, residual water, wilting point, turtuosity, matrix and total conductivity) were calculated in the CoupModel using the Brooks-Corey formulation for the retention curve and the Mualem formulation for the hydraulic conductivity (Jansson & Karlberg, 2004). Retention curves and texture analysis were made only on samples from one pit in each stand. Thus, it was not possible to determine statistical differences between stands. As retention measurements at pF 4 failed for the N. spruce stand and due to similarities in textural properties for the two stands, soil characteristics for the beech stand were used for both stands. LAI was used to estimate the interception capacity of canopy precipitation and also the partitioning of the global short wave radiation between canopy and soil surface. The vertical root distribution defines the zone from which water uptake occurs and therefore the amount of water available for transpiration.

Adjustment of surface resistance, soil physical properties (lambda and turtuosity), water capacity per LAI and temperature coefficients controlling water uptake by plants were based on observed values of the volumetric water content of the soil. All parameter values used to adjust the CoupModel are given in table 2a and table 2b. Model performance was evaluated on the basis of the coefficient of determination for a linear regression between simulated and observed values (R^2), root mean square error (RMSE) and the mean error (ME). Statistical results of the model simulations are shown in Table 3.

The simulation runs from July 10, 1998 to August 9, 2001 with daily output values. The investigated period was the year 2000. Measurements of mean water content in 0 – 20, 0 – 40, 0 – 60, 0 – 80 and 0 – 120 cm through the entire period were used to fit the model to observed data. Measurements of meteorological variables (see section 2.6) were assumed to be similar for both stands and used as input accordingly. Information about the vegetation was taken both from the Nødebo site (tree height, root distribution) and a location in Jutland named Ulborg (Hansen, 2003). The tree heights were set to 9 m in the beech stand and 23 m in the N. spruce stand. Absolute value of canopy resistance has been modified according to tree species and annual variations simulated as suggested by Person & Lindroth (1994). Water uptake was defined as a pressure head approach, where water uptake is calculated on the basis of response functions for water content and soil temperature (Jansson & Karlberg, 2004). The start of the growing season (and the corresponding water uptake) was defined with a trigging temperature approach (Jansson & Karlberg, 2004). The growing season began when the day length exceeded 10 hours and the accumulated temperature was above 9 ºC. It ended when the day length became less than 10 hours. As the beginning and end of the growing season is determined on the basis of meteorological variables the length of the growing season is identical for the N. spruce and beech.

Water leaving the lower boundary was used as a measure of the percolation from the forest ecosystem. Outputs of percolation are used to estimate leaching of elemental fluxes from January – December 2000.

2.8. Calculation of elemental fluxes in stemflow, throughfall and soil water

The annual input of the elements (Ca, Mg, K, Na, Fe, Al and Cl, SO_4-S, NO_3-N) in TF in kg ha^{-1} y^{-1} was calculated by multiplying the concentration of elements (mg L^{-1}) by the amount of water collected in the funnel converted to mm ha^{-1}. For the input of elements from SF, it was assumed that the tree from which SF was collected was representative of the entire stand. The number of trees ha^{-1} was multiplied by the amount of water collected (in L) and afterwards multiplied by the concentration (mg L-1) and converted to kg ha^{-1} y^{-1}. Seasonal trends and total leaching of the elements were calculated using model output of percolation (mm day^{-1}). The soil water was continuously extracted and sampled roughly on a weekly basis. Observed element concentrations in extracted soil water were assumed to represent the mean concentrations during the extraction time. Subsequently, daily values of percolation were multiplied by element concentrations to calculate daily values of leaching and finally converted to monthly and annual values.

2.9 Statistical analyses

Statistical analyses applied in this paper included simple linear regression calculating Pearson's coefficient of explanation, R^2 (Eq. 7), on observed pairs of values (Jansson & Karlberg, 2004). Significance was tested using a 95% confidence level, and relationships were significant if $R^2_{obs} > R^2_{crit95\%}$ implying the $p \leq 0.05$. $R^2_{crit95\%}$ were looked up in a table containing critical Pearson's coefficients of explanation. Furthermore, mean error (ME) and root mean square error (RMSE) used in this paper were calculated using the CoupModel.

Mean error was calculated using the following equation:

$$\frac{\sum sim(i) - \sum obs(i)}{n}$$

where sim(i) and obs(i) are the values at the i'te observation and *n* is the number of observations.

Root mean square error was calculated according to the following equation:

$$\sqrt{\frac{\sum (sim(i) - obs(i))^2}{n}}$$

where sim(i) and obs(i) are the values at the i'te observation and *n* is the number of observations.

3. Results

3.1. Observed and simulated water content

Time series of measured soil water storage (SWS) in mm for beech and N. spruce are shown in Figs. 2A and B. The temporal variation of SWS is similar for both stands and shows a distinct trend with the highest values during winter and spring, consistent with precipitation events, declining during May and reaching minimum values through the summer and early autumn. For the upper two layers the level of soil water (16 – 133 mm) storage is equal in both stands. The difference between the stands increases with depth. For the entire soil profile (0 – 120 cm) the level of SWS for beech is between 137 – 320 mm and 107 – 272 mm for N. spruce. The simulated SWS is shown as solid lines and reveals an acceptable fit to observations (Fig. 2 and Table 3) and within the error bars for replicate measurements observed for the 0 – 120 cm layer. The coefficient of determination for a linear regression (R^2) between observed and simulated water contents in the entire soil profile (0-120 cm) is 0.97 ($p<0.001$) for beech with a ME of –2.7 mm, equalling 1% of the mean simulated SWS. For N. spruce R^2 is 0.91 ($p<0.001$) with a ME of – 3.5 mm (2% of mean simulated SWS).

3.2. Water balance simulations

Simulated yearly outputs (Table 4) and monthly values of precipitation (P), actual transpiration (Et), actual interception evaporation (Ei), actual soil evaporation (Es) and percolation (A) (Figs. 2A, B and C) reveal important differences between the two tree species. Fig. 3A shows P on a monthly basis in the year 2000, which shows that there is no tendency in the variation of P during the year. Fig. 3B shows the monthly water balance for beech. Actual evapotranspiration (Ea), the sum of Et, Ei and Es, shows a clear temporal variation with the highest values (71 – 112 mm) from May – September. Actual evapotranspiration exceeds P from May – August, except in June. For beech, Et and Ei is low (0 – 2 mm) from January – April, thus Es dominates evaporation from February – April. From May – July, Et increases (34.5 – 86.4 mm) and gradually decreases (67.3 – 3.5 mm) from August – November and becomes very low in December (0.1 mm), whereas Ei remains relatively constant (14.9 – 32 mm) from May – November. The annual share of Ea in relation to P is 68% and equals 581 mm. Interception loss contributes with 18% of P equalling 158 mm on an annual basis. The annual Et is 339 mm, which constitutes 40% of P. Annual Es is four times lower than Ea and contributes annually with 10% of P (equal to 84 mm). In relation to Ea the shares of Ei, Et and Es are 27%, 58% and 14% respectively. The annual percolation from the beech stand is 292 mm and constitutes 34% of P. From February – April, the percolation is at a maximum (54 – 80 mm per month), it declines from May – August (33 – 6 mm) and reaches a minimum from September – December of 4 – 2 mm per month. Table 4 shows that throughfall (TF) equals soil surface infiltration (SI), thus indicating that surface runoff is unlikely and is consistent with lack of surface runoff as observed in the field.

Fig. 3C shows the water balance for the N. spruce stand. Generally, the temporal variation of Ea is much like that for beech except that Ea values are several times higher in January – March than what was calculated for the beech stand. Ea reaches the maximum from May – September (81 – 136 mm). The minimum Ea occurs in January at 28 mm. As opposed to the beech stand, Ei remains high throughout the year (23 – 43 mm). Transpiration in the N. spruce stand generally shows the same temporal variation as in the beech stand and values are higher in most cases. From April – July, Et increases from 12.3 – 80 mm, it remains constant through August – September (63 – 67 mm), declines to 15 mm in October, and reaches the minimum in November and December (0.2 – 3.1 mm). Es is constantly low and varies little (0.2 – 6.2 mm) throughout the year. The annual Ea is 823 mm and constitutes 96% of P. The annual interception loss is 396 mm, which equals 46% of P. The annual Et is 388 mm (45% of P). Soil evaporation amounts to 39 mm and constitutes only 5% of P on an annual basis. The division of Ea into the shares of Ei, Et and Es shows that Ei and Ea contribute equally with 48% and 47% of Ea, and Es constitutes 5%. Annual TF (464 mm) equals soil infiltration (SI).

As the input of water is the same in N. spruce and beech it can be deduced that the percolation in the N. spruce stand is lower. The annual percolation from spruce is 41 mm, which constitutes only 5% of P. The temporal variation of percolation on a monthly basis is shown in Fig. 3C. The percolation is at a maximum from May – July (6 – 8 mm) and is low (1 – 3 mm) from January – April and October – December. It is seen that the maximum of percolation is displaced in both stands compared to the minimum of Ea at the beginning of the year. This is due to the fact that the percolation is a measure of the water flow at 2.5 m depth and thus delayed compared to inputs at the surface.

3.3. Element concentrations and fluxes in throughfall, stemflow and soil water

Table 5 shows the annual mean concentrations (mg L^{-1}) and fluxes (kg ha^{-1} y^{-1}) of Ca, Mg, K, Na, Fe, Al and Cl, SO_4-S, NO_3-N in TF, SF and soil water below the root zone (see section 2.4) for the beech and N. spruce stands. Concentrations of elements in TF from the spruce stand generally exceed those in the beech plot. This is reflected in the fluxes of TF as all elements, except Al, show the largest flux in the N. spruce stand. Sodium and Cl fluxes between the two stands from TF are notable, as the input of Cl and Na is three times higher in the N. spruce stand. As it can be concluded from Table 5, the flux from SF is less than 10% of the flux from TF in both stands for all elements. The flux from SF of Mg, K, Al and NO_3-N is largest in beech. The amount of leaching of the different elements is generally largest in the N. spruce stand, but the leaching of Ca^{2+}, Fe and NO_3-N from beech exceeds that from the spruce. The most conspicuous differences in leaching between the two stands are seen for the following elements: NO_3-N (beech: 39, N. spruce: 0.5), Ca (beech: 65, N. spruce: 6), Na (beech: 16, N. spruce: 19), Cl (beech: 39, N. spruce: 47). The difference in leaching of NO_3-N is especially notable, because the mean annual concentration of NO_3-N (11.3 mg L^{-1}) in the beech stand equals the maximum limit of NO_3-N for drinking water in Denmark (Ministry of Environment, 1988). The consistently high concentrations of NO_3-N in the soil water, as indicated by the low standard deviation of 4.3, cause the high annual leaching of 39 kg ha^{-1} y^{-1}, while it is very small in the N. spruce stand at only 0.5 kg N ha^{-1} y^{-1} which is reflected in the low soil water concentration. The trend and magnitude of monthly leaching of NO_3-N from the beech and N. spruce stands are shown in Fig. 4. It can be seen that the leaching from the spruce stand during the whole period is several orders of magnitude smaller than the corresponding values for the beech stand, and the peak of NO3-N leaching is displaced towards the summer for N. spruce.

4. Discussion

4.1. Simulations of water balance

Fitting of the model showed that it was possible to simulate water percolation based on measurements of volumetric water content converted to water storage in mm. The statistically significant (R^2 = 0.91 – 0.97, $p<0.001$) simulations are supported by the low ME of –2.7 and –3.5 for beech and N. spruce respectively. Based on the fitting of the CoupModel it is assumed that the respective water balances are representative of the two forest ecosystems at Nødebo. The same conclusion at different locations was made by Ladekarl (2001) showing similar patterns of percolation from the forest soils. The values of percolation can therefore be used for both stands to calculate the leaching of elements (Fig. 3B and 2C).

A comparison of the water balance in beech and N. spruce reveals several distinct differences. In Table 4 the main constituents of the water balance are related to P. Actual evapotranspiration is largest in N. spruce, exceeding Ea for the beech stand by 29%. If the shares of Ei, Et and Es in relation to P are compared, the difference in Ea between N. spruce and beech is mainly due to differences in Ei. Transpiration is highest in N. spruce (45% of P) but is the same order of magnitude as in beech (40% of P). In both cases, Ei is low (5 and 10%). For Ei the shares are 18% for beech and 46% for N. spruce, thus the interception loss in spruce is more than twice of that in beech. A high interception loss in spruce forests was also reported by Alavi et al. (2001) and Mossin & Ladekarl (2003). Mossin & Ladekarl also concluded that a high interception loss would lead to low percolation. Ladekarl (2001) compared the water balances at several locations in Great Britain, Germany, France and Denmark and concluded that there was no significant difference in Et between beech and N. spruce. For the investigations listed in Ladekarl (2001) Et was in the range of 255 – 398 mm for beech forests and 204 – 400 mm for N. spruce forests, and the values simulated for the beech stand at Nødebo (Table 4) are in the same order as these values, but it is seen that the N. spruce stand at Nødebo is much lower than reported values. Ladekarl (2001) concluded that the main differences in the water balance between beech and N. spruce located on the same soil type were due to the differences in interception loss, which is also the case in this study.

Difference in interception was related to LAI and a stem/branch related component for the beach stand. Phenological observations at Nødebo (Elberling & Ladegaard-Petersen, 2005) show that the beech trees set leaf at the end of April/beginning of May and defoliate during October, which is similar to observations made at Ulborg. It is therefore assumed that the temporal variation of interception loss in beech and N. spruce at Nødebo is simulated satisfactorily.

The absolute level of interception is determined by the parameterisation of the model. A high interception will reduce TF and A. The amount of TF can indicate whether the interception is estimated correctly. The amounts of TF measured at Nødebo are 450 mm for beech and 300 mm for N. spruce. The simulated TF is 698 mm and 464 mm for beech and spruce, respectively. As the TF samplers used at Nødebo were open at the top, evaporation from the samplers is expected to reduce the collected amounts. It is not likely that evaporation from the TF funnels accounts for the entire difference between measured and simulated values. Because only two replicates of TF were installed in each stand it is possible that the true variation in TF amounts is not represented in the collected amounts at Nødebo.

Water balance simulations made for Stenholt Vang in the period of 1995 – 1997 (Bastrup-Birk et al., 2003) showed that percolation constituted between 36 and 30% of P for beech and between 26 and 22% for N. spruce. Percolation in the beech stand at Nødebo fell within these values, but was lower in the spruce stand. Both in terms of absolute amount, as compared to the nearby location of Stenholt Vang, and the relative difference between beech and N. spruce stands at different locations in Europe, the water balance for Nødebo was determined satisfactorily.

4.2. Element leaching

In order to validate the water balance, observed concentrations of Cl^- were used as a conservative element. The input and output fluxes of Cl^- exceeded the amount of any other investigated element (Table 5) and the concentration of Cl^- was higher in SW as compared to TF (Table 5). Stemflow was not considered further as the fluxes of elements were low as compared to TF (Table 5). Thus, the increase in concentration of Cl^- in the soil water could be used to calculate the loss of water due to evaporation. The ratios of Cl_{TF}/Cl_{SW} for beech and N. spruce were 0.49 and 0.31, respectively, showing that the amount of water input at the forest floor had been reduced by 51% and 69% through transpiration and soil evaporation. Using the model results (Table 4) the corresponding evaporation of TF from Et and Es was 61% and 92% for beech and N. spruce, respectively. The Cl^- approach underestimated the evaporation, and the differences in evaporation between beech and N. spruce using Cl^- concentration underestimated the calculated differences between the two stands. An explanation for this could be, that observed concentrations in TF on an annual basis cannot be compared to concentrations of Cl in soil solution as the input of Cl in TF is delayed compared to output from the root zone. Despite the inability of the Cl^- approach to validate calculated evapotranspiration it still showed that evaporation was much higher in the N. spruce stand. Subsequently, the CoupModel has been used to predict the tree-specific leaching of NO_3-N as a function of the water balance. As previously shown by Kennedy & Pitman (2004), NO_3 concentrations below the root zone in British soils have been successfully explained by differences in soil water contents and water balance.

If the same approach is used in the case of Nødebo, the concentration of NO_3-N in the water leaving the root zone can be calculated as a function of input (TF) and evaporation (Cl^-). Thus, an average concentration of 1.3 mg L^{-1} NO_3-N in TF results in a 2-fold increase in concentrations. However, the actual observed concentrations are roughly 10 times higher (Table 5), which indicates that other inputs than TF are responsible for the actual concentrations. This is in contrast to Kennedy & Pitman (2004). A NO_3-N enrichment is not seen for the N. spruce stand, which indicates that part of the added N from TF is taken up during downward transport.

The total input of elements at Nødebo is generally larger in N. spruce than in beech (Table 5), indicating that the atmospheric deposition is largest in spruce. This was also concluded by Rothe et al. (2002). The investigation published in Rothe et al. (2002) encompassed several locations across Europe and it was stated that the higher canopy deposition in N. spruce stands caused the leaching of NO_3-N to be highest in spruce compared to beech stands. Kristensen et al. (2004) showed that soil solution N was higher in conifers than in broadleaves when throughfall input of N was below 10 kg ha^{-1} y^{-1}. These findings are in contrast to the results obtained at Nødebo even though the input of N in N. spruce follows the trend presented in Rothe et al. (2002).

4.3. Forest soil N dynamics

The leaching of NO_3-N in beech is much higher than the leaching from N. spruce. This could only partly be explained by the lower percolation from the spruce stand as compared to the beech stand. Thus, differences in NO_3-N leaching from the two stands must include an analysis of the soil N dynamics in the two forest soils.

The work by Callesen et al. (1999) classified Danish forests soils on the basis of NO_3-N concentrations in soil solution. The investigation showed that >60% of the forests had an annual leaching below 2 kg N ha^{-1} y^{-1} (median concentration < 2 mg N L^{-1}) and had a low risk of leaching of NO_3-N below the root zone. Seven percent of the investigated forests had a median concentration of NO_3-N exceeding drinking water standards at 11.3 mg N L^{-1} and had a high risk of leaching of NO_3-N below the root zone. If the two stands at Nødebo are compared to the findings in Callesen et al. (1999), the N. spruce stand has a low risk of NO_3-N leaching whereas the beech stand has a large risk of NO_3-N leaching below the root zone. The high leaching of NO_3-N from the beech stand suggests that input of atmospheric N in the beech stand exceeds the rate of uptake and the forest ecosystem could possibly be saturated with nitrogen as defined in Aber et al. (1989) and Gundersen (1991). The low concentrations of NO_3-N in the lowest horizon in the N. spruce stand could indicate that N added from TF and SF and N released from decomposition is taken up by vegetation and immobilized by microorganisms during the downward transport in the soil. Gundersen et al. (2006) stated that thinning of the stand only affected the NO_3-N leaching to a minor degree, and as the latest thinning at Nødebo occurred in 1998, it is estimated that the effect of the thinning in 1998 was diminished at the start of the measurement period in December 1999.

Gundersen et al. (1998a) discussed the possibility using the C:N ratio of the forest floor to indicate the degree of NO_3-N leaching and classified the forests on the basis of the C:N ratio, with: C:N > 30 as N-limited and low risk of leaching; 25 < C:N > 30 as intermediate and moderate risk of leaching; C:N < 25 as N-saturated and high risk of leaching. Dise et al. (1998), Borken & Matzner (2004), Kristensen et al. (2004) support the findings in Gundersen et al. (1998a). Absolute amounts of leaching based on the C:N ratio were not proposed due to the great variance between locations with the same C:N ratio. The relationship between C:N of the forest floor and NO_3-N leaching was most evident for coniferous species but the use of C:N for deciduous species needs further investigation.

The low level of leaching agrees with the C:N of the forest floor in the N. spruce stand (~36) and is thus characterized as N-limited. Excess N is probably assimilated by the microorganisms and transferred to stabile pools, humus or aboveground biomass. The occurrence of NO_3-N below the root zone in the N. spruce stand reveals that the N-cycling is not completely tight and it may be expected that transport of N occurs by convective mass transfer with percolating water in larger pores, which agrees with the findings in section 4.2.

By contrast, the C:N ratio for the upper horizon in the beech stand is ~20 and is characterized as N saturated. The variation of the C:N ratio with depth shows a relative stabile C:N in the A – B2ws horizons (0 – 40 cm) and a minimum of 8 in the B3ws (37 – 57 cm), see Table 1. According to Gundersen et al. (1998a) the beech stand can be characterized as N-saturated, which agrees with the high amount of N leached. The use of C:N has mainly found application in coniferous forests, but works well at Nødebo for both types of forest.

The reason for the differences in the C:N ratio of the upper horizon is to be found in the properties of the organic substrate. At Nødebo there is no profound accumulation of an organic horizon in the beech stand but a pronounced O-horizon in the N. spruce plot. This indicates that the soil fauna decompose all newly added litter over one year in the beech stand, probably because the need for N in the microbial community has been satisfied (Johnson, 1992). This pattern is typical of nutrient-rich soils (Callesen et al., 1999). Due to the properties of N. spruce needles and the associated resistance to micrabial decomposition, input of mineral N through TF and SF has longer mean resisdence timess. Consequently, a relatively smaller amount of N are released into the soil water and consistent with an accumulation in the O-horizon.

Johnson (1992) reviewed N retention in forest soil and argued that non-biological N retention was small in acidic soils. As the soil pH_{H2O} in both stands at Nødebo varies between 3.7 – 4.9, non-biological retention of N is expected to be small. Therefore, the microbial community is expected to cause the N retention in both stands at Nødebo. The leaching of NO_3-Nin the beech suggests that the microbial community has a different composition with more nitrifying organisms responsible for release of NO_3-Ninto the soil solution (Zhong & Makeschin, 2004) than it is the case of the N. spruce stand. A constant addition of N from the atmosphere will increase the amount of nitrifying organisms and thus increase the soil solution concentration of NO_3^- (Johnson, 1992; Zhong & Makeschin, 2004). In turn, the nitrification is inhibited in the N. spruce stand due to the low concentration of NO_3-N in the soil water.

Because both stands are situated relatively close to the edge of the forest, an edge-effect (Beier & Gundersen, 1989) could play a part in the elevated concentrations of NO_3-N below the root zone. Spangenberg & Kölling (2004) found elevated fluxes of ions in TF at the forest edge and leaching. An edge-effect is only possible when winds are from an eastern direction because the two forest stands are situated in the easternmost part of the forest. It can be seen from Fig. 5 that a change toward eastern winds occurs in the spring and autumn. A deposition of N in the spring when leaves are absent in the beech stand could lead to increased amounts of N deposited directly on the forest floor compared to when the trees have leaves. In combination with low microbial activity, low vegetative uptake and high rates of water percolation in the winter and spring, the deposited N could leach into the soil and be transported unattended with the soil water beneath the root zone. Therefore, it is indicated that a certain edge-effect exists at Nødebo, at least for the beech stand. It was shown in section 4.2.that only a fraction of the NO_3-N could be explained by input from TF. It is not possible to identify a trend between the amount of input of N and leaching of N from the C-horizon. Gundersen et al. (1998b) found that NO_3-N leaching was correlated with an N-status of the ecosystem and not significantly correlated with N-deposition in coniferous and deciduous forest ecosystems, which supports the findings in this paper.

5. Conclusion

This study has shown that the CoupModel, a process oriented SVAT-model, was useful to document differences in water balance between two contrasting forest stands located in close proximity to each other on similar soil types. Using water balance modelling, chemical analysis of soil water and few geochemical parameters, a broad view of ecosystem functioning has been established, with respect to both the geochemical cycling of N and other important nutrients and the mass balance of water. It is concluded that the model outputs can be used to calculate monthly as well as annual fluxes of leaching from the root zone.

The main difference in the water balance was caused by interception loss through evaporation from the canopy, as the transpiration was in the same order of magnitude in the two species. The annual percolation was 292 mm from the beech stand and 41 mm from the N. spruce stand.

Leaching of elements in kg ha^{-1} y^{-1} was largest from the N. spruce stand and is probably due to the higher canopy deposition in spruce trees. The leaching of NO_3-N differed considerably between the two species, as NO_3-N leaching from the beech stand was 39 kg NO_3-N ha^{-1} y^{-1}, compared to 0.5 kg ha^{-1} y^{-1} in the N. spruce stand. On the basis of the leaching of NO_3-N it was concluded that the beech stand was possibly saturated with respect to N, due to excess atmospheric input of N in relation to the N uptake of the trees. By contrast, the N. spruce stand could be characterized as unsaturated with respect to N. The difference in NO_3-N leaching between the two species could be explained by several factors. The rich nutrient status of the soil in combination with a C:N ratio between 8 – 20 in the beech stand soil suggests that the need for N in the microbial community and vegetation is fulfilled through litter and soil organic matter decomposition and that the demand for external sources of N is small. Furthermore, a possible edge-effect could cause increased inputs of atmospheric N to the forest floor in the spring in the beech stand, leading to excess input of N in relation to demand. The small leaching of NO_3-N from the N. spruce stand suggests a high need for N in the vegetation and microbial community, thus increasing the retention of N. The N status of the two forest ecosystems shows that structure and functionality of the microbial community is different for the two stands, leading to differences in N retention and N leaching. The functionality and response of the two forest ecosystems in relation to the water balance and atmospheric deposition of N observed at Nødebo suggests that further attention is needed when selecting tree species for future afforestation projects.

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Tables

Table 1. Main soil characteristics at Nødebo for beech and Norway spruce, including carbon content, C:N ratio, pH(H_20), bulk density (ρ) and weight percentages of clay, silt and sand.

Beech					**Norway spruce**				
Horizons	Depth (cm)	C ($mg\ g^{-1}$)	C:N	pH (H_2O)	Horizons	Depth (cm)	C ($mg\ g^{-1}$)	C:N	*pH(H_2O)*
A1	0 – 10	53	20.8	3.7	O	8 – 0	376	36.5	3.7
E(B)	10 – 20	26	22.6	4.0	E	0 – 11	36	32.7	3.8
B2WS	20 – 37	23	22.4	4.5	B2	11 – 29	32	31.9	4.2
B3WS	37 – 57	5.3	8.0	4.8	B3	29 – 43	8.7	21.9	4.4
C1	57 – 100	0.74	11.5	4.9	C1	43 – 85	2.4	-	4.5
C2	100 – 150	1.5	30.1	-	C2	85 –	2.8	-	4.4

Horizons	Depth (cm)	ρ ($g\ cm^{-3}$)	clay (<2) %	silt (2-63) %	sand (63-2000) %	Horizons	Depth (cm)	ρ ($g\ cm^{-3}$)	clay (<2) %	silt (2-63) %	sand (63-2000) %
A1	0 – 10	0.84	6.2	25.9	67.9	O	8 – 0	-	-	-	-
E(B)	10 – 20	1.2	10.8	22	67.2	E	0 – 11	1.2	8.2	25.1	66.7
B2WS	20 – 37	1.1	11.5	22.6	65.9	B2	11 – 29	1.1	8.2	25.4	66.4
B3WS	37 – 57	1.3	10	17.2	72.8	B3	29 – 43	1.2	6.3	23.1	70.6
C1	57 – 100	1.5	9.5	17	73.5	C1	43 – 85	1.5	8.3	25.5	66.2
C2	100 – 150	1.3	9	18.3	72.7	C2	85 –	1.6	14.1	46.7	39.2

Table 2a. Parameter values used to adjust the CoupModel. Model parameters assigned to default values are not included.

Variable	Name	Unit	Beech	Norway spruce
Water Capacity Base independent of LAI	WaterCapacityBase	mm	1	0
Water Capacity per LAI	WaterCapacityPerLAI	mm m^{-2}	0.5	0.5
Within Canopy Resistance	WithinCanopyRes	s m^{-1}	0.5	0.5
Altitude of meteorological station	AltMetStation	m	50	50
Altitude of site	AltSimPosition	m	50	50
Reference height above displacement height of respective stand	ReferenceHeight	m	10	10
Rate coefficient for surface runoff from soil surface pool	SurfCoef	-	0.1	0.1
Maximum surface pool without generation of surface runoff	SurfPoolMax	mm	10	10
Minimum soil hydraulic conductivity	MinimumCondValue	mm d^{-1}	1E-4	1E-4
Latitude	Latitude	-	56	56
Critical threshold for water uptake	CritThresholdDry	cm water	1000	1000
Power coefficient for sensitivity of water uptake to potential transpiration rate	NonDemandRelCoef	-	0	0
Aggregate sorption coefficient in matrix domain	AScaleSorption	-	1	1
LAI	LAI	m^2 m^{-2}	0 – 4.5	8 – 8.5
Canopy surface resistance	Resistance surface	s m^{-1}	50 – 500	40 – 500

Table 2b. Soil physical properties used in the CoupModel for the beech and Norway spruce stands at Nødebo. Soil physical properties were calculated on the basis of retention analysis. Lambda represents a shape parameter of the water retention curve.

Depth (m)	Lambda (-)	Air entry (cm)	Saturation (%)	Wilting point (%)	Residual water (%)	Matrix cond. (mm d^{-1})	Total cond. (mm d_{-1})	Tortuosity (-)
0 – 0.1	0.195	5.3	55	6.5	0.1	3870	3870	1
0.1 – 0.2	0.188	1.5	57	6.5	0.1	5715	5715	1
0.2 – 0.37	0.186	1.0	57	6.5	0.1	4712	4712	1
0.37 – 0.57	0.228	4.0	44	2.5	0.1	3000	3000	1
0.57 – 1	0.235	2.1	42	2.5	0.09	3000	3000	1
1 – 1.5	0.266	1.2	40	2.5	0.06	3000	3000	1

Table 3. Statistical performance of the CoupModel.

Stand	Horizon (cm)	R^2	RMSE (mm)	ME (mm)	Mean measured (mm)	n
Norway spruce	0 – 20	0.82	7.0	1.1	48.6	60
	0 – 40	0.86	16.2	13.2	77.7	60
	0 – 60	0.91	13.9	6.1	116.1	60
	0 – 80	0.87	21.3	16.1	132.1	60
	0 – 120	0.91	16.7	–3.5	199.6	60
Beech	0 – 20	0.74	7.0	4.8	48.3	63
	0 – 40	0.68	22.2	19.0	79.7	63
	0 – 60	0.85	20.2	15.7	120.1	63
	0 – 80	0.93	28.0	26.5	140.1	63
	0 – 120	0.97	10.3	–2.7	231.0	63

Table 4. Annual simulated output in mm beech and N. spruce using the CoupModel. Outputs are also given as percentages of precipitation.

	Beech (mm)	% of P	**Norway spruce** (mm)	% of P
Precipitation	856	-	856	-
Transpiration	339	40	388	45
Interception loss	158	18	396	46
Soil evaporation	84	10	39	5
Evapotranspiration	581	68	823	96
Soil infiltration	692	-	461	-
Throughfall	698	82	464	54
Percolation	292	34	41	5

Table 5. Annual mean concentrations in mg L^{-1} of throughfall (TF), stemflow (SF) and soil water (SW) below the root zone for the beech and N. spruce stands. Standard deviation for the different elements is given in parenthesis. TF flux, SF flux and leaching are the corresponding fluxes in kg ha^{-1} y^{-1}. Letters indicate whether the values for the Norway spruce stand are greater than (a), equal to (b) or less than (c) the corresponding value for the beech stand.

	Beech					
	TF (mg L-1)	TF flux (kg ha^{-1} y^{-1})	SF (mg L-1)	SF flux (kg ha^{-1} y^{-1})	SW (mg L-1)	Leaching (kg ha^{-1} y^{-1})
Ca	2.3 (1.5)	10.7	2.6 (1.3)	0.23	20.7 (5.0)	64.6
Mg	0.8 (0.4)	3.5	1.3 (1.4)	0.14	1.9 (0.4)	6.3
K	1.8 (3.4)	9.5	3.0 (1.8)	0.27	0.3 (0.2)	0.9
Na	3.4 (3.5)	14.2	1.8 (8.0)	0.98	5.0 (0.9)	15.6
Fe	0.02 (0.03)	0.06	0.01 (0.02)	0.0009	0.04 (0.04)	0.1
Al	0.2 (0.3)	1.04	0.2 (0.3)	0.02	1.4 (0.4)	4.6
Cl	5.8 (6.0)	26.8	13.7 (23.2)	1.67	11.9 (4.8)	38.7
SO_4-S	1.2 (0.5)	5.7	2.0 (1.3)	0.20	4.4 (1.1)	11.4
NO_3-N	1.3 (0.8)	5.2	1.4 (0.9)	0.14	11.3 (4.3)	39.1
	N. spruce					
Ca	4.7 (2.2) (a)	14.3 (a)	12.4 (11.2) (a)	0.29 (a)	10.1 (2.3) (c)	6.4 (c)
Mg	3.9 (4.6) (a)	9.34 (a)	4.7 (6.3) (a)	0.12 (c)	9.0 (3.6) (a)	4.7 (c)
K	5.5 (5.0) (a)	15.4 (a)	10.5 (7.6) (a)	0.24 (c)	2.2 (1.0) (a)	1.5 (a)
Na	11.4 (11.5) (a)	42.5 (a)	33.0 (21.4) (a)	1.01 (a)	49.5 (22.8) (a)	18.3 (a)
Fe	0.1 (0.3) (a)	0.46 (a)	0.1 (0.1) (a)	0.002 (a)	0.1 (0.2) (a)	0.02 (c)
Al	0.2 (0.4) (b)	0.94 (c)	0.3 (0.5) (a)	0.01 (c)	11.6 (13.6) (a)	2.3 (c)
Cl	25.7 (21.2) (a)	88.8 (a)	69.9 (70.3) (a)	1.96 (a)	82.1 (47.0) (a)	46.7 (a)
SO_4-S	3.6 (1.3) (a)	10.2 (a)	8.0 (4.8) (a)	0.21 (a)	22.8 (0.6) (a)	9 (c)
NO_3-N	3.0 (2.0) (a)	6.62 (a)	2.0 (1.9) (a)	0.04 (c)	0.6 (0.7) (c)	0.5 (c)

Figure texts

Fig. 1 The Nødebo study site. The letters indicate the different stands. A: beech, B: Norway spruce and C: Norway spruce damaged during a storm in December 1999. In this study stands A and B were investigated.

Fig. 2. Simulations (solid lines) versus measurements of water storage (mm) for beech (A) and Norway spruce (B) in 1999 – 2001. The following layers are represented: 0 – 20 (■), 0 – 40 (▲), 0 – 60 (Δ), 0 – 80 (o) and 0 – 120 (•) cm. Error bars are shown for the 0 – 120 layer.

Fig. 3. Monthly values of precipitation (P) and water balance elements (evaporation and deep percolation) in mm for beech (A) and Norway spruce (B) stands at Nødebo in 2000. In A and B evaporation is shown as positive values and divided into transpiration (Et), interception evaporation (Ei) and soil evaporation (Es). The deep percolation (A) is represented as negative values.

Fig. 4. Monthly values of leaching (kg ha^{-1}) of NO_3-N from beech (◇) and Norway spruce (■) in 2000 at Nødebo.

Fig. 5. Wind direction from the meteorological station (Hansen (ed.), 2003). Values are floating mean values of 500 measurements. Records of wind direction were stored every 10 minutes. Values of the y-axis are designated with letters representing eight directions, with a 45º increment between values.

Figures

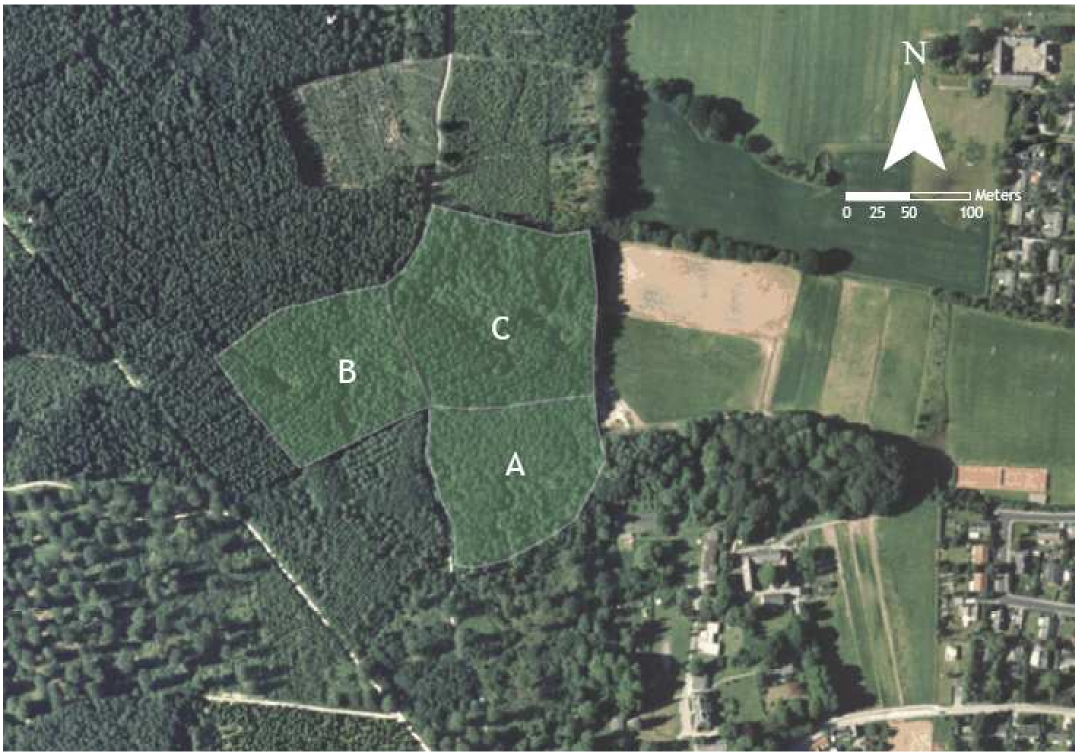

Fig. 1

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Deleted: The Nødebo study site. The letters indicate the different stands. A: beech, B: Norway spruce and C: Norway spruce damaged during a storm in December 1999. In this study stands A and B were investigated.

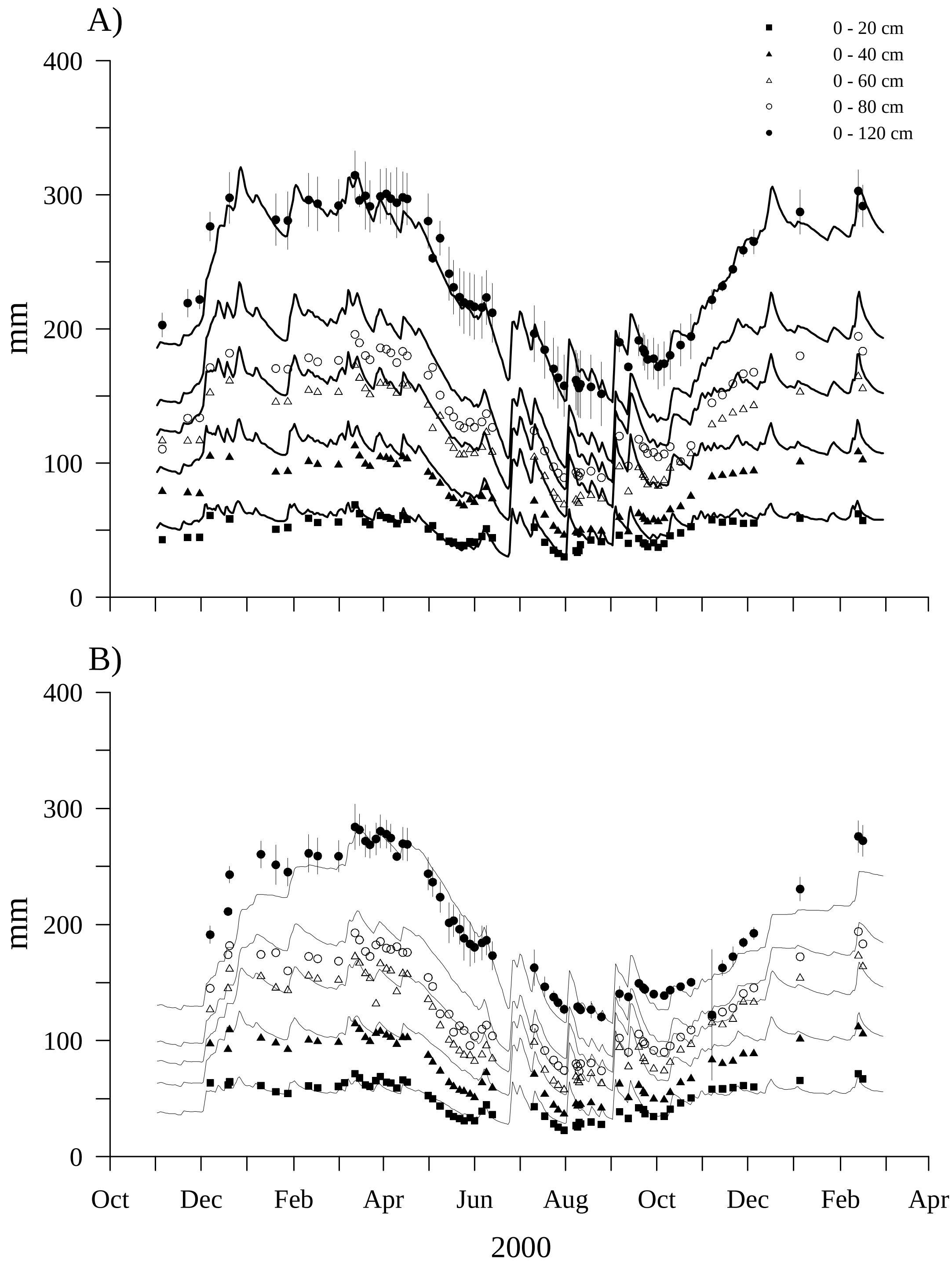
A)
0 - 20 cm
0 - 40 cm
0 - 60 cm
0 - 80 cm
0 - 120 cm
400
300
200
100
0
mm
B)
400
300
200
100
0
mm
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2000

Fig. 2

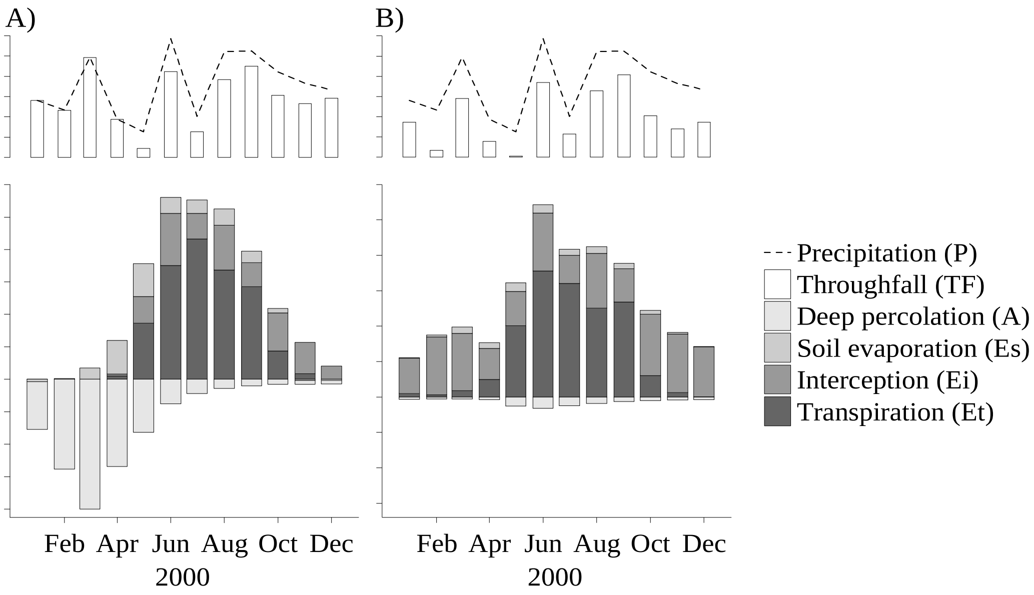
A)
B)
Precipitation (P)
Throughfall (TF)
Deep percolation (A)
Soil evaporation (Es)
Interception (Ei)
Transpiration (Et)
Feb Apr Jun Aug Oct Dec
2000
Feb Apr Jun Aug Oct Dec
2000

Fig. 3

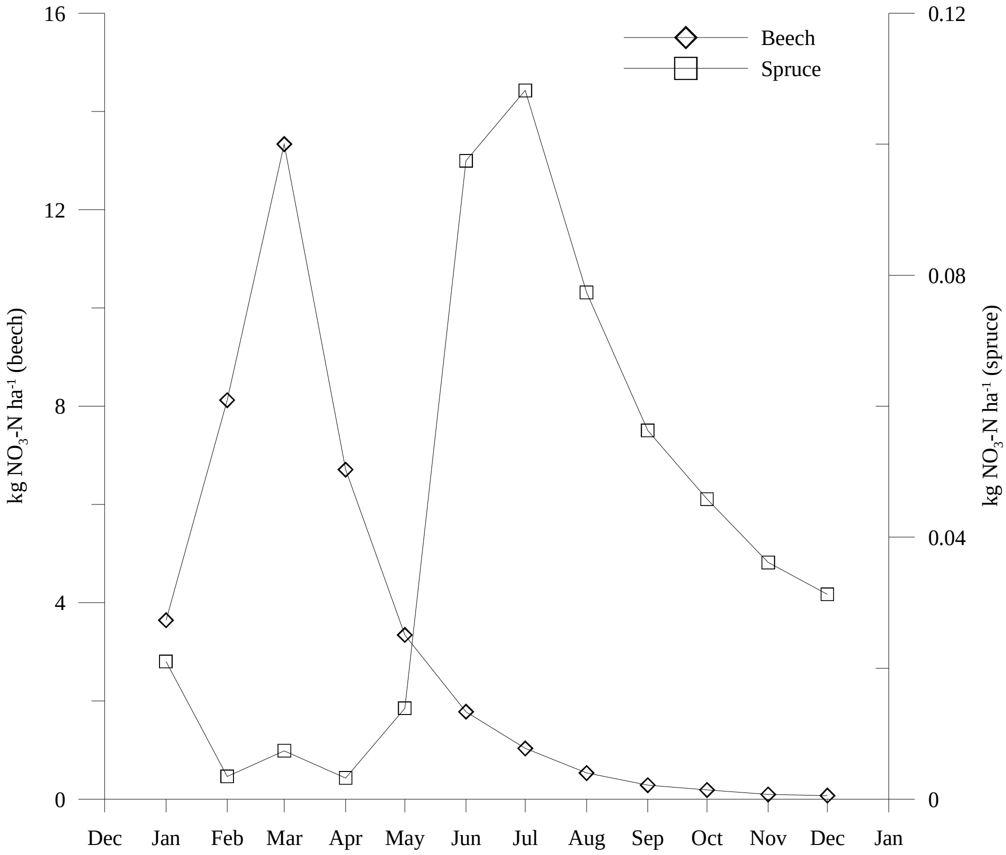
Beech
Spruce
kg NO3-N ha-1 (beech)
kg NO3-N ha-1 (spruce)
16
12
8
4
0
0.12
0.08
0.04
0
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

Fig. 4

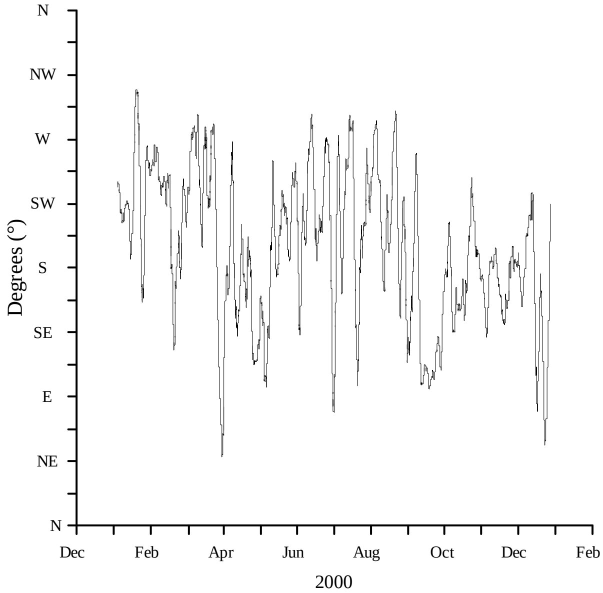

Fig. 5.