Environmental Pollution 158 (2010) 2014–2022

Contents lists available at ScienceDirect

Environmental Pollution

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

Combining sap flow and eddy covariance approaches to derive stomatal and non-stomatal O_3 fluxes in a forest stand

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Combined tree sap flow and eddy covariance-based methodologies yield stomatal O_3 flux as 33% in total stand flux.

ARTICLE INFO

Article history:
Received 24 November 2009
Accepted 29 November 2009

Dedication: This paper is published in memory of Prof. Dr. Heinrich Sandermann, an outstanding colleague and good friend in the common interest of unveiling mechanisms of ozone impact in trees.

Keywords:
Ozone flux
Sap flow
Eddy covariance
Penman–Monteith equation
Forests

ABSTRACT

Stomatal O_3 fluxes to a mixed beech/spruce stand (*Fagus sylvatica/Picea abies*) in Central Europe were determined using two different approaches. The sap flow technique yielded the tree-level transpiration, whereas the eddy covariance method provided the stand-level evapotranspiration. Both data were then converted into stomatal ozone fluxes, exemplifying this novel concept for July 2007. Sap flow-based stomatal O_3 flux was 33% of the total O_3 flux, whereas derivation from evapotranspiration rates in combination with the Penman–Monteith algorithm amounted to 47%. In addition to this proportional difference, the sap flow-based assessment yielded lower levels of stomatal O_3 flux and reflected stomatal regulation rather than O_3 exposure, paralleling the daily courses of canopy conductance for water vapor and eddy covariance-based total stand-level O_3 flux. The demonstrated combination of sap flow and eddy covariance approaches supports the development of O_3 risk assessment in forests from O_3 exposure towards flux-based concepts.

1. Introduction

The elevated surface-level ozone (O_3) concentrations have become a factor of climate change (IPCC, 2001, 2007; Ashmore, 2005; Sitch et al., 2007), tending to mitigate the carbon sink strength of vegetation, in particular forests, under the increasing atmospheric CO_2 level (Grams et al., 1999; Fiscus et al., 2005; Kozovits et al., 2005; King et al., 2005; Karnosky et al., 2003, 2005; Wipfler et al., 2005; Kubiske et al., 2006, 2007; Valkama et al., 2007). As O_3 regimes are expected to continue to increase with respect to those of pre-industrial times (Fowler et al., 2008; Vingarzan, 2004; Ashmore, 2005), risks to vegetation, including forests, require special attention (Skärby et al., 1998; Matyssek and Sandermann, 2003). Given this demand, O_3 risk assessment is challenged to become process-based and cause-effect related (Matyssek et al., 2008).

In view of such a challenge, steps have been taken in Europe towards flux-based O_3 risk assessment (Wieser and Tausz, 2006; Matyssek et al., 2007a), being aware that O_3 risk is driven by two components, i.e. the uptake of ozone (as the time integral of stomatal O_3 flux into plants), and the effective O_3 dose, constituting the plant's responsiveness per unit of O_3 uptake (Musselman et al., 2006; Matyssek et al., 2008). Given the O_3 uptake through stomata, which yields the phytomedically relevant O_3 dose (cf. Klaassen, 1986), O_3 flux-related risk assessment has so far relied on modeling (Emberson et al., 2000; Tuovinen et al., 2001). Current approaches assume the O_3 concentration in the free atmosphere above stands as the starting point for calculating stomatal O_3 uptake, relying on modeling of the boundary layer conductance for O_3 flux, the non-stomatal O_3 deposition (i.e. O_3 flux to all surfaces except stomata) and gas-phase chemistry related to emissions of biogenic volatile organic compounds (BVOC) from leaves (Kurpius and Goldstein, 2003; Hogg et al., 2007). A major shortcoming, however, is presently the lack of empirical data for validation, the more so as the extent of variation in stomatal O_3 flux has remained controversial (Fredericksen et al., 1996; Fowler et al., 2001; Altimir et al., 2006).

An empirical approach to assess stomatal O_3 uptake at the whole-tree level has recently been developed on the basis of sap flow measurements in tree trunks (Wieser et al., 2003, 2006; Matyssek et al., 2004, 2008; Nunn et al., 2007; Köstner et al., 2008).

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0269-7491/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2009.11.034

Since sap flow quantitatively reflects crown transpiration (Schulze et al., 1985; Köstner et al., 1998) as mediated by stomata and canopy boundary layers, derivation of canopy conductance for water vapor and ozone allows the quantification of O_3 uptake by the foliage, provided that O_3 exposure is measured within the canopy (Matyssek et al., 2008). This kind of assessment may be combined with the eddy covariance approach, yielding both stand-level water vapor and total O_3 fluxes, i.e. the sum of stomatal and non-stomatal O_3 fluxes (Mikkelsen et al., 2000; Gerosa et al., 2005; Altimir et al., 2006; Cieslik, 1998, 2004). This means, the comparison of sap flow and eddy covariance assessment can yield the non-stomatal O_3 flux. Hence, the outcome can validate modeled O_3 flux and uptake by means of independent, experimental datasets. To date, partitioning total stand O_3 flux in stomatal and non-stomatal contributions has only been achievable through calculations based on eddy covariance assessments (Massman, 1993; Nikolov and Zeller, 2003).

This study for the first time demonstrates the derivation of the non-stomatal O_3 flux as the differential outcome between two empirical approaches, i.e. the one yielding stomatal O_3 flux *via* sap flow measurement on trees, and the other stand-level total O_3 flux *via* eddy covariance determination. This implies that the stomatal canopy O_3 flux, as obtained upon tree-to-stand up-scaling of stomatal O_3 flux, is derived other, i.e. through a tree-ecophysiological approach, than through the conventional calculation from meteorological data (Gerosa et al., 2005). The new concept of stomatal and non-stomatal O_3 flux assessment is exemplified at a closed-canopy site of a mixed forest of Norway spruce (*Picea abies*) and European beech (*Fagus sylvatica*; Nunn et al., 2006; Matyssek et al., 2007b).

2. Material and Methods

2.1. Study site and plants

The study was performed at Kranzberger Forst near Freising/Germany (48°25′N, 11°39′E, elevation 485 m a.s.l.) in a mixed stand of 53–60-year-old Norway spruce (*P. abies*) and European beech (*F. sylvatica*) from July 2 through 29, 2007. The stand had developed a closed canopy, and stand density amounted to 829 trees ha^{-1}, basal stem area to 46.4 m^2 ha^{-1}, and projected leaf area index (LAI) to 5.6 m^2 m^{-2} (Wipfler et al., 2005; Grote and Reiter, 2004). Stand foliage was concentrated between 17 and 24 m above ground (Reiter et al., 2005). Long-term averages of annual air temperature and precipitation were 7–8 °C and 750–850 mm, respectively (Rötzer et al., 2009). The growing season extended from mid-April through the end of October. The site has been introduced in preceding studies on responses of the adult forest trees to experimentally enhanced chronic ozone (O_3) stress (e.g. Nunn et al., 2005a,b, 2006, 2007; Löw et al., 2006, 2007; Matyssek et al., 2007b; Kitao et al., 2009) as generated through free-air canopy O_3 fumigation (Nunn et al., 2002; Werner and Fabian, 2002; Karnosky et al., 2007). The present study focuses on assessed O_3 fluxes at canopy level under the unchanged ambient O_3 regime as prevailing at the forest site.

2.2. Assessments of environmental conditions and xylem sap flow

The methodological set-up was the same as detailed in Nunn et al. (2007). Temperature, relative humidity (RH), air pressure and O_3 levels of the ambient air were continuously monitored at 25 m above ground at the top of the canopy (psychro- and baro-transmitter, ThiesClima, Germany; O_3 analyzer: ML8811, Monitor Labs, USA), checking O_3 recording each day for consistency across zero lines and spans. Only minor vertical O_3 gradients existed within the foliated canopy (Nunn et al., 2002). Precipitation was recorded in a clearing at about 1 km distance from the study site (data by courtesy of LWF, G. Gietl.).

Sap flow density (S) through the trunks of five beech and four spruce trees was measured at breast height (DBH) with custom-made Granier sensors (Granier, 1985), Accounting for variations in S across the cross-sectional trunk sapwood area, two sensors were installed in the trunk at 4 and 6 cm depth in addition to the one at 2 cm in two trees of each species. Sensor positions were vertically aligned at equal distances within 30 cm, and were shielded by a thermally insulating styrofoam cover. The upper probe of each sensor was supplied with a constant heat of 140 mW, as the temperature difference between the heated upper and the non-heated lower reference probe was used to calculate S according to the empirical equation (Granier, 1985):

$$S = 0.0714^*(\Delta T_{max}/\Delta T_{act})^{1.23}$$

where ΔT_{max} is the maximum temperature difference occurring at night with the transpiration approaching zero. Zero correction was done once a week during the night with highest ΔT (i.e. weekly ΔT_{max}), ensuring variation in nightly transpiration between days, confirmed by leaf gas exchange assessment, to be covered by analysis. ΔT_{act} represents the instantaneous temperature difference. S at depths beyond 6 cm was linearly extrapolated towards the heartwood area on the basis of S at 2, 4 and 6 cm depth (see above and Nunn et al., 2007; Matyssek et al., 2009). The product of S and cross-sectional sapwood area at DBH yielded whole-tree transpiration (E_C ml m^{-2} min^{-1}). Micro-climatic and sap flow data were recorded as 10-min means (DL2e data logger, Delta-T-Devices, Burwell, Cambridge; UK).

2.3. Assessment of crown conductance for water vapor and whole-tree O_3 uptake

Crown conductance for water vapor (G_C; expressed as "mmol H_2O m^{-2} s^{-1}") was derived from measured E_C according to Nunn et al. (2007) (see overview of Table 1 on methodologies, terminology and abbreviations of covered parameters):

$$G_C = E_C/\Delta w, \quad \text{with } \Delta w = VPD/P$$

where P is the air pressure [kPa], VPD is the water vapor pressure deficit of the air [Pa] and Δw is the leaf/air mole fraction difference of water vapor (cf. Cowan, 1977) at canopy height. In expressing Δw, leaf temperature at the canopy level was assumed to be equal to air temperature, since most of the foliage was shaded in the closed canopy. Since Δw was assessed at canopy height, G_C which was scaled to the foliage area of each tree, was assessed under the influence of boundary layer and aerodynamic impacts inside the canopy. Foliage area was calculated on the basis of DBH and allometric equations by Burger (1950) for beech and Patzner (2004) for spruce. In the case of beech projected foliage area, and in the case of spruce total foliage surface area was used as reference, accounting for the actually O_3-absorbing surfaces each in hypostomatic beech leaves and amphistomatic spruce needles (Wieser, 2002, Wieser et al., 2003; Nunn et al., 2006). A minimum G_C level (G_{Cmin}) of 10% of the mean maximum stomatal conductance during the daylight hours was employed (cf. Nunn et al., 2007) when Δw was <1 Pa kPa^{-1}, because stomata were not fully closed at any time, even during night (Nunn et al., 2005b; i.e. G_{Cmin} being 19.5 mmol m^{-2} s^{-1} in beech, and 4 mmol m^{-2} s^{-1} in spruce). G_{Cmax} was confined at high air humidity in beech to 250 mmol m^{-2} s^{-1} and in spruce to 60 mmol m^{-2} s^{-1} (cf. Nunn et al., 2007).

Assuming zero O_3 concentration at the mesophyll surface (cf. Laisk et al., 1989; Moldau and Bichele, 2002), the whole-tree O_3 uptake was calculated according to:

$$F_{O_3} = [O_3]^*G_C{}^*0.613$$

where F_{O_3} is the foliage area-related whole-tree O_3 flux or uptake rate [nmol m^{-2} s^{-1}], $[O_3]$ is the O_3 concentration of the ambient air [nl l^{-1}], G_C is the foliage conductance for water vapor [mmol m^{-2} s^{-1}] (cf. Cowan, 1977), and *0.613* is the conversion factor accounting for the lower diffusivity of O_3 relative to water vapor in air (Nobel, 1983). At DBH, S started at about 2 h after sunrise (and associated increasing Δw), indicating temporary use of the tree-internal water storage capacitance in crown transpiration (Nunn et al., 2007). This time shift relative to the onset of crown transpiration at sunrise was accounted for according to Matyssek et al. (2004, 2008) when calculating G_C.

2.4. Eddy covariance measurement of total ozone and water vapor fluxes

The eddy covariance method (see e.g. Baldocchi et al., 1988; Verma, 1990; Lee et al., 2004) was used to measure the water vapor fluxes and the total ozone fluxes at

Table 1
Methodology, assessment position, and terminology of measured and calculated tree and stand parameters.

Parameter	Eddy flux measurement (stand-level)	Sap flow measurement (stand level upon up-scaling from single trees)
transpiration	total stand evapotranspiration (E_t)	canopy transpiration (E_C)
conductance (for water vapor)	total stand conductance (G_t)	canopy conductance (G_C)
O_3 flux	total stand O_3 flux (F_{O_3t}) (derived from measurement) stomatal O_3 flux (F_{O_3s}) (calculated through Penman equation)	canopy stomatal O_3 flux (F_{O_3c})