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# Field measurements of atmosphere–biosphere interactions in a Danish beech forest

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A field station was established in a beech forest near Sorø, Denmark in the spring of 1996 to provide a platform for studies of atmosphere–biosphere interactions. The station is equipped with a 57-m mast and a 24-m scaffolding tower. The mast makes it possible to measure profiles of gaseous atmospheric compounds and meteorological variables and to undertake measurements of fluxes by the eddy covariance method. The tower gives access to the tree canopy where branch and leaf level exchange of water vapour and $CO_2$ is measured. Soil-atmosphere exchange of gaseous compounds is investigated with gas flux chambers on the soil surface. Water-mediated transport of C and N is measured in throughfall, stemflow and soil water. The paper provides information on the site, vegetation, climate and soil and gives a description of the instrumentation and other technical installations at the site. The paper also presents and discusses example results from the measurements such as meteorological variables (temperature, wind speed, wind direction, radiation, rainfall and relative humidity), gaseous concentrations ($O_3$) and fluxes ($CO_2$, $CH_4$ and $N_2O$), water mediated transport ($NO_3^-$ and $NH_4^+$ in rainfall, throughfall, stemflow and soil water) and measurements on the trees (leaf area index, specific leaf area, litter fall, $CO_2$ exchange at branch and leaf level, maximum photosynthetic capacity). The forest acted in all years as a carbon sink with an average uptake of 190 g C $m^{-2}$ $yr^{-1}$. Contributions from $CH_4$ and $N_2O$ in terms of global warming potential (GWP) were less than 10% of the $CO_2$. $CH_4$ was deposited and $N_2O$ emitted, almost neutralising each other in terms of GWP. Leaves at the top of the canopy had the highest photosynthetic capacity (mid summer maximum of 50 $\mu$mol $m^{-2}$ $s^{-1}$) and leaves at the bottom the lowest (20 $\mu$mol $m^{-2}$ $s^{-1}$), indicating a clear acclimation to light. Sun leaves generally had significantly lower specific leaf area (118 $cm^2$ $g^{-1}$) and water content (42%) than shade leaves (specific leaf area:

282 $cm^2$ $g^{-1}$; water content: 53%). On an annual basis about 24% of the precipitation was lost as evaporation, 66% reached the forest floor as throughfall and 10% as stemflow. Due to leaching of $NO_3^-$ from the trees, the forest floor received 30% more nitrogen than in precipitation, resulting in a total input of 2.9 g N $m^{-2}$ $yr^{-1}$). The soil water was almost completely depleted in $NO_3^-$ with $NH_4^+$ constituting 97% of the total available inorganic nitrogen.

## Introduction

The atmosphere–biosphere interactions constitute a complex system which is generally agreed to play an important role in the climate system. One of the best-documented and most important indicators of global atmosphere change is the increase in concentrations of a number of trace gases in the atmosphere, among these the biologically active gases carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and ozone ($O_3$). Despite much research, however, there is still a considerable uncertainty regarding the processes that determine the concentrations and distribution of trace gases in the atmosphere and the causes and consequences of atmospheric change. Pollutants (such as nitrogen and sulphur compounds) that enter the atmosphere through anthropogenic activities also play an important role in the dynamics of plant growth and element cycling in terrestrial ecosystems, and are therefore also important for the feedback mechanisms between atmosphere and biosphere.

There is an increasing demand for the ability to predict future changes in the physical and chemical characteristics of the atmosphere in order to access the growth conditions in a changing climate. Therefore models have been developed on global as well as regional and local scales. Such modelling activities need input from many sources, e.g. remote sensing, atmospheric chemistry and physics as well as from ecosystem process studies. There is a very rapid development in the information that can be gained from remote sensing by satellites and consequently also a need for an interpretation of the information by measurements at ground level ("ground truth"). The approaches can be global models based on so-called inverse modelling or models derived from process studies and extended to regional and global level by up-scaling. Since the interaction between the atmosphere and the biosphere is important for the physical and chemical properties of the atmosphere as well as for the growth of plants, this calls for an interdisciplinary approach involving scientists such as atmospheric physicists and chemists, plant ecologists and soil scientists. In addition to a detailed knowledge of the processes determining atmosphere–biosphere interaction there is also a need for studies of the variation over time. As there is a considerable variation in climate and thereby growth conditions from year to year, continuous measurements need to be carried out over such a long time that it is possible to study interannual variation.

To study atmosphere–biosphere interaction in detail and to provide long-term data series we decided to establish a field station in a typically Danish deciduous forest. The field station, named "Sorø" (pronounced *Soroe*) after the nearest town, was established in the spring of 1996 and continuous measurements commenced on 1 June 1996. Over the years the station has hosted a number of projects starting with the EU-funded projects Euroflux ($CO_2$ flux over forest ecosystems) (1996–1999) (Valentini *et al.* 2000) and its continuation CarboEuroFlux (2000–2003). In connection to the EU-project FOREXNOX (1996–1998) (exchange of nitrogen oxides over forests) an intensive field campaign was carried out involving guest teams from England and The Netherlands (e.g. Gallagher *et al.* 2000). Later the field station hosted a nationally funded project under the Danish Environmental Research Programme concerning carbon and nitrogen dynamics in forest and agricultural field (SOROFLUX 1997–2000) (e.g. Ambus *et al.* 2001, Beier *et al.* 2001). As a part of the SOROFLUX project a satellite field station was operated on an agricultural field immediately west of the forest. During the years 2000–2003 the infrastructure was funded by the EU-project CORE (atmosphere biosphere interactions) and presently the field station hosts the EU-project NOFRETETE (nitrogen oxides emissions from European forest ecosystems). In addition to these projects the locality has been a main site for the EU-funded FORCAST project (forest carbon–nitrogen trajectories).

The purpose of this paper is to provide a comprehensive overview of the facilities and instrumentation at the station, to provide general background information on climate, soil and characteristics of the forest stand, and to give examples of results in order to show some of the capabilities of a multidisciplinary oriented field station.

## Site description

The station is located at 55°29´13´´N, 11°38´45´´E at an elevation of 40 m above mean sea level in the forest "Lille Bøgeskov" (translates into "Small Beech-forest") near Sorø on the island of Zealand. It is believed that the forest has never been under cultivation and that beech trees have been dominating in the area since 2500 B.C. The forest is mentioned in writing for the first time in 1697 where it is described as mainly consisting of young beech trees (Østergård 2000).

The soils in the area are brown soils classified after the American Soil Taxonomy system as either Alfisols or Mollisols (depending on a base saturation under or over 50%) with a 10–40 cm deep organic layer. The carbon pool in the soil (down to 1 m depth) is 20 kg m$^{-2}$. The C/N ratio is about 20 in the upper organic soil layers falling to about 10 in the lower mineral layers. The parent material is relatively rich in lime (25%–50%). However most of this is leached from the upper horizons of the forest soil, resulting in a low pH (4–5) and a lower base-saturation (Østergård 2000). The ground water table fluctuates between 0.2 m in winter and at least 2 m below the surface during summer (Ladekarl 2001).

The trees around the station are 82-year-old beech (*Fagus sylvatica* L.) trees with an average tree height of 25 m. The roughness length is 1.6 m and the displacement height 19.0 m (Dellwik and Jensen 2000). The terrain is flat and there is a homogeneous fetch of 0.5–1 km depending on direction. Average tree diameter is 38 cm, the stand density is about 283 stems ha$^{-1}$ and the wood increment calculated on the basis of yield tables (Møller 1933) was approximately 11 m$^3$ ha$^{-1}$ yr$^{-1}$. The peak leaf area index of the canopy is about 5 m$^2$ m$^{-2}$ at mid summer. The main part of the surrounding forest is beech forest of varying age but there are also scattered stands of conifers (mainly Norway spruce (*Picea abies* (L.) Karst.) as well as single trees of other conifers such as European larch (*Larix decidua* Mill.). In total, conifers constitute about 20% of the footprint area. In April before bud-break there is a flourishing forest floor vegetation mainly composed of *Anemone nemorosa* L. and *Mercurialis perennis* L. Later in the summer, when penetrating light is scarce, the green vegetation on the forest floor mainly consists of patches of grasses.

The general climate at the Sorø site is determined by its geographical location in the northern temperate zone on the western side of the European landmass, close to the North Sea, the temperature of which is influenced by the warm Gulf Stream. Therefore, the station has a maritime temperate climate dominated by westerly winds and frequent passes of frontal systems. As a result the usual weather is characterized by cool and unsteady summers and warm and changeable winters. However, it does happen occasionally that easterly winds dominate, carrying to the station the severe winters and hot summers of the continent. Table 1 gives an over-

**Table 1**. Characteristics of the climate at the field station. Temperature was measured at 37 m (i.e. above the canopy); wind speed and wind direction was measured at 57 m; precipitation was measured at 25 m. The length of the growing season was calculated on basis of the net ecosystem $CO_2$ exchange, i.e. it is the number of days of the period with generally negative flux (uptake) on a daily basis.

| Parameter | Mean (minimum, maximum) |
|---|---|
| Annual temperature | 8.3 (7.7, 9.0) °C |
| Temperature in January | 1.4 (–1.0, 2.2) °C |
| Temperature in July | 16.2 (14.8, 18.0) °C |
| Wind speed | 3.9 m s$^{-1}$ |
| Main wind direction | W to SW |
| Annual precipitation | 730 (520, 1013) mm |
| Growing season length | 148 (137, 159) days |

**Table 2**. List of quantities measured continuously and with automatic data acquisition at the field station. Part 1: Installations in the mast. The height of measurement or intake is given as well as the number of replicates (× *x*). The column DAQ-system indicates which of the five named computer systems acquires the data.

| Quantity | Measurement height | Method/instrument | DAQ-system |
|---|---|---|---|
| **Mast:** | | | |
| Diffuse and total solar radiation | 57 m | Sunshine Sensor BF2, Delta-T Devices Ltd, Cambridge, U.K. | "Flux" |
| Global radiation | 57 m | Pyranometer CM11, Kipp & Zonen, BV, Delft, The Netherlands | "Flux" |
| Global radiation | 43 m | Solar radiation sensor 2770, Aanderaa, Bergen, Norway | "Aanderaa" |
| UV-B radiation | 57m | UV-S-B-T Radiometer, Kipp & Zonen, BV, Delft, The Netherlands | "Flux" |
| PAR | 57m | Quantum sensor, LI-190SA, LI-COR Inc., Lincoln, NE, U.S.A. | "Flux" |
| Net radiation | 30 m | NR Lite, Kipp & Zonen, BV, Delft, The Netherlands | "Flux" |
| Radiation balance | 30 m | Albedometer, CM14, Kipp & Zonen, BV, Delft, The Netherlands | "Flux" |
| Air temperature | 10 m, 21 m, 37 m, 43 m, 57 m | Pt-100, Risø National Laboratory, Denmark | "Flux" (10 m, 37 m, 57 m), "Aanderaa" (21 m, 43 m) |
| Leaf surface temperature | 25 m | IR-Thermometer, KT15, Heimann Optoelectronics GmbH, Wiesbaden, Germany | "Flux" |
| Relative humidity | 25 m (× 2), 43 m | HMP 45A, Vaisala, Helsinki, Finland | "Flux" (25 m), "Aanderaa" (43 m) |
| Wind speed | 37 m, 41 m, 43 m, 48 m, 57 m | Cup anemometer P2244, Risø National Laboratory, Denmark | "Flux", "Aanderaa" (43 m) |
| Wind direction | 43 m, 57 m | Wind vane, Risø National Laboratory, Denmark | "Aanderaa" (43 m), "Flux" (57 m) |
| Precipitation | 25 m | Tipping bucket rain gauge, Semi-Pro, Pronamic, Silkeborg, Denmark | "Flux" |
| Atmospheric pressure | 2 m | Barometric pressure transmitter, PTA427(A), Vaisala, Helsinki, Finland | "Flux" |
| Wind velocity and temperature fluctuation | 43 m | Sonic anemometer, SOLENT 1012 R2, Gill Instruments Ltd., Lymington, U.K. | "Flux" |
| Wind velocity and temperature fluctuation | 4 m | Sonic Anemometer, USA-1, Metek, Elmshorn, Germany | "Trunkspace" |
| $CO_2$ and $H_2O$ fluctuation | 43 m (intake), 4 m (intake) | Infrared gas analyzer, LI-6262, LI-COR Inc., Lincoln, NE, U.S.A. | "Flux" (43 m), "Trunkspace" (4 m) |
| $O_3$ concentration | 0.1 m , 0.5 m, 1 m, 5 m, 15 m (× 2), 30 m, 41 m | UV photometry analyzer, TEI-49C, Thermo Environmental Instruments, Franklin, MA, U.S.A. | "Profile" |
| NO and $NO_x$ concentration | 0.1 m , 0.5 m, 1 m, 5 m, 15 m (× 2), 30 m, 41 m | Chemiluminescence detector, AC41M, Environnement SA, Poissy, France | "Profile" |
| $CO_2$ concentration | 0.1 m , 0.5 m, 1 m, 5 m, 15 m (× 2), 30 m, 41 m | Infrared gas analyzer, ADC-2000, Analytical Development Company, Hoddesdon, U.K. | "Profile" |
| Flow in tubes for fluctuation measurements and profile | | Sierra Top-Trak 820 mass flow meter, Sierra Instruments Inc., Monterey, CA, U.S.A. | "Flux" (43 m), "Trunkspace" (4 m), "Profile" |

view of the climate characteristics of the site. For more quantitative information, *see* the Results section below.

## Facilities at the field station

The main facilities at the field station are a meteorological mast with a height of 57 m and a cross section of 30 cm × 30 cm and a scaffolding tower with a height of 24 m and a cross section of 3 m × 3 m. There are two instrument huts supplied with mains power and ISDN telephone lines. Many measurements are made continuously with instruments that are automatically delivering their signals to data acquisition systems. In addition to the automatic instrumentation a number of measurements are made either by manual collection of samples or in shorter campaigns.

### Atmospheric measurements

Tables 2 and 3 give an overview of the measurements and instruments that are running continuously and from which the signals are logged by computers. The tables specify measurement heights and the models and origins of the instruments applied. The instrumentation covers meteorological measurements: atmospheric pressure, wind speed, wind direction, global radiation, net radiation, total and diffuse solar radiation, UV-B radiation, photosynthetic active radiation (PAR), relative humidity, temperature (air, leaf surface, soil), soil heat flux, soil moisture and rain. Profiles are measured of wind speed, PAR, air temperature and soil temperature.

Instrumentation for flux measurements is placed at two heights: at 43 m (18 m above the canopy) and at 4 m (in the trunkspace). At these two heights sonic anemometers are mounted. Next to the sonic anemometers are inlets for

**Table 3**. List of quantities measured continuously and with automatic data acquisition at the field station. Part 2: Installations in the scaffolding tower and on the ground. The height of measurement or intake is given as well as the number of replicates (× *x*). The column DAQ-system indicates which of the five named computer systems acquires the data.

| Quantity | Measurement height | Method/instrument | DAQ-system |
|---|---|---|---|
| **Scaffolding Tower:** | | | |
| PAR | 19 m (× 2), 14.5 m (× 2), 4 m | Quantum sensor, LI-190SA, LI-COR Inc., Lincoln, NE, U.S.A. | “Flux” |
| **Ground Level:** | | | |
| Soil temperature | 2 cm, 5 cm (× 11), 10 cm | Pt-100, Risø National Laboratory, Denmark | “Flux” (2 cm, 10 cm), “Soilbox” (5 cm (× 10)), “Aanderaa” (5 cm (× 1)) |
| Soil heat flux | 5 cm (× 2) | Heat Flux Sensor HFP01, Hukseflux Thermal Sensors, Delft, The Netherlands | “Flux” |
| Soil moisture | 0–6 cm | TDR, ThetaProbe ML2x, Delta-T Devices Ltd, Cambridge, U.K. | “Aanderaa” |
| Soil moisture | 0–16 cm (× 2) | TDR, TRIME-EZ, Imko Michromodultechnik GmbH, Germany | “Flux” |
| Rain | 0.5 m | Rain detector, DRD11A, Vaisala, Helsinki, Finland | “Soilbox” |
| Stemflow | 1 m (× 5) | Tipping bucket, Prenart Equipment Aps, Copenhagen, Denmark | “Flux” |
| $CO_2$ soil-atmosphere exchange | 0 m (× 5) | Infrared gas analyzer, CIRAS-2 DC, PP Systems, Hitchin, U.K. | “Soilbox” |
| NO, $NO_x$ soil-atmosphere exchange | 0 m (× 5) | Chemiluminescence detector, TEI-42CTL, Thermo Environmental Instruments, Franklin, MA, U.S.A. | “Soilbox” |
| $O_3$ soil-atmosphere exchange | 0 m (× 5) | UV photometry analyzer, $O_3$41M, Environnement SA, Poissy, France | “Soilbox” |
| Flow rate through soil chambers | 0 m (× 5) | Mass flow meter, F112, Bronkhorst, Ruurlo, The Netherlands | “Soilbox” |

Teflon tubes (inner diameter 8 mm) through which air is drawn at 20 SLPM by two diaphragm compressors (N 145.1.2 AN.18, KNF Neuberger, Freiburg, Germany) to the instrument hut with two infrared gas analyzers (LI-6262) measuring fluctuations in the concentrations of $CO_2$ and $H_2O$. Further details of the methodology applied for the flux measurements are given in Aubinet *et al*. (2000).

Studies of similarity theory Nakamura and Mahrt (2001) confirm that the height for the flux measurements is sufficient for the measurements to be made in the surface layer of the forest avoiding the roughness sublayer. The adequacy of the fetch was studied by Dellwik and Jensen (2000) during a three-week campaign in May–June 1996. The friction velocity measured by sonic anemometers at three heights (31 m, 43 m and 55 m) was compared. It was found that there was no significant flux divergence with height under unstable and neutral conditions. In contrast, very long fetches are required to measure parameters in equilibrium with the forest canopy under stable conditions.

A system is installed for the purpose of measuring profile concentrations of gases such as $CO_2$, $O_3$, NO and $NO_2$. The system consists of a series of Teflon tubes (inner diameter 4.8 mm) with inlets at different heights on the meteorological mast (0.1 m, 0.5 m, 1 m, 5 m, 15 m, 30 m, 41 m). The tubes are sets of two different lengths: 25 m for heights up to 15 m; 50 m for heights from 15 m to 41 m; i.e. at 15 m both lengths are applied in order to make it possible to compensate for tube effects. A constant flow is maintained through the tubes by a diaphragm compressor (N145.1.2 AN.18, KNF Neuberger, Freiburg, Germany) with a total flow rate of 20 SLPM monitored by a mass flow meter (Sierra Top-Trak 820). PTFE coated valves (Type 117, Bürkert GmbH & Co. KG, Ingelfingen, Germany) are installed on the individual tubes to allow the air intake to the monitors to be shifted between the different heights. The measurement time at each height can be controlled by a computer; currently measurements are made during 3 minutes from each height. $CO_2$ is measured with an ADC-7000 infrared gas analyzer, $O_3$ with a TEI-49C UV photometry analyzer and $NO/NO_x$ with a AC41M chemiluminescence analyzer (*see* Table 2 for manufacturer specifications).

Precipitation above the canopy is collected by 2 funnels (Ø 16 cm) mounted on top of the scaffolding tower (25 m height) and throughfall precipitation passing through the canopy and falling on the forest floor is collected by 10 funnels placed at 1 m height randomly on the forest floor and sampled monthly. Additionally, in 1999 a campaign of additional throughfall measurements with 45 additional samplers was conducted for a total of 8 months. The additional samplers were installed systematically at different distances and directions in relation to the trees in order to reveal the potential pattern in throughfall amounts on the forest floor.

Stemflow precipitation running along the stems to the forest floor is collected by 5 stemflow collectors. The collectors consist of a PE tube fixed to the stems by PTFE grease connected to a tipping bucket device measuring the stemflow amount in 0.5 l fractions and continuously taking a 0.1% sample for chemical analysis.

## Plant

$CO_2$ and $H_2O$ exchange at the branch scale was measured by the use of a gas analysis system developed by the University of Copenhagen and Risø National Laboratory. Three clap-cuvettes each with a size of 40 × 40 × 10 cm (L × W × H) enclosing branches of beech trees with 10–30 leaves were measured continuously in campaigns in 2000 and 2001 lasting 2–3 weeks. The branch and leaves were fixed in a horizontal position by the use of a net of nylon strings connected to an aluminum frame. Transparent PTFE film was attached on an aluminum frame, which could be opened and closed automatically via an actuator. Each cuvette was equipped with two PAR sensors (Hamamatsu, gallium-arsenide photodiodes modified according to Pontailler (1990) located inside the cuvette and two temperature sensors (thermocouples type T) fixed under the leaves. Air inside and outside the cuvettes was sampled while the cuvette was closed, which lasted about 3 min after which the cuvette opened for 15 min. Data from the last minute was used in the calculations. The airflow rate was monitored by two flow meters (0–20 LPM, Micro switch, Honeywell AWM5104VN) and delivered to a $CO_2$ and $H_2O$ analyzer (Ciras DC, PP Systems, Hitchin, U.K.). A computer system was controlling sampling and data collection. The area of the leaves and branch was determined by analysis of digital pictures.

By the use of two types of gas exchange systems (LCA-3, broad leaf cuvette, ADC Bio-Scientific Ltd. Hoddesdon, U.K.) and (CIRAS-1, PP Systems) gas exchange was followed at leaf level over two seasons in 1999 and 2000. The leaves were divided into four canopy layers related to the height in the canopy. Layer 1 was close to the top and consisted of sun leaves only while Layer 4 was lowest in the canopy and consisted of shade leaves only. Layers 2–3 were intermediate light levels. In the 1999 season 2604 measurements were made, distributed on 34 days in the period from 6 May to 28 October. In the 2000 season 1525 measurements were done distributed on 23 days in the period from 23 May to 2 November. Photosynthesis was measured using a LCA-3 infrared gas analyzer with a Parkinson broad leaf chamber (PLC), with a leaf area of 6.2 $cm^2$. Two apparatus were in use. PAR and transpiration were registered simultaneously with photosynthesis. For each day of measurements, one to three rounds in the scaffold were performed, starting either at the bottom level or the top level, measuring all twigs on a given level before moving to the next. From each marked twig a leaf was chosen for analysis of photosynthesis and the leaf placed in the chamber, still attached to the twig. The measurements were performed whenever the rate of photosynthesis was stable, usually within two to four minutes. With a CIRAS-1 connected to a PLC (broad) automatic cuvette measurements of photosynthesis ($A_{max}$) were performed in a controlled environment with a chamber temperature of 20 °C, $CO_2$ concentration of 1800 ppm and PAR levels at 1500 $\mu$mol $m^{-2}$ $s^{-1}$. The leaves were allowed 2–5 minutes to adapt to the conditions, and measurements were taken when the rate of photosynthesis was stable. In 1999, 925 and in 2000, 780 measurements were done under controlled conditions. Two instruments were in use.

The Granier technique (Granier 1985) was used to measure sap flow on 12 trees in long time series from May to November in 2000, 2001 and 2002. Each tree was equipped with two sensor systems measuring sap flow in two depths (0–2 cm and 2–4 cm) at ca. 1.3-m height. Measurements were taken every 5 min and stored as half hourly averages on a data-logger (CR7, Campbell Scientific, Inc., Utah, USA).

The LAI-2000 PCA (LI-COR, Nebraska, USA) was used to measure Leaf Area Index (LAI) of the canopy from single points on transects at intervals of 15 meters. Measurements were conducted in four 200 m transects south and southwest from the tower in 2000 (autumn), 2001 (autumn) and 2002 (growth season). The LAI-2000 PCA encompasses five sensors, each simultaneously measuring light intensities (blue range) in five concentric Field of Views or FOVs centered at zenith angles of 7, 23, 38, 53 and 68 degrees, and respectively referred to as PCA sensors 1, 2, 3, 4 and 5 (Nackaerts *et al.* 2000). According to Planchais and Pontailler (1999) the instrument underestimates LAI. Consequently, LAI was calculated on the basis of sensors 2–5 only because this procedure increases the measured LAI as compared with measurements with all rings. However, as pointed out by Planchais and Pontailler (1999) neglecting one or two rings could bias the results. Above canopy readings were taken before and after below canopy measurements.

To determine specific leaf area (SLA) and leaf water content five sun leaves and five shade leaves were sampled from five trees over the growth season 2002 with intervals of ca. three weeks. The leaves were taken to the laboratory in plastic bags and the fresh weight and area (CI-203CA, Portable Laser Area Meter, CID, inc., USA) was determined immediately after returning. The dry weight was determined after two days at 80 °C.

The yearly production of litter was measured in 1998–2000 by collection of litter by means of 20 open litterfall collectors (Ø 40 cm) placed along 4 randomly chosen transects with 5 samplers at each transect with a fixed distance of 2 meters between the samplers. From 2000 onwards litterfall was collected by 25 open samplers (Ø 30 cm) placed in a grid with 10 meters between the samplers. The collectors were sampled monthly.

Stem diameter, at breast height, was measured by the use of a large aluminum caliper that encompassed the whole tree and repeated five times on the same cross-sections. Measurements were taken on 21 marked trees, south of the tower, in March from 1998 to 2002 except 2001. Variations in tree stem diameter were measured on one beech tree in long time series from May to November in 2002. The variations were detected at two heights on both the xylem and the whole stem and the time resolution was one min. (Sevanto *et al*. 2003).

## Soil and soil surface measurements

Exchange of gases ($CO_2$, NO, $NO_2$, $O_3$, $N_2O$ and $CH_4$) at the soil surface was measured with chambers, both static and dynamic. A number of manual static chambers have been installed in the soil for measurements of $N_2O$ and $CH_4$ exchange. The chambers are made of 30 cm diameter (15-cm long PVC pipes, which have been pushed 5 cm into the soil (volume 7.1 $dm^3$). Samples of headspace air are taken by a syringe through a butyl stopper penetrating the removable Perspex lids. In December 2002 an automated gas sampling system (AGPS; UIT, Dresden, Germany) was installed. The AGPS is connected to an automatically opening two-compartment static chamber (area 70 cm × 70 cm and volume 49 $dm^3$). The cover compartment of the automated chamber is made of FOREX, which slides horizontally onto a stainless steel frame. The AGPS allows up to 13 sampling cycles within a 24-hour period; for each cycle the chamber is sealed for 105 minutes and three headspace samples are collected at 40-minute intervals.

Samples from both manual and automatic chamber systems are stored in 3.5 ml pre-evacuated Venojects® for subsequent GC-analysis. $N_2O$ concentrations are determined on a Shimadzu GC 14B with Electron Capture Detector. The GC is coupled to an automatic headspace sampler (Mikrolab, Århus, Denmark). $CH_4$ and $CO_2$ concentrations are determined on a HP 6890 with Flame Ionization ($CH_4$) and Thermal Conductivity ($CO_2$) detectors.

Soil-atmosphere fluxes of $N_2O$ and $CH_4$ based on the manual chambers are available for 1998–1999 (Ambus *et al*. 2001). Regular $N_2O$ flux-measurements were initiated again in April 2002 (Ambus unpubl.).

Fluxes of $CO_2$, NO, $NO_2$ and $O_3$ were determined by the application of automatically opening dynamic chambers (area 28 cm × 28 cm and volume 12 $dm^3$) made of Teflon placed on a steel frame. The chambers were continuously flushed with ambient air supplied by a 55 l $min^{-1}$ diaphragm compressor (N145.1.2 AN.18, KNF Neuberger, Freiburg, Germany) at 9 $dm^3$ $min^{-1}$ to each chamber. Flow rates through the chambers were measured with mass flow meters (F112, Bronkhorst, Ruurlo, The Netherlands). $CO_2$ concentrations were determined with an IR gas analyzer (ADC-7000, Analytical Development Company Ltd., Hoddesdon, England); NO/$NO_x$ concentrations with a chemiluminescence analyzer (Thermo Environmental Instruments 42 CTL); $O_3$ concentrations with an UV photometry analyzer (Environnement $O_3$ 41M). A rain detector (DRD11A, Vaisala, Helsinki, Finland) controlled the lids so that all chambers open during rain events. Fluxes were calculated from the flow rate through the chamber and the difference in the concentration at stationarity (at least 10 min after lid closure) and the concentration in a reference chamber. Further details are given by Pilegaard *et al*. (2001).

Water mediated transport of C and N in the soil is measured on a monthly basis by sampling soil water extracted beneath the root-zone. Water is extracted by porous PTFE soil water samplers (PRENART Superquarz) connected to a vacuum pump providing constant tension. Sampling is done by 12 samplers installed in 2 groups — 6 samplers are installed close to the stems (< 1 meter) and 6 are placed apart from the stems (> 3 meters). Within each of the two groups the samplers are placed randomly. The division into two groups makes it possible to take into account potential differences in soil water content and soil water movement generated by the pattern in water input by throughfall and stemflow.

## Data acquisition, storage, transmission and access

Five computer systems are used for acquiring the data from all automatic instruments as listed in

Tables 2 and 3. One system (“Flux”) takes care of most of the meteorological measurements and the flux measurements of heat, $CO_2$ and $H_2O$ above canopy. Another system (“Trunkspace”) is denoted to the flux measurements in the trunk-space. Both these systems calculate the fluxes online averaged over 1/2 hour and store all raw data. A third system (“Soilbox”) is controlling the dynamic chambers and acquiring and storing all data related to these measurements. These three systems all run Risø-DAQ, an MS-DOS based data acquisition system developed at Risø National Laboratory. These computers can be remotely accessed and controlled by software, InSync CoSession (SpartaCom Technologies Inc, Tucson, AZ, U.S.A.). The three systems are connected to a fourth computer running Microsoft Windows NT. This computer automatically transmits all data every third hour to a central computer at Risø National Laboratory by means of an ISDN-based modem connection. The profile system is controlled by a computer (“Profile”) running the MSWindows based data acquisition system LabView (National Instruments Corporation, Austin, TX, U.S.A.). This computer controls the valves and logs data from flow meter and instruments for air concentration measurements. A set of basic meteorological measurements (air and soil temperature, wind speed, global radiation, relative humidity and soil moisture) is logged by a data-logger (“Aanderaa”) (model 3660, Aanderaa Instruments, Bergen, Norway). This system has a backup power supply that ensures continuous logging of meteorological measurements in the case of mains power failure. Data are transferred to Risø National Laboratory by a modem connection every 1/2 hour and displayed at http://www.risoe.dk/vea-data/soro/sorodata.htm. All raw-data from the site are stored in a central database and backed up on CD-ROM.

## Selected results and discussion

### Meteorology

The distribution of winds at the site for the period 1996 to 2002 is depicted in Fig. 1. The predominance of westerly to southwesterly winds is clearly shown. There was a secondary maximum towards east-southeast, while winds from south and north to northeast were comparatively rare. The figure also gives the probability of different wind speed classes. The maximum occurrence was in the class from 3 to 5 m s$^{-1}$. Wind speeds below 0.5 m s$^{-1}$ were very rare (0.45% of the time).

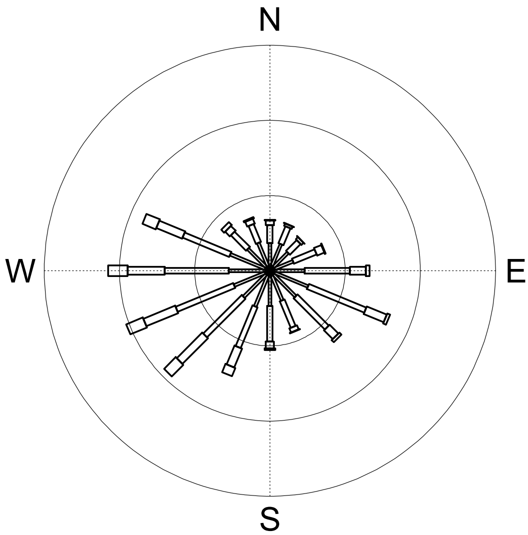


**Fig. 1**. Wind rose showing the probability of winds from the various sectors (16 sectors of 22.5°). Circles indicate 5%, 10%, and 15% of the time respectively. For each direction, the bar is subdivided to also show the wind speed distribution. The intervals shown are 0.5 to 3 m s$^{-1}$; 3 to 5 m s$^{-1}$; 5 to 7 m s$^{-1}$; and larger than 7 m s$^{-1}$ in that order outwards. Less than 0.5 m s$^{-1}$ is designated as calm (0.45% of the time). Observations are 30 min mean values measured at 57 m above terrain.

The observed monthly mean temperature at 37 m for the same period is shown in Fig. 2. The median varied from about 1 °C in winter to about 16 °C in summer. The diurnal variation (not shown) had a typical amplitude of 7 °C in June and 3.5 °C in December, but with an observed maximum variation from 5 to 29 °C in June and –12 to 11 °C in December over the years of measurements at the site.

For precipitation on the other hand, there is no clear annual cycle in the mean monthly values. The median for the 6 years was about 60 mm per month, perhaps with a tendency to a weak minimum in spring (March, April, May) and maximum in October (Fig. 2b). The

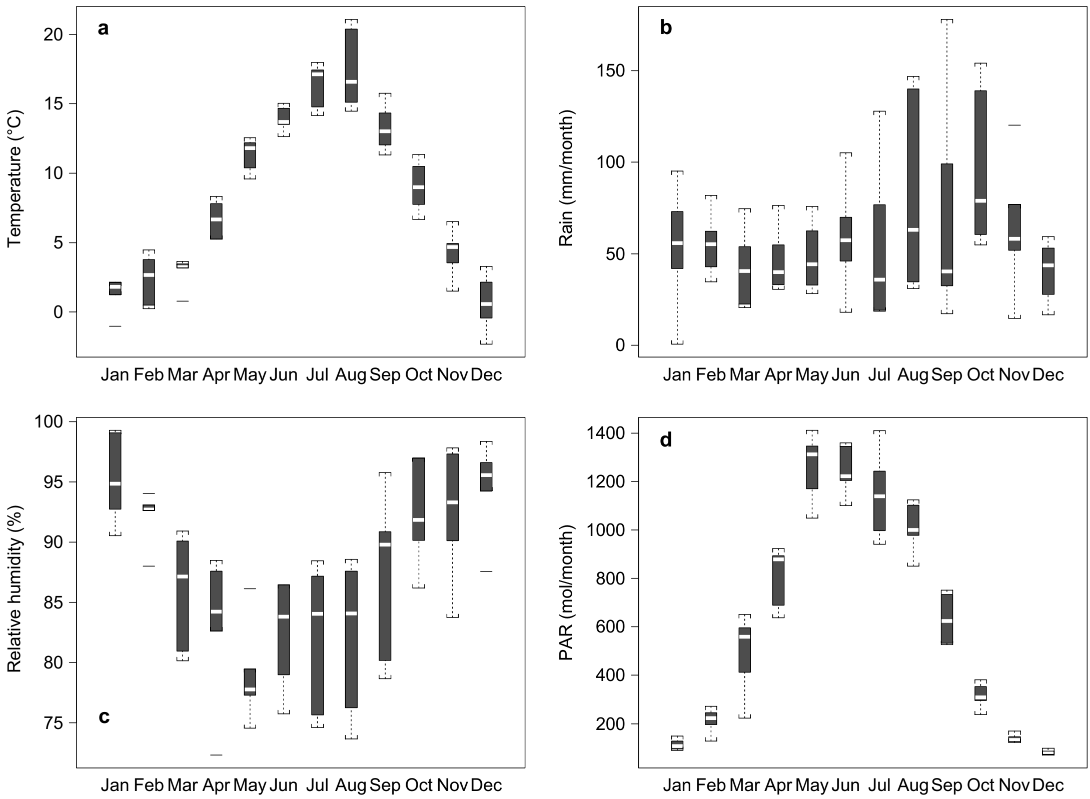


**Fig. 2**. Boxplots of monthly mean values over the years 1996–2002 of (**a**) temperature measured at 37 m; (**b**) precipitation (the gauge is sitting at 25 m, just in the mean height of the canopy, i.e. sheltered by the highest branches; (**c**) relative air humidity measured at 25 m; (**d**) photosynthetic active radiation (PAR) (the PAR value is inferred from measurements of global radiation at 57 m by assuming that 2.3 μmol is equal to 1 Joule of solar radiation (McCartney 1978). Explanation of boxplots: The white stripe in the middle of the shaded box is the median for the 6 years from 1996 to 2002. The box encloses the middle 50% of the cases (± 25% on each side of the median). The "whiskers" shown above and below the boxes represent the largest and smallest observed value. However if that value is higher (or lower) than 1.5 box height from the end of the box the value is indicated with a horizontal line without a connecting vertical dotted line.

most prominent feature is the large inter annual variability in the summer and fall (July through October), especially in August. The annual mean precipitation was 730 mm but it varied from 520 mm (in 1997) to 1013 mm (in 2002).

The monthly mean relative air humidity varied between 75% and 100% with median values from 80% to 95%, lowest in summer and highest in winter (Fig. 2c). The parameter with the largest amplitude in the annual variation is of course the solar radiation. In terms of PAR its median value was from under 100 to over 1300 mol per month. However, inter annual variation was quite large (Fig. 2d). In June for example, it varied 500 mol during the years of observation, which must be a significant factor in the resulting carbon accumulation.

## Air concentrations and gaseous fluxes

The concentration of $O_3$ exhibited a well-known pattern with the highest concentrations found in the hours after noon and the lowest during the late night (Fig. 3). $O_3$ is generated by photochemistry and the $O_3$ is later consumed by reaction with NO and other compounds in the air as well as by uptake in plants and destruction at surfaces. Because no $O_3$ is produced during the night the concentration decreases. In general

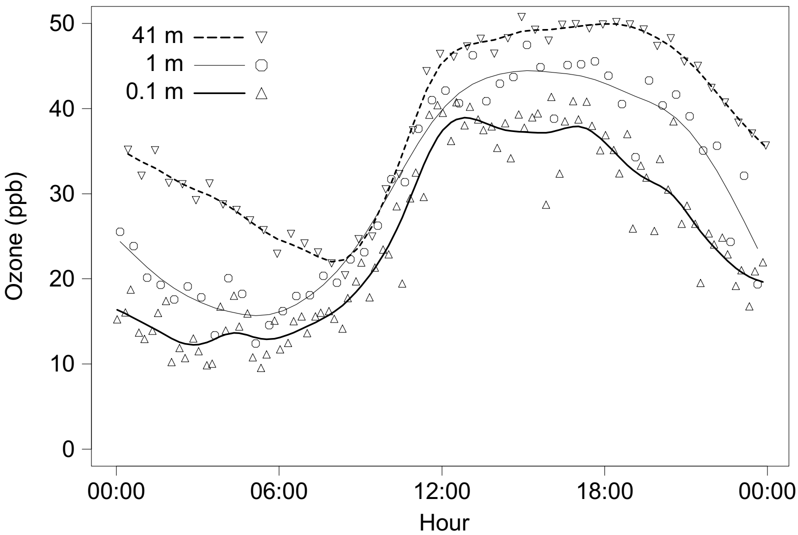


**Fig. 3**. Concentration of $O_3$ (ppb v/v) during 25 May 2002 in three heights (0.1 m, 1 m and 41 m). Points are measurements averaged over 1 min after a stabilization time to each height of 2 min; lines are smoothed splines.

the highest concentrations were found above the canopy and the concentrations decreased markedly towards the soil surface. During the morning hours the air was again well mixed and the $O_3$ concentration increased in the trunkspace due to entrainment of air with higher $O_3$ concentration from above the canopy. The low $O_3$ concentration in the trunkspace was mainly due to the low ventilation and thus longer residence time, but some $O_3$ was also removed by uptake in the canopy. The even lower concentrations just above the soil surface were probably due to destruction at the soil surface and to the reaction with NO emitted from the soil. However, the NO flux from the forest floor in Sorø was found to be low (0–1 ng NO-N $m^{-2}$ $s^{-1}$) (Pilegaard 2001), only occasionally peaks up to 15 ng NO-N $m^{-2}$ $s^{-1}$ were observed. This sink for $O_3$ is therefore of relatively minor importance in Sorø.

Figure 4 shows a comparison of the mean monthly (June and September) diurnal variation in fluxes of $CO_2$ above the canopy, in the trunkspace, and at the soil surface. In June the canopy flux showed a very clear pattern with a high (downward) flux during the day with a maximum of about –18 $\mu$mol $m^{-2}$ $s^{-1}$. During the night there was an efflux of $CO_2$ slightly above 5 $\mu$mol $m^{-2}$ $s^{-1}$. The trunkspace flux showed much smaller diurnal variation with an average efflux of $CO_2$ (1.87 ± 0.09 $\mu$mol $m^{-2}$ $s^{-1}$), lowest during the day indicating uptake of $CO_2$ by the understorey vegetation. The soil respiration showed a weak diurnal variation with a maximum during the afternoon coinciding with the soil temperature maximum at a 5-cm depth, which is lagging behind the air temperature by about 3 hours. The average soil respiration in June was 2.03 ± 0.01 $\mu$mol $m^{-2}$ $s^{-1}$, which was very close to the average trunkspace flux. In September the canopy flux was much smaller with a maximum of –9 $\mu$mol $m^{-2}$ $s^{-1}$ during the day and 3.5 $\mu$mol $m^{-2}$ $s^{-1}$ during the night. The diurnal variation in the trunkspace flux was smaller than in June corresponding to very little green vegetation on the forest floor. The average flux in the trunkspace (2.14 ± 0.05 $\mu$mol $m^{-2}$ $s^{-1}$) equaled that of the soil respiration (2.12 ± 0.01 $\mu$mol $m^{-2}$ $s^{-1}$). The respiration from the trees can thus be estimated to around 3 $\mu$mol $m^{-2}$ $s^{-1}$ in June and much lower (1.4 $\mu$mol $m^{-2}$ $s^{-1}$) in September. More details about the $CO_2$ fluxes measured at the site are given in Valentini *et al*. (2000), Pilegaard *et al*. (2001), and Granier *et al*. (2002).

Figure 5 illustrates the fluxes of $CH_4$ as measured over an entire year beginning in March 1998. The negative values for the $CH_4$ flux indicate a consistent downward flux of this component, driven by oxidation in the soil. The largest $CH_4$ uptake occurred in August–September when a combination of dry and warm conditions provided conditions for fast diffusion and oxidation of $CH_4$ in the soil. More detailed information on the soil-atmosphere fluxes of $CH_4$ and $N_2O$ are available in Ambus *et al*. (2001).

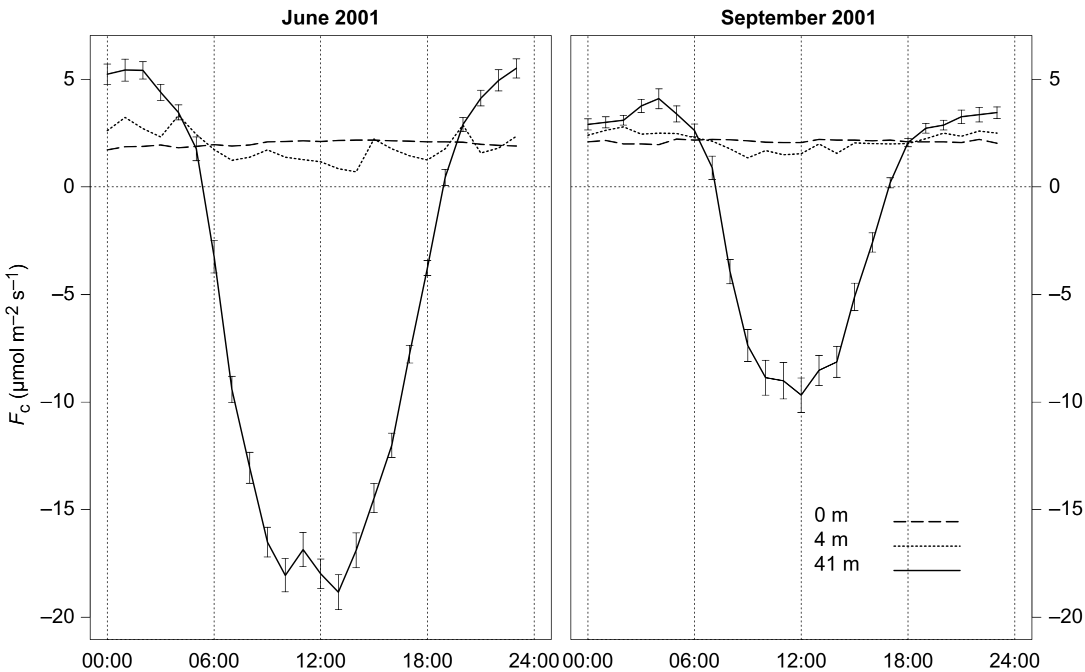


**Fig. 4**. Mean monthly diurnal variation in fluxes of $CO_2$ ($F_c$) during June and September 2001 measured above canopy and in trunkspace by eddy covariance and at soil surface by dynamic chambers. Bars denote ± standard error of the mean.

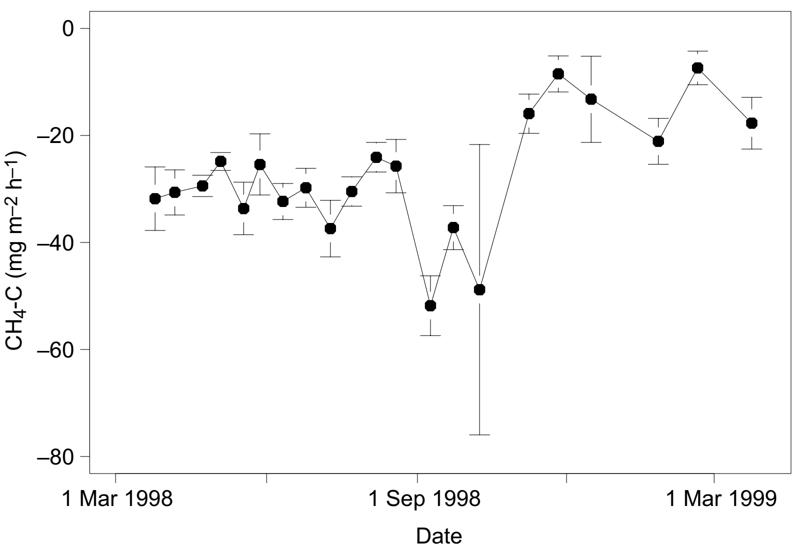


**Fig. 5**. Fluxes of methane measured in soil chambers over the course of one year from March 1998 to March 1999. Points are means of six replicate chambers and bars show ± standard errors of the mean.

The net greenhouse effect based on $CO_2$ units has been computed considering all the biogenic greenhouse gases measured at the site (Table 4). The net result is almost equivalent to the effect of $CO_2$ alone, however it is noteworthy that the more or less counterbalanced contributions of $CH_4$ and $N_2O$ are in the range of 7%–9% of the total budget despite the quantitatively insignificant fluxes of these components. As opposed to the above canopy $CO_2$ flux measurements, $CH_4$ and $N_2O$ were measured at the soil surface and it could be argued that canopy reactions of one or

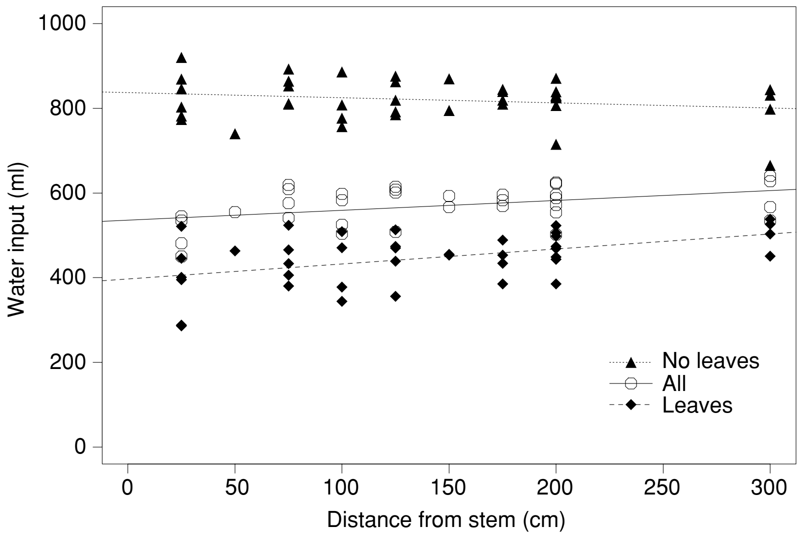


**Fig. 6**. Water input per funnel per sampling split into seasons with leaves and no leaves. Results from the throughfall campaign January to September 1998 ($n$ = 39 funnels). Lines show linear regressions: $R^2$ (No leaves) = 0.0392, $R^2$ (All) = 0.1728, $R^2$ (Leaves) = 0.212.

both components would influence the source or sink strength. However, although it is well documented that aerenchymatic plants act as conduits for both $CH_4$ and $N_2O$ (e.g. Yu *et al*. 1997) and that upland crop plants may convey $N_2O$ to the atmosphere via the transpiration stream (Chang *et al*. 1998), forest canopy reactions of $CH_4$ and $N_2O$ have never been reported.

## Throughfall, stemflow, soil water and litterfall

Water fluxes to the forest floor by throughfall and stemflow have been measured from 1998 through 2002. It is known from spruce forests that the water and element input with throughfall exhibits a strong spatial pattern related to the distance to the nearest stem (Beier *et al*. 1993). Therefore, a similar potential spatial pattern for the beech forest at Sorø was investigated by collecting throughfall in 39 funnels placed systematically at different distances (0.5–3 m) and in different directions (N, E, S and W) relative to the stems during January to September 1998 (6 sampling campaigns in total).

The results show no significant patterns in throughfall related to stem distance (Fig. 6). However, if the data is analyzed separately for the growing season (leaf covered season: May–November) and the dormant season (trees without leaf cover: November–May) the variation increased during the leaf covered season with a standard deviation of 13.9% of the average as compared with only 5.5% during the dormant season. Furthermore, a small but insignificant trend with increasing throughfall amounts at greater distances from the stem was seen during the growing season (Fig. 6). Considering the variability and the small and insignificant trend we conclude that a systematic spatial pattern in the throughfall distribution does not have to be taken into account and the throughfall flux is reasonably well estimated as the average flux in the 10 randomly placed throughfall funnels.

Annual mean input of precipitation was 756 mm yr$^{-1}$ of which 61% was assigned to the growing season (Table 5). As the water passed through the canopy, 24% of the water was lost by evaporation resulting in a water input to the forest floor of 572 mm yr$^{-1}$ by throughfall (87%) and stemflow (13%). The 24% canopy loss differed significantly among the seasons with a loss

**Table 4**. Exchange of greenhouse gases ($CO_2$, $N_2O$, $CH_4$) during 1 year (1 March 1998–2 February 1999). Global warming potential (GWP) is mass based (Seinfeld and Pandis 1997).

| Element | Annual flux | GWP (20 years) | Greenhouse effect ($CO_2$ units) |
|---|---|---|---|
| $CO_2$ | –260 g m$^{-2}$ | 1 | –260 g m$^{-2}$ |
| $N_2O$ | 0.079 g m$^{-2}$ | 290 | 23 g m$^{-2}$ |
| $CH_4$ | –0.299 g m$^{-2}$ | 32 | –19 g m$^{-2}$ |
| All | | | –256 g m$^{-2}$ |

of 36% and 7% during the growing and dormant seasons respectively. On the other hand there was no seasonal difference in the separation between stemflow and throughfall (stemflow accounts for 13%).

The annual input of nitrogen by precipitation was 2171 mg N m$^{-2}$ of which $NO_3^-$ accounted for 54% (Table 5). As the precipitation passes through the canopy, the water interacts with the canopy by washing off dry deposited elements and by leaching or uptake of elements by the canopy surface causing a total input of nitrogen to the forest floor of 2850 mg N m$^{-2}$ of which $NO_3^-$ accounted for 54%.

Throughfall was always enriched by $NO_3^-$ as compared with precipitation due to wash off of dry deposited $NO_3^-$. The largest enrichment occurred during the growing season where the leaf cover provided the biggest potential for dry deposition and canopy interaction. The throughfall flux of $NO_3^-$ was 33% and 8% higher as compared with precipitation during the growing and leafless seasons, respectively (Table 6). Summing throughfall and stemflow the total annual flux of $NO_3^-$ to the forest floor was 1605 mg N m$^{-2}$ as compared with 1166 mg N m$^{-2}$ in precipitation which resulted in an enrichment of 38%.

In contrast to $NO_3^-$, the mean annual flux of $NH_4^+$ in throughfall was reduced by 8% as compared with the flux in precipitation (Table 6). This reduction indicates that $NH_4^+$ is assimilated in the canopy. Surprisingly there was no major difference in assimilation between the growing and the dormant season, which would be expected with the biggest canopy uptake during leaf cover. However, also the dry deposition is much bigger during leaf cover, which to some extent outbalances the expected difference between the growing and the dormant season. Also, the stemflow accounts for 26% of the annual $NH_4^+$ flux to the forest floor, while only 10% of the $NO_3^-$.

In 1998–1999 we monitored concentrations of $NO_3^-$ and $NH_4^+$ in the top 0–15 cm soil (Fig. 7). During this period the available soil inorganic N (Ni) was dominated by $NH_4^+$, which constituted more than 97% of the total Ni-pool except on three occasions when minor spikes in $NO_3^-$ con-

**Table 5**. Mean annual input of water, $NO_3^-$ and $NH_4^+$ by precipitation, stemflow and throughfall during 1998–2002 at the beech forest at Sorø and the percentage enrichment of water and elements as precipitation passes through the canopy. Canopy enrichment of water equals evaporation.

| | Precipitation | Throughfall | Stemflow | Canopy enrichment |
|---|---|---|---|---|
| Water (mm) | 756 | 497 | 75 | –24 |
| $NO_3^-$ (mg N m$^{-2}$ yr$^{-1}$) | 1166 | 1437 | 168 | 38 |
| $NH_4^+$ (mg N m$^{-2}$ yr$^{-1}$) | 1005 | 925 | 320 | 23 |

**Table 6**. Mean seasonal input of water, $NO_3^-$ and $NH_4^+$ by precipitation, stemflow and throughfall during 1998–2002 at the beech forest at Sorø and the percentage enrichment of water and elements as precipitation passes through the canopy. Canopy enrichment of water equals evaporation.

| Season | Precipitation | Throughfall | Stemflow | Canopy enrichment |
|---|---|---|---|---|
| Water (mm) | | | | |
| Growing | 463 | 259 | 39 | –36 |
| Dormant | 293 | 238 | 35 | –7 |
| $NO_3^-$ (mg N m$^{-2}$ yr$^{-1}$) | | | | |
| Growing | 707 | 939 | 88 | 45 |
| Dormant | 460 | 498 | 79 | 25 |
| $NH_4^+$ (mg N m$^{-2}$ yr$^{-1}$) | | | | |
| Growing | 609 | 555 | 204 | 25 |
| Dormant | 396 | 370 | 115 | 22 |

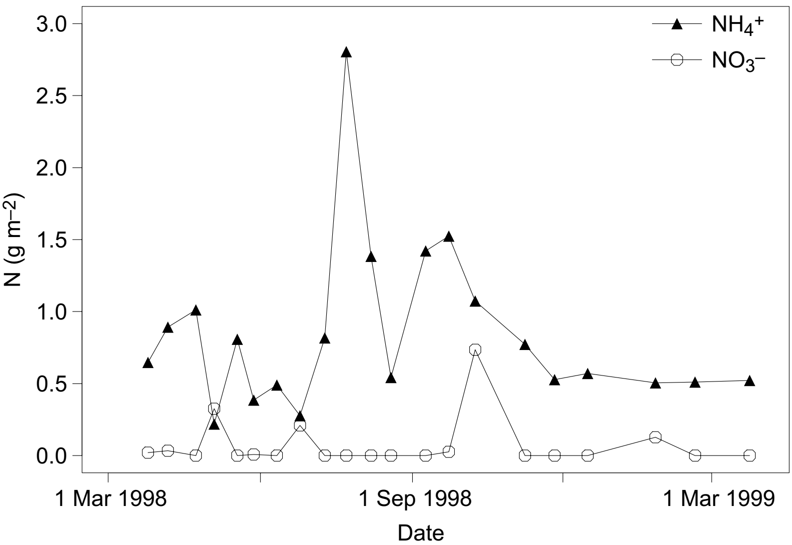


**Fig. 7**. Contents of ammonium-N and nitrate-N in the top 0–15 cm soil depth over the course of one year from March 1998 to March 1999.

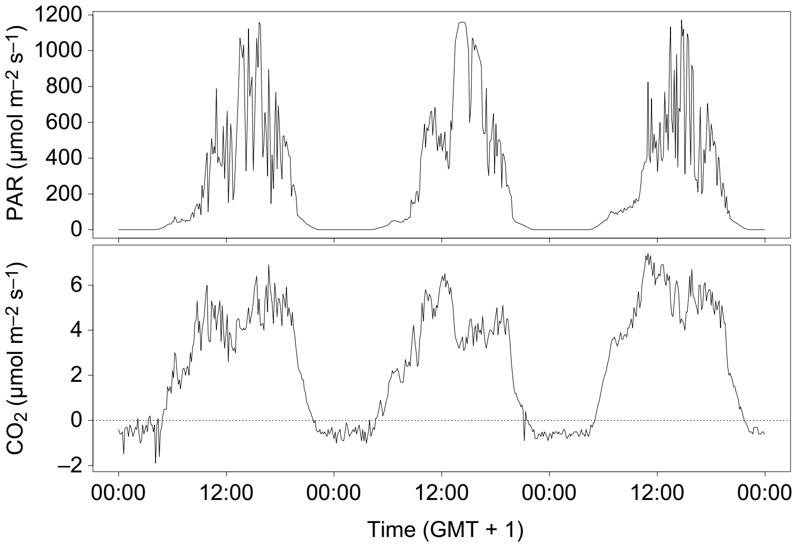


**Fig. 8**. Branch $CO_2$ net exchange in the top of the canopy in relation to PAR. Measurements from three days and nights from 17 to 19 June 2001.

centrations were observed. This $NH_4^+$ dominance is contrasting the proportion of $NH_4^+$ and $NO_3^-$ in throughfall indicating a strong $NO_3^-$ sink in the soil, probably via leaching of the very mobile $NO_3^-$ ion, plant assimilation or microbial utilisation.

The percolation of water to the groundwater has previously been estimated to account for 32% of the input (Beier *et al*. 2001) which equals 242 mm water for the period reported here. Since the nitrogen content in the soil water leaving the root zone is normally very low (< 0.1 mg $l^{-1}$ — data not shown) the yearly leaching of nitrogen to the groundwater is generally small (< 100 mg N $m^{-2}$ $yr^{-1}$) (Beier *et al*. 2001).

The largest input of C and N to the soil surface was by the internal flux with litterfall. The mean annual litterfall at the area was 470 g DW $m^{-2}$ $yr^{-1}$ amounting to 235 g C $m^{-2}$ $yr^{-1}$ and 10 g N $m^{-2}$ $yr^{-1}$ (Beier *et al*. 2001).

## Measurements at plant level

$CO_2$ uptake in one branch chamber ("clap cuvette", 40 × 40 cm) over three days and nights in June 2001 is shown in Fig. 8. The branch was

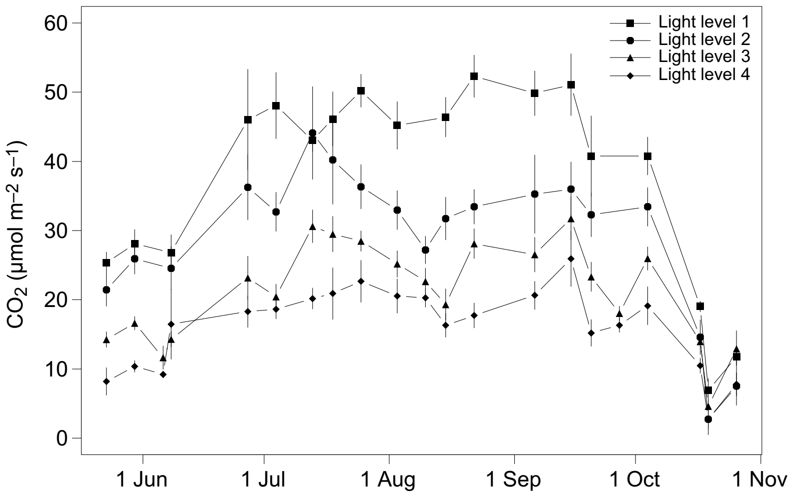


**Fig. 9**. Seasonal photosynthesis ($A_{max}$) in four canopy layers at constant levels of temperature (20 °C), $CO_2$ (1800 ppm) and PAR (1500 µmol $m^{-2}$ $s^{-1}$).

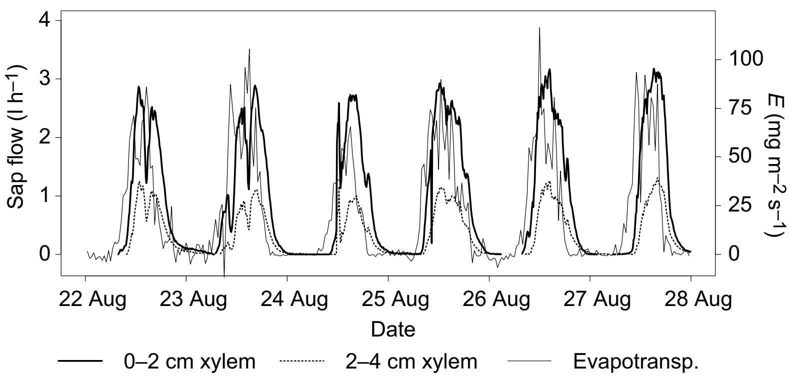


**Fig. 10**. Sap flow in two xylem depths (0–2 cm and 2–4 cm) and evapotranspiration (E) during 22 through 27 August 1998.

positioned in the top of the canopy. Measurements were taken continuously at intervals of 15 min. At low PAR levels, the uptake followed the incoming PAR. The average night respiration was 0.51 µmol $m^{-2}$ $s^{-1}$.

Average light levels in the four canopy layers were measured simultaneously with the LCA3 gas exchange measurements in 2000. On average the canopy layers received 471, 178, 103 and 30 µmol $m^{-2}$ $s^{-1}$ respectively referred to layer 1 to 4. The highest $A_{max}$ values were found in canopy layer 1 followed by layer 2, 3 and 4, and this reflects acclimation to light (Fig. 9). From mid May to mid June $A_{max}$ was only half of the maximum value obtained from late June to mid September. The senescence began to have an effect on $A_{max}$ from mid September.

Typical sap flow responses in two xylem depths during six days and nights in relation to evapotranspiration are shown in Fig. 10. Evapotranspiration began at sunrise, while sap flow initiated up to two hours later. The outer xylem was transporting more water than the older inner xylem. After sunset the evapotranspiration ceased, while the xylem continued to conduct water for some hours.

LAI measurements from 2002 are shown in Fig. 11. Before frondescence of the beech trees LAI was 0.7 and increased to a maximum value of around 5 in July. LAI began to decrease in October and minimum LAI was reached in late November. Specific leaf area (SLA) was fairly constant over the season (Table 7). Average SLA for the shade and sun leaves were 282 and 118 $cm^2$ $g^{-1}$, respectively. Water content was highest in shade leaves as compared with that in sun leaves (53% *vs.* 42%). In the beginning of August the lowest water content was seen for both type of leaves indicating water stress. The average stem diameter was 38.1 cm ± 1.9 cm (S.E.) in 2002. Annual average stem increment from 1998 to 2002 was found to be 6.16 mm $yr^{-1}$.

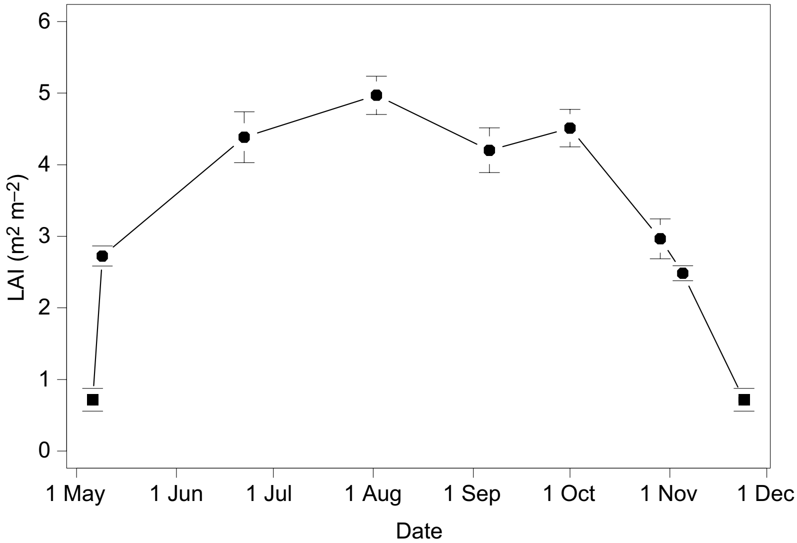


**Fig. 11**. Development of Leaf Area Index ($m^2$ leaf $m^{-2}$ ground) during the growing season 2002. Square symbols represent data based on measurements in December and weekly observations of bud break and defoliation. Points represent measurements throughout the season. Bars represent standard errors.

A summary of the characteristics of the beech forest stand is given in Table 8.

## Summary and outlook

The paper has provided some examples of the different scientific issues addressed at the field station during the last 7 years. Combining information from different investigations can give new insight.

The $CO_2$ exchange has been studied by the eddy flux technique above the canopy and in the trunkspace and by chamber techniques at the branch and leaf level and at the soil surface. The combination of results of soil respiration, trunkspace and above canopy flux in June showed that the total night time respiration was 5 $\mu$mol $m^{-2}$ $s^{-1}$, the soil respiration 2 $\mu$mol $m^{-2}$ $s^{-1}$, leaving about 3 $\mu$mol $m^{-2}$ $s^{-1}$ to the total respiration of the trees. The branch chamber measurements showed nighttime respiration in June of 0.5 $\mu$mol $m^{-2}$ $s^{-1}$ on a leaf area basis. This value can be scaled with the LAI of 4 in June, resulting in 2 $\mu$mol $m^{-2}$ $s^{-1}$ on a projected area basis. Thus it can be implied that the respiration of the stems

**Table 7**. Water content and Specific Leaf Area for sun and shade leaves in growing season 2002.

| Type of leaves | Date | Water content (%) | S.E. | Specific Leaf Area ($cm^2$ $g^{-1}$) | S.E. |
|---|---|---|---|---|---|
| Shade | 22 Jul | 59.1 | 4.5 | 282 | 18.2 |
| | 27 Jul | 52.1 | 1.7 | 277 | 22.7 |
| | 15 Aug | 52.1 | 2.4 | 287 | 16.1 |
| | 3 Sep | 45.9 | 1.5 | 268 | 17.4 |
| | 25 Sep | 54.8 | 0.6 | 279 | 12.2 |
| | 29 Oct | 54.8 | 1.0 | 301 | 19.2 |
| Shade total | | 53.1 | 2.8 | 282 | 16.9 |
| Sun | 22 Jul | 41.1 | 2.6 | 119 | 9.7 |
| | 27 Jul | 40.7 | 3.2 | 106 | 10.5 |
| | 15 Aug | 42.4 | 2.0 | 116 | 11.2 |
| | 3 Sep | 37.7 | 1.6 | 116 | 9.9 |
| | 25 Sep | 44.8 | 1.1 | 116 | 8.3 |
| | 29 Oct | 47.8 | 2.0 | 134 | 20.1 |
| Sun total | | 42.4 | 2.5 | 118 | 11.7 |

and twigs should have been about 1 $\mu$mol m$^{-2}$ s$^{-1}$. This estimate will be compared with direct measurements on stems and twigs in the near future.

The net exchange of $CO_2$ measured by eddy covariance over the forest canopy has consistently shown that the forest is a carbon sink. The average value during 1996–2002 is –190 g C m$^{-2}$ yr$^{-1}$ with a range of –71 to –288 g C m$^{-2}$ yr$^{-1}$. Soil chamber studies of other greenhouse gases ($CH_4$ and $N_2O$) showed that they had a contribution on a $CO_2$ equivalent basis of less than 10% of the $CO_2$ and since they had opposite signs ($N_2O$ being emitted, $CH_4$ being deposited) their net influence was almost negligible.

The cycling of nitrogen was investigated in precipitation, throughfall, stemflow and soil water. The total input of nitrogen to the forest with precipitation was 2 g m$^{-2}$ yr$^{-1}$, with $NO_3^-$ and $NH_4^+$ in almost equal amounts. The throughfall was enriched in $NO_3^-$ indicating leaching from the canopy, but slightly depleted in $NH_4^+$. The net result was a 30% higher N deposition to the forest floor as compared with deposition through precipitation only. In contrast to the precipitation and throughfall the soil water was completely dominated by $NH_4^+$ indicating strong leaching or uptake of $NO_3^-$. The internal cycling of N with litterfall was much higher (10 g m$^{-2}$ yr$^{-1}$).

The establishment of the Sorø field station has proved very useful for interdisciplinary field studies and has provided a Danish platform for a large number of national and international projects. Scientists from many countries in Europe and from the United States have carried out research at the site and results from the station have been utilized for a large number of purposes. We plan to run the station for at least 5 more years, hopefully much longer, and intend to continue to improve and extend the facilities and the permanent continuous measurements. In the future we would like to extend the measurements to include particles and volatile organic compounds. This will enable us to make more complete studies of the interaction of the forest with the physics and chemistry of the atmosphere.

**Table 8**. Characteristics of the beech stand surrounding the field station.

| Parameter | Value (year of determination) |
|---|---|
| Age (from planting year) | 82 yr (2003) |
| Height | 25 m (2003) |
| Roughness length | 1.6 m (Dellwik and Jensen 2000) |
| Displacement height | 19 m (Dellwik and Jensen 2000) |
| Fetch | 0.5–1 km (depending on direction) |
| Diameter at breast height | 38 cm (2002) |
| No. of stems | 283 stems ha$^{-1}$* |
| Leaf area index (LAI) | 5 m$^2$ m$^{-2}$ (peak value 2002) |
| Specific leaf area (SLA) | 282 cm$^2$ g$^{-1}$ (sun leaves)<br>118 cm$^2$ g$^{-1}$ (shade leaves) |
| Litterfall | 470 g m$^{-2}$ yr$^{-1}$ (1998–2000) |
| Stem increment | 6.16 mm yr$^{-1}$ (1998–2002) |
| Wood increment | 11 m$^3$ ha$^{-1}$ yr$^{-1}$* |
| Net ecosystem exchange | –190 ± 30 (S.E.) g C m$^{-2}$ yr$^{-1}$ (1996–2002) |

*Values not measured but inferred from yield tables with entries 80 years.

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