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SILVA FENNICA

a quarterly journal of forest science

Climate Change, Biodiversity and Boreal Forest Ecosystems

Papers selected from the International Boreal Forest Research Association Conference held in Joensuu, Finland, 30 July–5 August, 1995

Vol. 30(2–3), 1996

The Finnish Society of Forest Science
The Finnish Forest Research Institute

Contents

Preface

Projections concerning future population growth on the global level indicate that there will be an increase from the current 5.7 billion to 11 billion by the year 2100 (Source: World Bank). Predictions concerning the world's population growth do, however, vary from 6.4 to 17.6 billion in scenarios produced by the United Nations. Compared with the time horizons of the boreal forests, this is about the same time that it takes for a pine seedling to grow into a mature tree. With increasing numbers of people demanding higher standards of living and with increasing urbanisation taking place, it is likely that greater amounts of greenhouse gases than hitherto will be produced and these will also influence the demand for forest products. International conventions on decreasing emissions of greenhouse gases are important in the endeavour to slow down the build-up of these gases in the atmosphere. Since many greenhouse gases have relatively long lifespans in the atmosphere, the concentration of these gases will increase even if the current level of emissions is retained. Recent scenarios predict increases of 1.0–3.5 °C in the global mean surface temperature by the year 2100. The expected increase depends, for example, on which one of the emissions scenarios for energy production and consumption one is referring to. Complicated climate models have succeeded in simulating the development of the mean temperature of the earth starting from a reference year in the late 18th century. Models including the effects of greenhouse gases give overestimates of the increase in mean temperature. If the effects of aerosols are included, the simulations are closer to the measured mean temperature. Scientific knowledge about this complex and difficult atmosphere-ocean-land system has improved and simulated predictions are coming closer to the measured temperature.

The boreal zone has experienced climate changes in the past when the ice sheets retreated before the present inter-glacial period. This period created major changes in ecological communities and the distribution of species. A drastic difference in the climatic warming in the beginning of the present inter-glacial and the predicted climate change is the rate of the temperature increase, which could be in the order of ten or more times faster than the temperature increase that the boreal ecosystem have experienced so far. Succession in the boreal ecosystem is a slow process and hence rapid changes in the environment could generate complex responses by the ecosystem. It is of utmost importance to increase scientific knowledge about how the species and interaction of species in the ecosystem may respond to environmental changes. An understanding of these responses should be achieved at all hierarchical levels of ecosystems and covering long enough periods of time.

During the 1980s public concern was expressed over the future of forests and it led to universal changes in the attitude to forests. The UNCED Earth Summit conference held in Rio de Janeiro in 1992 and the commitment of governments to sustainable development made biodiversity of ecosystems into a basic element of sustainable management of forests. Biodiversity is coupled to the global change in complex ways, including direct, interactive and long-term impacts of human activities on ecosystems. European and international processes are in progress for promoting the implementation of the UNCED resolutions in the field of management, conservation and sustainable development of forests. The broad objectives of these processes are to develop sustainable management of forests, to enhance international research concerning forestry, and to develop appropriate criteria and indicators for sustainable forest management in order to monitor and evaluate sustainability. Although a lot of scientific research is available about species diversity and the successional development of boreal forests, research is needed for tackling the matter of development of ecosystems under changing environments, human impacts, and different management strategies.

The International Boreal Forest Research Association (IBFRA) was founded in 1991 with the mission to "promote and co-ordinate research to increase the understanding of the role of the circumpolar boreal forests in the global environment and effects of environmental change". The Second International Science Conference of IBFRA was held between 30 July and 5 August, 1995, in Joensuu, Finland, on the theme of "*Climate Change, Biodiversity and Boreal Forests*". IBFRA's endeavour is that research results and the synthesis of knowledge produced by its activities are presented and published in recognised scientific forums and publications. The speakers at the Joensuu Conference were invited to submit manuscripts expanding their presentations at the meeting for inclusion in a special edition of the journal *Silva Fennica*. The manuscripts were subject to peer review by the journal. This special edition of *Silva Fennica* contains nearly thirty articles from a global group of experts providing scientific, economic, and policy perspectives on climate change and biodiversity in context of boreal forests. The papers cover a wide range of topics on how boreal forests may respond to the changing environment and how the productivity and biodiversity of boreal forests may develop under various managing practices. In addition to the global perspective of boreal forests, this issue of *Silva Fennica* includes research results obtained in the course of the Finnish Research Programme on Climate Change (SILMU). Results of special interest are those pertaining to research focusing on the boreal forests of Russia.

We hope that this issue will be a source of new knowledge in the endeavour to outline the wide range of the potential consequences that global change may have for boreal forests. Our intention is that the research results published in this issue will serve to complement the scientific basis for the sustainable management of boreal forest resources and provide new perspectives for the development of constructive policies to improve management strategies for preserving the vitality of the boreal forests and their potential as a source of economic and social well-being. Progress in the scientific understanding of and knowledge on the boreal forests and their responses to global change will help in constructing and assessing decisions. An integral element of scientific progress is that it stimulates research to tackle challenging problems of international relevance.

Helsinki, Finland, June 1996

Eeva Korpilahti
Editor

Seppo Kellomäki
Timo Karjalainen
Sini Niinistö
Conference Steering Committee

Acknowledgement

First of all, we would like to acknowledge all the contributors to this special issue, as well as the reviewers of the manuscripts, and not forgetting Dr Eeva Korpilahti and her staff in Silva Fennica editorial office. The sponsors of the IBFRA 1995 conference were The Finnish Research Programme on Climate, the Finnish Ministry of Agriculture and Forestry, and the Finnish Ministry of Education, and they are gratefully acknowledged. Also support from European Forest Institute, Finnish Forest Research Institute, and Faculty of Forestry at the University of Joensuu is acknowledged with grateful appreciation.

We would like to thank Professor Erkki Annila, Dr Markku Kanninen, Professor Eino Mälkönen, Professor Eljas Pohtila, and Dr Risto Päivinen for their valuable work in planning and setting up the conference as members of the steering committee of the IBFRA 1995 conference.

Seppo Kellomäki
Timo Karjalainen
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Statement of the Joensuu IBFRA 1995 Conference

Boreal Forests

The world's forested ecosystems are a vital link in the exchange of carbon dioxide between the atmosphere and the biosphere. In this context, the boreal forests of Eurasia and North America have a special role in controlling the global carbon cycle, since boreal forested ecosystems and peatlands account for more than one-third of the carbon accumulated in the biosphere. However, these boreal forests also provide economic, environmental and social benefits, thus making the northern regions habitable.

The predicted global climate change is among the major factors affecting future economic and social development in the boreal zone. Research and international collaboration are needed to create a solid knowledge base for, (1) the assessment of the ability of boreal forests to mitigate the effects of global change, and (2) on the growth and development of boreal forests under a changing climate.

Conservation of biodiversity has become one of the major issues of public concern. Population pressure on forests in the boreal zone is less than elsewhere, but forests in the boreal zone are, nevertheless an important source of well-being. The concept of biodiversity, and measuring and applying it in forest management, is currently an important research gap.

Changes in tropical forests were the first to attract interest all over the world. Since boreal forests are now also a subject of major interest, the different processes in these two large ecosystems should be emphasized.

International Boreal Forest Research Association

The International Boreal Forest Research Association (IBFRA) was founded in 1991, and consists of the six boreal zone countries: Canada, Finland, Norway, Russia, Sweden and the U.S.A. The three major areas of interest within IBFRA are the effects of global climate change, monitoring and classification of boreal forests, and biodiversity and forest management.

Although excellent research has been carried out on the effects of global climate change on boreal forests, more research and funding are urgently needed since the boreal forests are predicted to undergo more changes than tropical or temperate forests within the coming decades. It is also important to use monitoring as an important tool in studying changes in boreal forests.

The Joensuu Conference

IBFRA met for the 6th time in Joensuu, Finland, 30th July–5th August 1995, and the theme was "Climate Change, Biodiversity and Boreal Forest Ecosystems". One hundred participants attended this scientific conference, representing 13 countries; this indicates the broad research interest in boreal forest issues even outside the boreal countries themselves. Information was presented in 79 presentations (45 oral and 34 posters), which highlighted the recent progress in research aimed at increasing our understanding of climate change and biodiversity related to boreal forest ecosystems. Atmospheric prediction models increasingly agree on the fact that the greatest magnitude of warming will be in boreal forest zones. Evidence was also presented that both temperature and growth enhancing effects of elevated CO_2 are already affecting the boreal forests.

As we look in to the future, IBFRA is pleased that the importance of boreal forests to the well being of the Earth and its people is being increasingly recognized. At the same time, researchers are concerned that the boreal forest resource is changing more rapidly than we are developing the knowledge needed for sustainable management. IBFRA will continue to strive for enhancement of this necessary knowledge base and to facilitate international scientific cooperation regarding boreal forest ecosystems. The countries participating in IBFRA should have a special responsibility in this respect.

Next IBFRA Conference

The next IBFRA conference will be held in Russia in 1996. Interest and participation in the IBFRA conferences in 1994 (Saskatoon, Canada) and this year in Joensuu show that IBFRA has a promising future and the association looks forward to continuing its activities in support of boreal forest research.

Eljas Pohtila
President of the International
Boreal Forest Research Association

Silva Fennica 30(2–3)

Part I
Climate Change

Measurements of O_3, CO_2 and H_2O Fluxes over a Scots Pine Stand in Eastern Finland by the Micro-meteorological Eddy Covariance Method

Mika Aurela, Tuomas Laurila and Juha-Pekka Tuovinen

Aurela, M., Laurila, T. & Tuovinen, J-P. 1996. Measurements of O_3, CO_2 and H_2O fluxes over a Scots pine stand in eastern Finland by the micrometeorological eddy covariance method. Silva Fennica 30(2–3): 97–108.

The eddy covariance technique is a novel micrometeorological method that enables the determination of the atmosphere-biosphere exchange rate of gases such as ozone and carbon dioxide on an ecosystem scale. This paper describes the technique and presents results from the first direct measurements of turbulent fluxes of O_3, CO_2 and H_2O above a forest in Finland. The measurements were performed during 15 July–5 August 1994 above a Scots pine stand near the Mekrijärvi research station in Eastern Finland. The expected diurnal cycles were observed in the atmospheric fluxes of O_3, CO_2 and H_2O. The data analysis includes interpretation of the O_3 flux in terms of the dry deposition velocity and evaluation the dependency of the net CO_2 flux on radiation. The eddy covariance method and the established measurement system has proved suitable for providing high-resolution data for studying ozone deposition to a forest as well as the net carbon balance and related physiological processes of an ecosystem.

Keywords eddy covariance technique, ozone deposition, net carbon balance, micrometeorology, Scots pine stands
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1 Introduction

An understanding of the gas and energy exchange at the atmosphere/biosphere interface plays an increasingly important role in studies on air pollution and climate dynamics. As an example, the tropospheric ozone problem has been recently addressed by the UN-ECE Convention on the Long-Range Transport of Air Pollutants by adopting new air quality standards to protect crops and forests that are based on the critical level concept (Fuhrer and Achermann 1994). The critical levels are derived from experimental data on the dependency of ozone-induced effects on plants under exposure to atmospheric ozone. By defining more specifically the circumstances when the damage is likely to occur (i.e. elevated concentrations, growing season, daylight hours), the present approach introduces a major improvement over employing simple long-term mean concentrations as indices of air quality. However, the ultimate relation between the atmospheric concentrations (exposure) and the actual effect-inducing dose (deposition flux) experienced by the receptors is not considered explicitly. Another recent issue is that of climate change, in which the surface exchange of greenhouse gases, such as CO_2 and O_3, has been identified as a key research area for reducing the uncertainty in climate scenarios (Houghton et al. 1995).

Micrometeorological methods provide a means of quantifying the gas and energy exchange at the surface on an ecosystem scale. The most sophisticated of these methods is the eddy covariance technique, in which the high-frequency fluctuating components of the vertical wind velocity and, for example, the gas concentration are measured and correlated to produce a direct measurement of the vertical flux density of the component at the surface. The need for fast-response analyzers has been a problem, but during the last decade suitable instruments have become available for several compounds, e.g. for ozone (Güsten et al. 1992) and carbon dioxide (LI-6262... 1991). In addition, general micrometeorological requirements exist regarding statistical stationarity and horizontal homogeneity of the near-surface atmospheric flow (e.g. Businger 1986). These features make the eddy covariance method rather laborious and less suitable for the continuous monitoring of atmospheric deposition, but highly useful for providing data for studying processes (e.g. Erisman et al. 1994a). Recently, however, long term flux measurement campaigns based on the eddy covariance technique have been conducted successfully.

The processes of interest within this study are related to the deposition of ozone and the carbon balance in a boreal forest. In a previous study (Aurela 1995), the eddy covariance facility of the Air Quality Department of the Finnish Meteorological Institute was used for measuring ozone fluxes above an agricultural field. This paper describes results from the first direct measurements of turbulent fluxes of O_3, CO_2 and H_2O above a forest in Finland. The measurements were performed above a Scots pine stand at the Mekrijärvi research station in Eastern Finland in collaboration with the Faculty of Forestry of Joensuu University (Kellomäki 1994).

2 Material and Methods

2.1 Eddy Covariance Method

The general approach adopted in micrometeorological methods is to measure the turbulent flux above the surface assuming the flux divergence below the measuring height to be negligible. The eddy covariance method is the most direct approach to measuring turbulent fluxes of different compounds. Taking the time averages as area averages it offers an excellent tool for estimating fluxes on an ecosystem scale. In this method, the high-frequency fluctuating components of the vertical wind velocity (w) and, for example, the gas concentration (c) are measured and correlated to give a direct measurement of the flux density

$$\overline{F_c} = \overline{w'c'} \quad (1)$$

where the primes denote deviations from mean values and the overbars denote means over periods of typically 30 min. Similarly, by observing the fluctuations in the horizontal wind velocity, u, temperature, T, and specific humidity, q, the turbulent fluxes of momentum, sensible heat and latent heat can be measured. (In Eq. 1, c is then replaced by ρu, $\rho c_p T$ and ρλq, respectively, where ρ is the density of dry air, c_p the specific heat of air at constant pressure and λ the latent heat of vaporization of water.)

The fundamental requirement in flux measurements with the eddy covariance technique is to get the contributions from all sizes of turbulent eddies, implying a typical sampling frequency of no lower than 5 observations per second. In practice, however, the limiting factor is the frequency response of the sensors. Furthermore, general micrometeorological requirements exist regarding the statistical stationarity of the near-surface atmospheric flow and the horizontal homogeneity of the surface. The homogeneity requirement imposes stringent conditions with respect to the measurement site and the measurement height. In practice, flow conditions with an adequate fetch to provide equilibrium with the surface are often obtained only in limited wind sectors. The measurement height should be low enough to conform with the limited fetch, but still uninfluenced by the local inhomogeneity of the surface. The minimum height is also limited by the height-dependence of the size of the turbulent eddies. According to Businger (1986) the minimum operating height is 6πp, where p is the path length of the sensor.

Even under ideal flow conditions there is a need for the addition in Eq. 1 of the small mean vertical velocity produced by the sensible heat and water vapour fluxes with their associated density fluctuations, if these are conserved in the sampling system (Webb et al. 1980).

2.2 Measurement Site

The measurement site (62°52'N, 30°55'E, elevation 175 m a.s.l.) is located near the Mekrijärvi research station of Joensuu University in eastern Finland, not far from the Russian border. The terrain is heathland mainly covered by Scots pine (*Pinus sylvestris*) having a height of 6 to 7 metres. An adequate fetch is obtained in wind directions from 160 to 340 degrees. To the south there is a narrow bog area at a distance of 150 m beyond which the forest continues at the same height, but not as dense. In directions from 80° to 160° the fetch varies from 50 to 100 m and the associated data should be taken as uncertain. To the north, there is a logging area that limits the useful measurement sector. In the wind sector used, the fetch varies from 200 to 400 metres, which can be considered satisfactory. The aerodynamic roughness length (z_0) of 0.5 m was calculated from the wind measurements by assuming the zero-plane displacement (d) to be 3/4 of the average height of the roughness elements (Thom 1971).

2.3 Instrumentation

2.3.1 Eddy Covariance Instruments

The eddy covariance measurements were performed on an elevatable platform at a height of 10 m. The measurement system consisted of an ATI SWS-211 sonic anemometer, a LI-COR LI-6262 CO_2/H_2O analyzer and a GFAS OS-2 ozone analyzer (see Table 1). The SWS-211 is a three-axis acoustic anemometer which also works as a fast-response thermometer, providing an accurate measurement of the virtual temperature, $T_v = T(1 + 0.61q)$ (Kaimal and Gaynor 1991). The measurements with the LI-6262 are based on the difference in absorption of infrared radiation passing through two gas sampling cells (LI-6262... 1991). The OS-2 is based on surface chemiluminescense reactions of ozone with an organic dye (Güsten et al. 1992). The relative accuracy of the OS-2 is adequate for eddy covariance measurements, but it has no absolute accuracy, so we used a slow-response ozone monitor based on UV-absorption for calibrating the OS-2 every half-an-hour.

The sonic anemometer was mounted at the end of a rotatable bar 2.5 m in length, directed manually towards the prevailing wind direction. The mouth of the inlet tubes for the OS-2 and the LI-6262 was attached 0.3 m away from the vertical wind component path of the sonic anemometer, resulting in a small lateral separation of the sensors. The length and the radius of the tube of the OS-2 were 0.7 m and 1 cm, respectively, and the flow rate was 100 l/min. For the LI-6262, the air was sampled through a tube of 1.55 mm in radius and 4 m in length. The flow rate was kept at 6 l/min, as controlled by a critical orifice. This

Table 1. Instrumentation at the Mekrijärvi site.

Component	Sensor	Height (m)	Data collection frequency (Hz)
Eddy covariance data			
CO_2	LI-6262, LI-COR, USA	10	5
H_2O	LI-6262, LI-COR, USA	10	5
O_3	OS-2, Gesellschaft für Angewandte Systemtechnik, Germany	10	10
O_3	Model 49, Thermo Environmental Instruments Inc., USA	10	0.1
3-D Wind	SWS-211, Applied Technologies Inc., USA	10	10
Air temperature	SWS-211, Applied Technologies Inc., USA	10	10
Meteorological data			
Air temperature	HMP35D, Vaisala, Finland	1, 3	
Surface temperature	DTS12G, Vaisala, Finland	0	
Humidity	HMP35D, Vaisala, Finland	1, 3	
Net radiation	Suomi-Franssila	3	
PAR	LI-190SZ, LI-COR, USA	3	

design guarantees a turbulent flow in the inlet tubes and consequently a small attenuation of fluctuations. A sampling rate of 10 Hz was used for the sonic anemometer and the OS-2. The LI-6262 data was collected through the serial port with an output rate of 5 Hz.

2.3.2 *Supporting Meteorological Instruments*

Additional meteorological data were obtained from a weather station situated 10 metres north of the eddy covariance tower. Temperature and humidity were measured at two heights (1 and 3 m). Temperature was also measured at the surface. Photosynthetically active radiation (PAR) and net radiation were measured at 3 m. Regarding radiation measurements, we had some tree shadowing problems in the afternoon, so all the afternoon radiation data had to be disqualified. The instrumentation of the meteorological tower is shown in Table 1.

2.3.3 *Data Collection*

Sonic wind and temperature data were input digitally from the SWS-211 to a personal computer (PC 386). The data from both O_3 monitors were digitized by the A/D converter in the SWS-211 and combined with wind and temperature data. The LI-6262 data were input directly to the PC through a second serial port. The collection was carried out by a modified version of a program due to McMillen (1986), using an averaging period of 30 min. The lags between the time series resulting from the air tubes and the lateral displacement of sensors were taken into account in the on-line calculation of the flux quantities. The lag time was determined by maximising the covariances between the vertical wind speed and the gas concentration. The drifts and trends not associated with turbulent transport were removed by using a 200-s running mean filter, and the coordinate frame was rotated to correct for a possible misalignment of the sensor (McMillen 1988). This procedure also provides a correction for non-optimal terrain. Ozone fluxes were corrected for the density fluctuations related to heat and water vapour fluxes (Webb et al. 1980). For the LI-6262 data this was not found necessary. By measuring simultaneously the carbon dioxide and water vapour concentrations the LI-6262 is capable of correcting the CO_2 concentrations proportional to dry air (LI-6262... 1991). Due to the damping of the temperature fluctuations in the inlet tube, the

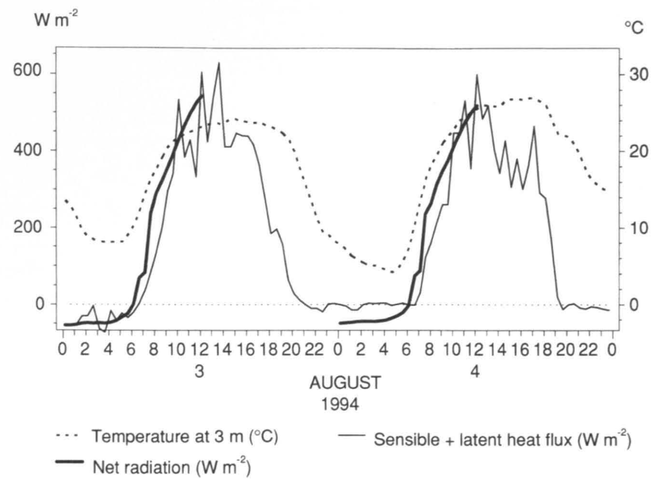

Fig. 1. The net radiation, the sum of the sensible heat and latent heat fluxes, and the temperature at the Mekrijärvi research site over a two-day period. The zero-level for all variables is marked with a dashed line.

corresponding heat-originated density fluctuations are assumed to be negligible.

All the supporting meteorological data were collected into a Vaisala QLI50 data-logging front end and archived by the PC 286. Data were saved as 10-min averages together with minima and maxima for each period.

3 Results

The measurement campaign was performed over the period 15 July to 5 August 1994. Due to the limited wind sector for acceptable flow conditions and some technical problems, part of the data obtained had to be discarded. Presented here are some results from the longest undisturbed period 3–4 August 1994.

3.1 Meteorological Conditions

On the selected days, 3–4 August 1994, the weather was fair, being almost cloudless on the 3rd but becoming partly cloudy at noon on the 4th. During the daytime the wind direction was in the sector 160° to 280°, with wind speeds varying mainly from 1.5 to 2.5 m s^{-1}. During the night before 3 August the wind direction was between 90 and 100 degrees. The night between 3 and 4 August was quite calm and the wind direction was unstable. The relative humidity was typically 50 % during the days, reaching almost 100 % during the night.

Time series of temperature, net radiation and the sum of the sensible heat flux and the latent heat flux are presented in Fig. 1. At 3 m the temperature varied from 5 to 27 °C, the fluctuation being somewhat smaller at 10 m. Net radiation is only presented for the forenoon because of the shadowing problems with the radiometers in the afternoon. Observed maximum PAR values on these two days were about 1300 µmol m^{-2} s^{-1}, corresponding to maximum net radiation values of 600 W m^{-2}. Fig. 1 shows that the total heat flux is very similar in magnitude to the net radiation. The components, the sensible and latent heat flux, are close to each other in magnitude, both having a maximum of 300 W m^{-2} in

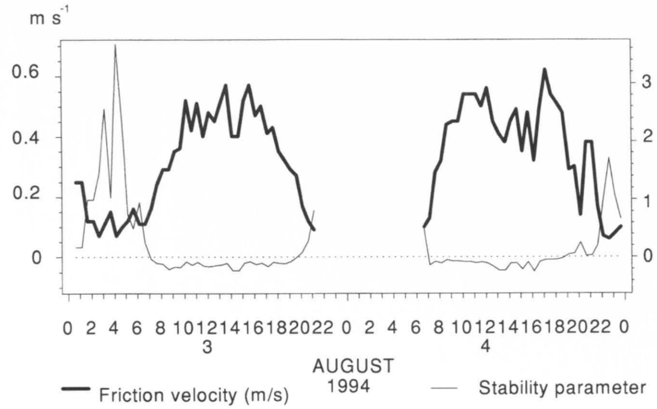

Fig. 2. The friction velocity and the dimensionless stability parameter at 10 m at the Mekrijärvi research site over a two-day period. The zero-level for all variables is marked with a dashed line.

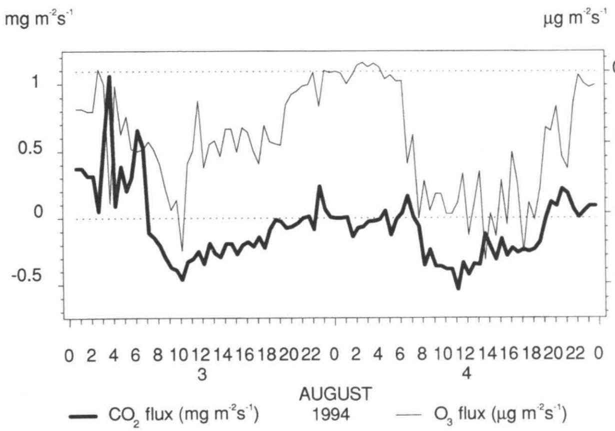

Fig. 3. CO_2 and O_3 flux densities measured at the Mekrijärvi research site. The zero-levels for the fluxes are marked with dashed lines.

the afternoon. In the forenoon, from 6 to 10 o'clock, the surplus of net radiation is converted into warming of the ground and biomass.

The turbulent properties of the flow can be characterised by two further quantities, the friction velocity and the stability parameter (Fig. 2). The friction velocity, $u_* = (-\overline{u'w'})^{1/2}$ represents the vertical flux of momentum and can be taken as a measure of mechanical turbulence. An appropriate measure of the surface-layer stability is the dimensionless height, $\zeta = (z - d) / L$, where z is the height above the ground, d the zero-plane

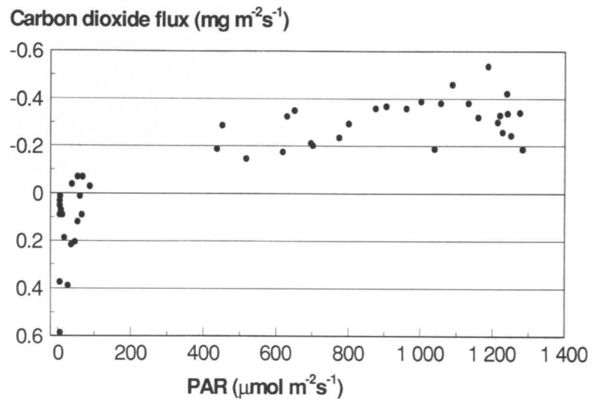

Fig. 4. CO_2 flux density versus PAR at the Mekrijärvi research site 3–4 August 1994. All afternoon observations have been discarded due to uncertain radiation measurements. Negative values represent downward flux.

displacement height and L the Obukhov length (the ratio of the turbulence production by buoyancy and shear forces, $L = -u_*^3 \overline{T_v} / (\kappa g \overline{w'T_v'})$, where $\kappa = 0.4$ is the von Kármán constant and g the acceleration due to gravity).

The strong diurnal cycle depicted in Fig. 1 is also present in the friction velocity and the stability parameter. During the daytime, the surface layer is moderately unstable ($\zeta \approx -0.2$ at z = 10 m) as a result of strong buoyancy, but it is rapidly stabilised as radiative heating is diminished. At the same time the mean wind and mechanical turbulence are reduced, and highly stable conditions prevail during the night (the data are discarded in Fig. 2 as the turbulent quantities become ill-defined).

3.2 CO_2 and O_3 Fluxes

Soil and vegetation can act both as a source and a sink for atmospheric constituents. The decomposition of organic matter releases carbon dioxide from the soil into the atmosphere, whilst for vegetation the fluxes are bi-directional (photosynthesis/respiration). For ozone, vegetation and the soil constitute a powerful sink, and no emission of ozone takes place. Ozone and carbon dioxide fluxes for the measurement period are shown in Fig. 3. Negative fluxes indicate deposition to the forest surface.

Both the daytime photosynthesis and the nocturnal respiration are observed in the atmospheric CO_2 fluxes. The ozone flux has a clear diurnal cycle having its maximum around midday and effectively vanishing for the duration of the night. Both fluxes are controlled by turbulent mixing and physiological processes. The effect of the atmospheric turbulence is seen clearly in the short-term co-variation between the fluxes in Fig. 3. During the daytime the variations in the curves are well correlated, while at night, when CO_2 is emitted from the soil and vegetation, they are anticorrelated.

The daytime changes in CO_2 fluxes can be explained by the variations in photosynthetically active radiation (PAR), which drives the assimilation. In addition, PAR largely controls the opening of leaf stomata, which form the primary pathway for respiration and the uptake of CO_2 by plants. Fig. 4 presents the observed relationship of the net CO_2 flux to PAR. The CO_2 uptake increases strongly with increasing radiation until a threshold value of 400 µmol m^{-2} s^{-1} is reached.

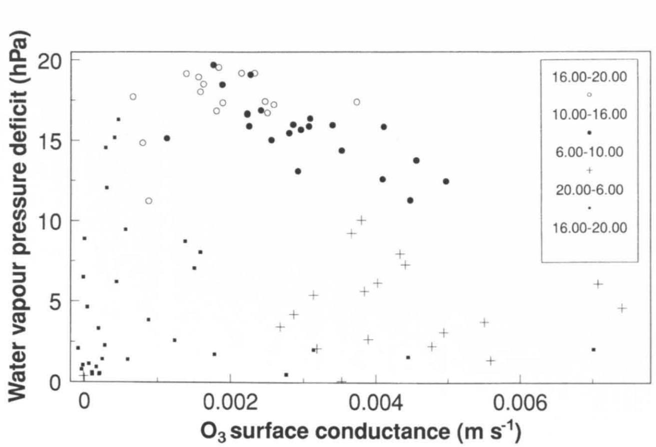

Fig. 5. Surface conductance of O_3 and water vapour pressure deficit. Symbols represent half-hour averages during the period from 3 August 00.40 to 5 August 9.40 (local time).

The direction of the net flux is reversed from net release to net uptake at a low PAR value of less than 100 µmol m^{-2} s^{-1}. At the higher end, increasing radiation does not much affect the carbon dioxide flux. All afternoon values have been discarded from this data set due to tree shadows on the radiometers, and therefore it is not possible to evaluate if the behaviour remains monotonous at higher PAR.

3.3 Dry Deposition Velocity of Ozone

Scaling the ozone flux densities by the mean concentrations produces a quantity, the deposition velocity $v_d = \overline{F_c} / \overline{c}$ of ozone, that can be used as a generalized measure of the deposition rate. Although the ozone concentration and the ozone flux both exhibit a diurnal cycle, they are not proportional by a constant value. Thus v_d also exhibits a diurnal cycle, which is governed by both the physiological functioning of the leaf stomata and the turbulent transport above the canopy.

The effect of the atmospheric processes can be differentiated by assuming the deposition process to be controlled by three series resistances, of which the surface resistance, r_s (or its inverse, the surface conductance), represents solely the biological and chemical affinity between the depositing component and the receptor surfaces. The surface resistance can be obtained from the flux measurements as a residual in the total resistance after subtracting the other two resistances, namely the atmospheric resistance r_a and the molecular resistance r_b, for which standard micrometeorological formulations exist (Garratt 1992, Hicks et al. 1987):

$$r_a = \frac{1}{\kappa u_*}\left[\ln\left(\frac{z-d}{z_0}\right) - \Psi_h(\zeta)\right] \quad (2)$$

and

$$r_b = \frac{2}{\kappa u_*} Le^{2/3} \quad (3)$$

where z_0 is the roughness length, Ψ_h is the diabatic influence function for heat and Le is the Lewis number (the ratio of diffusion coefficients for heat and gas). The bulk surface resistance obtained thus represents all the possible sinks of ozone, the most important of these being via stomata (e.g. Erisman et al. 1994b).

The surface resistance depends on a number of factors, including the dependence of the stomatal conductance on PAR, temperature, water vapour pressure deficit and water potential. Fig. 5 shows the surface conductance (1 / r_s) as a function of the vapour pressure deficit, VPD, which is defined as the difference between the temperature-dependent saturation vapour pressure and the water vapour pressure in the ambient air. Assuming that the leaf temperature equals the ambient air temperature, the VPD can be taken as a difference of water vapour pressures outside and inside the leaf and it can be used as a measure of the drying power of the air. A clear diurnal cycle is seen in the surface conductance, organized here as a circular shape that results from simultaneous cycles of humidity and radiation-derived forcings. The different times of the day are clustered in a way that shows higher conductances in the forenoon than in similar radiation conditions in the afternoon. This is most likely due to differences in the air humidity. In the forenoon the humidity is higher and and plants keep their stomata wider open. In the afternoon, when the air gets drier, plants try to save water and partly close their stomata, resulting in a decrease in the surface conductance.

Concerning the deposition velocity, the surface resistance constitutes the major part of the total resistance during most of the period considered in Fig. 3. Similar results have been obtained by e.g. Lamaud et al. (1994). Exceptions to this are periods with low wind speed and high hydrostatic stability, when the total resistance to deposition is dominated by the atmospheric resistance. A daytime (06-18 local time) mean value of 0.25 cm s^{-1} was obtained for the dry deposition velocity of ozone during the 2-day period, the 30-min averages ranging from 0.1 to 0.5 cm s^{-1}. Night values were typically less than 0.05 cm s^{-1}.

3.4 Accuracy of the Fluxes Measured by the Eddy Covariance Method

There are several sources of uncertainty involved in eddy covariance measurements, both of theoretical and practical origin, as summarised e.g. by Businger (1986). These are briefly discussed in this section. Theoretically, the assumptions justifying the use of Eq. 1 are never completely fulfilled, but the effects of horizontal advection and entrainment from above the boundary layer, for instance, are difficult to quantify. Chemical reactions below the measurement height potentially affect the flux divergence of chemically-active species like ozone. At Mekrijärvi this is not very probable, as the measurement site is not close to any significant NO sources.

In deriving Eq. 1, it is assumed that the mean vertical wind velocity is zero. Even in ideal flow conditions, non-homogenous terrain and misalignment of the anemometer may produce an apparent vertical wind component. These are corrected for in the applied acquisition programme by defining the coordinate system with respect to the streamlines of the flow (McMillen 1988).

In contrast with the other popular micrometeorological technique, the gradient method, the absolute accuracy is normally not a problem with the eddy covariance method. However, the averaging time being a compromise for stationarity, there remains a relatively large statistical uncertainty in the flux measurements because of the intermittency of the turbulent transport. With the averaging time of 30 min used here, an accuracy of 20 % can be expected for an individual flux value (van Pul 1992).

A part of the actual flux may be lost as a result of incomplete representation of the real turbulent spectrum. A small loss is due to the digital high-pass filter used to remove the non-turbulent motions which also depletes the low-frequency end of the covariance spectrum. The time constant of 200 s used here may cause a maximal flux reduction of 5 % in unstable conditions (McBean 1972). A more serious removal of contributing frequencies and the corresponding flux is likely to take place at the high end of the spectrum, if the response time of the analyzer is not adequate. Likewise, a small attenuation of high frequencies may be attributed to the separation of the gas sampling inlets from the wind sensor.

High frequencies may also be attenuated in the inlet tube especially if the tube flow is laminar (e.g. Leuning and Moncrieff 1990). In the present system, turbulent flow is maintained (the Reynolds number is 2800 for the LI-6262 tube flow), which results in a negligible attenuation of high-frequency concentration fluctuations, as calculated according to the theory presented by Lenschow and Raupach (1991). The damping of temperature fluctuations can still be important for the CO_2/H_2O measurements. In this study all fluctuations are assumed to have vanished and thus no density correction (Webb et al. 1980) is made. A proper way would be to take this correction into account partly depending on the portion of the remaining temperature fluctuations.

The time response of the fast ozone analyzer used in this study is better than 0.1 s (Güsten et al. 1992) and that of the CO_2/H_2O instrument proved to correspond to its sampling rate of 5 Hz when tested in the laboratory before the field campaign. Therefore, no frequency response corrections, as proposed e.g. by Moore (1986), were found necessary for the ozone data, though they might be appropriate for CO_2 and H_2O. Nevertheless, the analog filter applied to remove the aliased energy resulting from the noisy performance of the A/D converter may have lead to an average flux loss <~10 %. This was estimated on the basis of spectrum analysis of the Mekrijärvi data and the universal co-spectra developed for momentum and heat by Kaimal et al. (1972). The loss depends on the importance of the smallest turbulent eddies in the transport process, thus being least during unstable flow (daytime conditions).

With micrometeorological methods, measurements can be taken above the surface of interest without disturbing the surface itself. Instrumentation may, on the other hand, disturb the atmospheric flow. If not taken into account this may lead to considerable errors (Wyngaard and Zhang 1985), especially due to transducer shadowing of the acoustic anemometer. In the ATI instrument used in this study, the shadowing effect is corrected for internally. However, there remains the danger of flow disturbances by the measurement mast and individual surface elements.

Errors may also be introduced in the results inferred from the flux observations on account of necessary further assumptions, for instance, with respect to flux-gradient relations. Within the parameters presented here, the roughness length and the aerodynamic resistance are affected by the presumed flux-gradient profiles. The traditional profiles used also in this study have been shown to fail in the so-called roughness sublayer close enough to the roughness elements of the surface (Garratt 1992). It is possible that the aerodynamic resistances obtained in this study are somewhat overestimated as a result of this effect. However, as the aerodynamic part seldom dominates the total resistance, only small relative errors are introduced into the surface resistance.

4 Conclusions

Surface fluxes of O_3, CO_2 and H_2O were measured over a Scots pine stand by the eddy covariance technique. Results from a 2-day period were presented here. The eddy covariance method and the established measurement system has proved suitable for providing high-resolution data for studying ozone deposition to a forest and the net carbon balance and related physiological processes of an ecosystem.

Clear diurnal cycles were observed in the atmospheric fluxes of O_3, CO_2 and H_2O. Daytime changes in CO_2 fluxes are primarily caused by variations in photosynthetically active radiation. Ozone flux is interpreted here by calculating the deposition velocity and the surface conductance, the latter providing a measure of the purely biological and chemical part of the deposition process. It was observed that conductances in the forenoon are higher than in similar radiation conditions in the afternoon. This is most likely due to differences in the air humidity. This should be taken into account, for example, when evaluating the overstepping of critical levels from monitored ozone concentrations. The same concentration in the same radiation conditions can cause different doses depending on the environmental conditions.

In future the measurement system will be developed further, focusing especially on data screening procedures based on spectrum analysis. The parameterisation of the ozone flux will be extended to include a multi-path surface resistance so that the performance of suggested general parameterisation schemes (e.g. Erisman et al. 1994b) can be evaluated.

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