Environmental Pollution 159 (2011) 1024–1034

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Ozone flux over a Norway spruce forest and correlation with net ecosystem production

Miloš Zapletal [a,b,*], Pavel Cudlín [c], Petr Chroust [a], Otmar Urban [d], Radek Pokorný [d], Magda Edwards-Jonášová [c], Radek Czerný [d], Dalibor Janouš [d], Klára Taufarová [d], Zbyněk Večeřa [e], Pavel Mikuška [e], Elena Paoletti [f]

[a] Ekotoxa s.r.o. - Centre for Environment and Land Assessment, Otická 37, 746 01 Opava, Czech Republic
[b] Silesian University at Opava, Faculty of Philosophy and Science, Masarykova 37, 746 01 Opava, Czech Republic
[c] Institute of Systems Biology and Ecology of the AS CR, v.v.i., Na Sádkách 7, 37005 České Budějovice, Czech Republic
[d] Institute of Systems Biology and Ecology of the AS CR, v.v.i., Poříčí 3b, 60300 Brno, Czech Republic
[e] Institute of Analytical Chemistry of the AS CR, v.v.i., Veveří 97,60200 Brno, Czech Republic
[f] Institute of Plant Protection, National Research Council of Italy, via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy

Net ecosystem production of a Norway spruce forest decreases with increasing deposition and stomatal uptake of ozone.

ARTICLE INFO

Article history:
Received 25 November 2010
Accepted 28 November 2010

Keywords:
Ozone deposition
Stomatal conductance
Deposition velocity
Friction velocity
Gradient method
Tropospheric ozone
Net ecosystem production

ABSTRACT

Daily ozone deposition flux to a Norway spruce forest in Czech Republic was measured using the gradient method in July and August 2008. Results were in good agreement with a deposition flux model. The mean daily stomatal uptake of ozone was around 47% of total deposition. Average deposition velocity was 0.39 cm s^{-1} and 0.36 cm s^{-1} by the gradient method and the deposition model, respectively. Measured and modelled non-stomatal uptake was around 0.2 cm s^{-1}. In addition, net ecosystem production (NEP) was measured by using Eddy Covariance and correlations with O_3 concentrations at 15 m a.g.l., total deposition and stomatal uptake were tested. Total deposition and stomatal uptake of ozone significantly decreased NEP, especially by high intensities of solar radiation.

1. Introduction

Quantification of ozone (O_3) deposition to forest ecosystems is important for many reasons. Tropospheric O_3 is one of the most important phytotoxic air pollutants (Paoletti et al., 2007). There is evidence that ambient O_3 concentrations can cause a range of effects in European forests, including visible leaf injury, growth reduction, and altered sensitivity to biotic and abiotic stresses (Karlsson et al., 2003; UNECE, 2005). Several authors have measured and modelled O_3 deposition fluxes to conifer forests in Europe and USA (Duyzer and Weststrate, 1995; Pilegaard et al., 1995a, 1995b; Emberson et al., 2000a, 2000b, 2000c, 2001; Zeller and Nikolov, 2000; Panek et al., 2002; Klemm and Mangold, 2001; Keronen et al., 2003; Tuovinen et al., 2004; Hole et al., 2004; Mikkelsen et al., 2004; Matyssek et al., 2007). No reports, however, are available about how measurements of O_3 uptake into a forest canopy correlate with net ecosystem production (NEP), which makes hard to predict O_3 effects on the long-term growth of forests (Manning, 2005).

Knowledge about physiological and physical processes controlling O_3 fluxes to forests is still imperfect (Cieslik, 2009). Stomatal O_3 flux can be estimated as the product of O_3 concentrations close to the leaf/needle and the inverse of the sum of resistances along the O_3 diffusion pathway to the leaf tissues (Ashmore et al., 2004). This sum is a function of several factors, including atmospheric turbulence, canopy height and structure, species-specific phenology, and environmental factors, e.g. air humidity, temperature, irradiance, soil water availability and vapour pressure deficit, which influence the stomatal component of resistance.

Three main micrometeorological methods are available for measuring O_3 fluxes to forest canopies: the vertical gradient method, the eddy-covariance technique and the eddy accumulation technique (Cieslik et al., 2009). We applied the gradient method to a Norway spruce canopy, where concurrent eddy-covariance measurements of NEP were carried out. Measurements of total O_3 flux by the gradient method were also compared with values from

* Corresponding author.
E-mail address: milos.zapletal@ekotoxa.cz (M. Zapletal).

0269-7491/$ – see front matter
doi:10.1016/j.envpol.2010.11.037

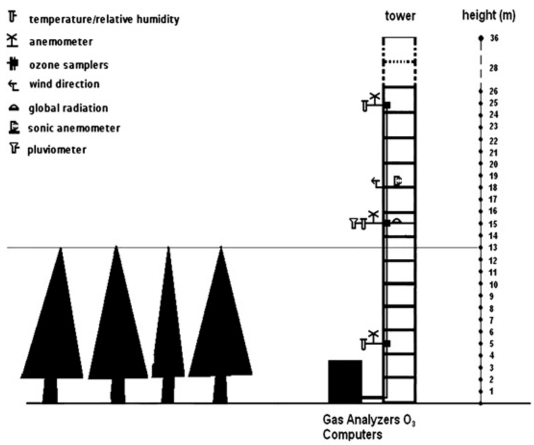

Fig. 1. Measurement tower and instrumentation set-up at the experimental research site Bily Kriz.

the multiplicative model which differentiates between stomatal and non-stomatal deposition components (Emberson et al., 2000a, 2000b, 2000c, 2001; Ashmore, 2003; Ashmore et al., 2004; Tuovinen et al., 2004), that UNECE has accepted as a tool for estimating total and stomatal O_3 fluxes (UNECE, 2004). The ongoing revision of the Long Range Transboundary Air Pollution Convention's Gothenburg Protocol is exploring the role of stomatal flux as the governing cause of O_3 damage to vegetation (ICP Vegetation, 2009). Also, the next revision of the EU Clean Air Directive could benefit from consideration of these recent developments in O_3 risk assessment and may wish to consider introducing the flux index for vegetation (ICP Vegetation, 2009). The accumulated stomatal O_3 flux over a threshold Y during the growing season (AFstY) has been renamed as Phytotoxic Ozone Dose (POD_y) (ICP Vegetation, 2009). Critical levels were derived for the POD responsible for either a 2% or a 4% reduction in annual growth (whole tree biomass) of young trees of up to 10 years of age, depending on species (ICP Vegetation, 2010). The age criterion was set to reflect the age of the trees used in the O_3 exposure experiments contributing data to the response function. For Norway spruce, a POD_1 of 8 mmol m^{-2} was recommended (ICP Vegetation, 2010, based on results by Karlsson et al., 2007). Tuovinen et al. (2004) have already shown a good agreement between measured and modelled stomatal O_3 fluxes to two coniferous (Scots pine in Finland, Norway spruce in Denmark) forests in Northern Europe. There is however a strong need for supporting POD critical levels in mature trees and consistency of measured and modelled stomatal fluxes for Norway spruce forests in central Europe (Emberson et al., 2000c; Wieser and Emberson, 2003, 2004).

High ambient long-term concentrations of O_3 have been observed in the Czech Republic since the early 1990s (Zapletal, 1999a, 1999b; Hůnová et al., 2003). Ozone concentrations and deposition fluxes to coniferous and deciduous forests in Czech Republic have been modelled (Zapletal and Chroust, 2007), while direct measurements of O_3 fluxes over Czech forest canopies are missing.

The aims of this study were: to measure daily cycles of O_3 deposition velocities and fluxes above a conifer forest in Czech Republic; to compare deposition velocities measured by the gradient method with results of the multiple resistance model; to support EU environmental protection policy by calculating micrometeorological indices of accumulated stomatal O_3 uptake (POD_0 and POD_1); and to test whether elevated stomatal uptake of O_3 implies a reduction of NEP.

2. Material and methods

2.1. Site description

The forest stand is situated in the Bily Kriz experimental research site (Moravian-Silesian Beskydy Mountains, 49° 33′ N, 18° 32′ E, NE of Czech Republic, 908 m a.s.l.), is part of the CARBOEUROPE network and includes field laboratory, meteorological station and air quality control station. It represents the mountain region conditions of Central Europe. The site is located in a background area without industrial sources. The climate is cool (annual mean temperature 5.5 °C) and humid (annual mean relative air humidity 80%) with high precipitation (annual amount 1000–1400 mm). The geological bedrock is Mesozoic Godula sandstone (flysch type), with ferric podzols. The forest stand was planted in 1981 with 4-year-old seedlings of *Picea abies* (L.) Karst (99%) and *Abies alba* Mill. (1%) on a slope (11°–16°) oriented SSW over an area of 6.2 ha. The stand density was 1430 trees ha^{-1} in 2008. Meteorological and environmental measurements were made on a 36-m tall experimental tower placed in an area with mean tree height of 13 m (Fig. 1). The data presented here are from July to August 2008. Wind direction (eddy-covariance system, InSituFlux, Sweden) was measured at 18 m a.g.l.. Wind speed (anemometer AN1, Delta-T, Great Britain), air temperature (HOBO, Onset Computer Corporation, USA), relative humidity (HOBO, Onset Computer Corporation, USA) were measured at 5, 15 and 25 m a.g.l.. Global radiation (SG420, Tlustak, Czech Republic) was measured at 15 m a.g.l.. Leaf area index (LAI) was measured by Plant Canopy Analyzer LAI 2000 (Li-Cor, USA) along a 1 m grid of 49 fixed measurement points during the growing season (April–September). For effective LAI recalculation to the hemi-surface values, a specific correction set-up was used (Pokorný and Marek, 2000). Surface of stems and branches (i.e. WAI – woody area index) was evaluated on the basis of site specific allometric relations with stem diameter at breast height (Pokorný and Tomášková, 2007). Ozone concentrations at 5, 15 and 25 m a.g.l. were measured by O_3 analysers (O341M, Environment SA, France). Air was sampled continuously at each of the three height levels via Teflon tubes. All data were stored as half-hourly averages. All O_3 analysers had discrete identical sample lines (length 30 m, diameter 4 × 6 mm, Teflon® PTFE). As a protection against insect and particulate matter a filter (Savillex 47 mm filter membrane, 5–6 micron, PTFE, insert in clamp – Savillex 47 mm single stage filter assembly, 1/4" MNPT × 1/4" MNPT, Tefzel® clamp) was placed at the intake between the inlet and the sample line. The ultraviolet photometric analyzer determined O_3 concentration by measuring the attenuation of light due to O_3 in the absorption cell, at a wavelength of 254 nm. The concentration of O_3 is directly related to the magnitude of the attenuation. The filter at the analyzer inlet was changed every month during other service/repair work. The filter was not observed to be visibly dirty, and the change of the filter did not show any remarkable change in the concentration data. Regular calibration checks included checking the span coefficient and zero offset, and linearity check. Ozone concentrations were measured by an ultraviolet photometric analyzer (TEI model 49C, Thermo Environmental Instruments Inc., Franklin, MA, USA, S/N 56126-306). The analyzer was regularly calibrated at the Czech Hydrometeorological Institute Praha against a PM 003 – working standard – ultraviolet photometric analyzer O_3 TEI 49C (S/N 54541-300), traceable to the Standard Reference Photometer (SRP 15). An experiment with all sampling tubes from the same height showed that systematic differences in the concentrations measured with different tubes were not detectable.

2.2. Gradient method and eddy-covariance measurements

Deposition velocity V_d was determined by the gradient method (Fowler and Duyzer, 1989; Hummelshoj, 1994):

$$Fmeas = -\frac{ku*(c(z_2) - c(z_1))}{\ln((z_2 - d)/(z_1 - d)) + \psi_h((z_1 - d)/L) - \psi_h((z_2 - d)/L)} \quad (1)$$

$$V_{dmeas} = -F_{meas}/c(z) \quad (2)$$

where: F_{meas} is vertical O_3 flux; k is the von Kármán's constant; u_* is the friction velocity computed from eddy-covariance measurements of vertical and longitudinal

Table 1
Typical values of u_* (m s^{-1}) and V_{dmeas} (cm s^{-1}) obtained from the measurements at the Bily Kriz experimental research site from July to August 2008.

Parameter	Unstable	Neutral	Stable
z/L	−0.25–−0.1	−0.1–0.1	0.1–0.3
Occurrence (%)	2	87	11
u_*	0.09	0.24	0.11
V_{dmeas}	0.19	0.40	0.21
[a]u_*	0.08	0.22	0.10
[a]V_{dmeas}	0.18	0.37	0.19

[a] After application of a correction function.