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New initiative

Quantification of ozone uptake at the stand level in a *Pinus canariensis* forest in Tenerife, Canary Islands: An approach based on sap flow measurements

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Sap flow measurements can be used for estimating ozone uptake at the stand level and for parameterisation of O_3 uptake models.

Abstract

Ozone uptake was studied in a pine forest in Tenerife, Canary Islands, an ecotone with strong seasonal changes in climate. Ambient ozone concentration showed a pronounced seasonal course with high concentrations during the dry and warm period and low concentrations during the wet and cold season. Ozone uptake by contrast showed no clear seasonal trend. This is because canopy conductance significantly decreased with soil water availability and vapour pressure deficit. Mean daily ozone uptake averaged 1.9 nmol m^{-2} s^{-1} during the wet and cold season, and 1.5 nmol m^{-2} s^{-1} during the warm and dry period. The corresponding daily mean ambient ozone concentrations were 42 and 51 nl l^{-1}, respectively. Thus we conclude that in Mediterranean type forest ecosystems the flux based approach is more capable for risk assessment than an external, concentration based approach.

Keywords: Heat dissipation; Canopy conductance; Ozone uptake; Mediterranean

1. Introduction

Analysis on the impact of ozone (O_3) impact on forest stands requires the knowledge of site-specific O_3 formation, transport, and deposition. Within the canopy, the leaves are the primary site of O_3 uptake, with the stomata representing the interface for O_3 uptake from the atmosphere into the foliage. Methods for quantifying O_3 uptake at the canopy level include eddy covariance techniques (Zeller and Nikolov, 2000) and modelling approaches (Emberson et al., 2000). Eddy correlation measurements assess total deposition and stomatal O_3 uptake can hardly be separated from adsorption onto non-transpiring external surfaces (Zeller and Nikolov, 2000). Models by contrast, need a site-specific parameterisation, especially with respect to evaporative demand and soil water availability (Wieser and Emberson, 2004).

O_3 uptake at the canopy level can also be derived from sap flow measurements. Because transpiration and O_3 flux into the foliage are coupled via the stomata, sap flow measurements in the trunk of entire trees (Wieser et al., 2003) combined with stand density data provides a basis for estimating O_3 uptake at the canopy level. In addition, this latter technique is inexpensive, assesses foliage gas exchange in the presence of the actual site conditions neglecting non-stomatal deposition, and can be used in heterogeneous and mountainous landscapes

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where aerodynamic methods are strongly limited due to the patchiness of the vegetation and gusty winds. Therefore, in this study we combined micro-climatic, ambient air O_3 concentration data, and sap flow measurements through tree trunks with stand density data in order to estimate whole-canopy ozone uptake. The focus is on a *Pinus canariensis* stand in Tenerife, Canary Islands, a habitat with strong seasonal changes in water availability and evaporative demand.

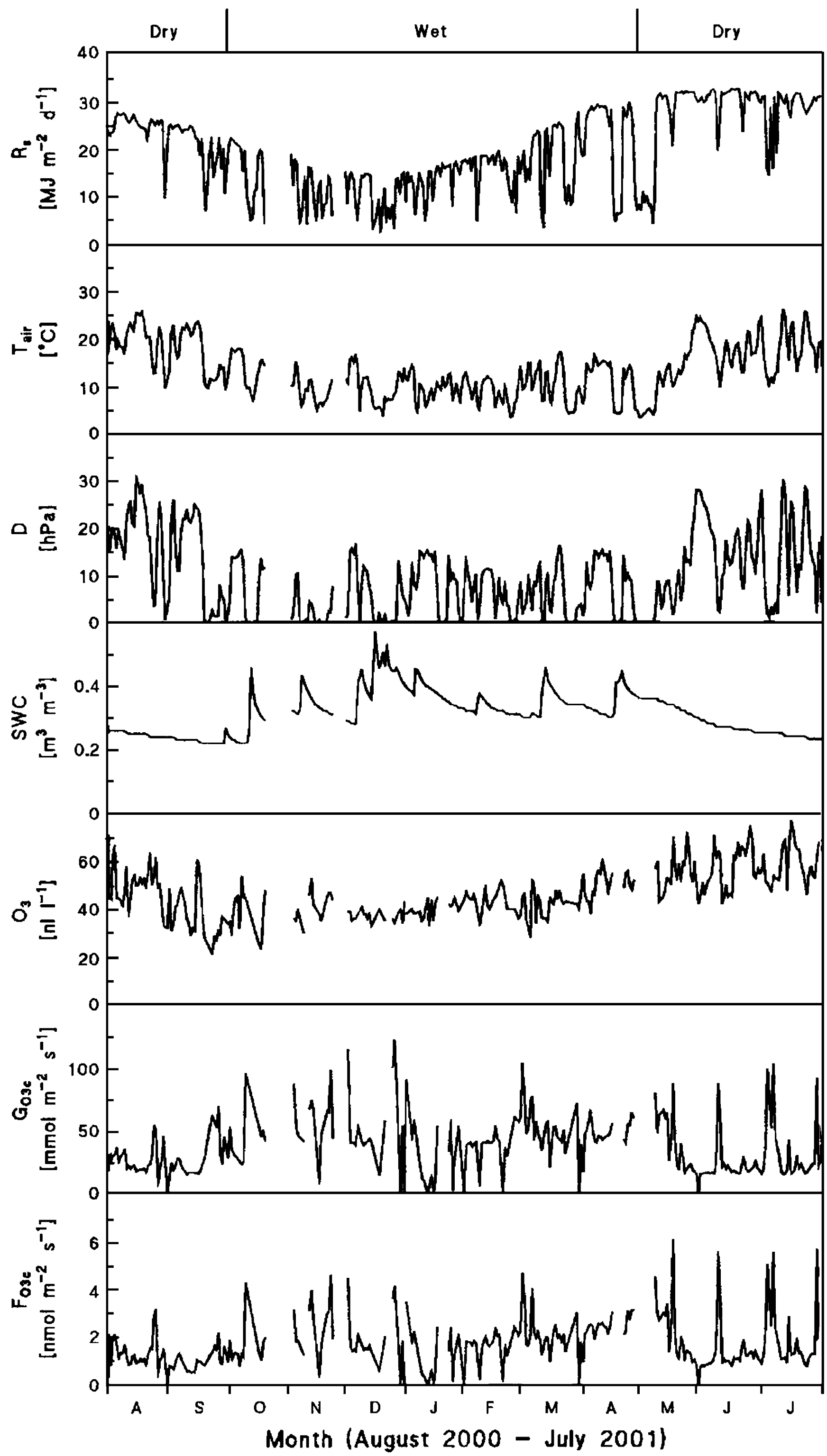

Fig. 1. Seasonal course of daily sum of solar radiation (R_s), daily mean air temperature (T_{air}), daily mean vapour pressure deficit (D), daily mean soil water content (SWC), daily mean ambient ozone concentration (O_3), ground area scaled canopy conductance for ozone (G_{O3c}), and ground area scaled ozone flux (F_{O3c}) in a *Pinus canariensis* forest at Tenerife, Canary Islands during the period 1 August, 2000 to 31 July, 2001.

2. Material and methods

The study was carried out in an open 50-year-old *P. canariensis* forest (stand density 825 trees ha^{-2}, basal stem area 53.8 m^2 ha^{-1}, leaf area index 3.4 m^2 total needle surface area per m^2 ground surface area) in the mountains of La Victoria, approximately 20 km south-west of La Laguna, Tenerife, Canary Islands (Morro de Isarda, El Gaitero, 28°35′N, 27°15′W, 1650 m a.s.l.). The study site is characterised by a Mediterranean climate with strong seasonal changes in water availability and evaporative demand (Fig. 1).

Air temperature, relative humidity (RHA1, Delta-T, Cambridge, UK), and solar radiation (LI190 SA, Li-Cor, Lincoln, NE, USA) were monitored 2 m above the top of the canopy, and soil water content was monitored in 40 to 45 cm soil depth with a Theta Probe (Delta-T). All environmental parameters were recorded with a DL2 data logger (Delta-T) programmed to record 30-min averages of measurements taken every minute. Ambient air O_3 concentration was monitored with two UV-absorption ozone analysers (Model TEI 49C; TECO) at the Izana Observatory 13 km west of the study site.

Sap flow density of six *P. canariensis* trees was monitored continuously from August 1, 2000 to July 31, 2001 by means of the heat-balance approach (Kucera et al., 1977) with a 12-channel battery-operated sap flow meter connected to a data logger unit (P4.1; Environmental Measuring System, EMS, Brno, Czech Republic). Data were recorded as 15-min means of measurements taken every minute. Whole tree transpiration was then calculated by multiplying sap flow density with the length of the circumference of the xylem at measuring height. Canopy transpiration related ground surface area (E_c) was calculated by applying a diameter class technique similar to that common in forest inventories (Cermák et al., 2004). Finally, whole-canopy conductance for water vapour related to ground surface area (g_c) was estimated from E_c using a simplified inverted Penman-Monteith equation:

$$g_c = \gamma E_c / \rho c_p D$$

where γ is the psychometric constant, λ is the latent heat of water vaporisation, ρ is the density of the air, c_p is the specific heat of air at constant pressure, and D is the vapour pressure deficit. Because D was calculated from climatic measurements above the canopy (see above), boundary layer and aerodynamic conductance are included in the estimation of g_c. Due to the open canopy, the low LAI, and hence a strong coupling to the atmosphere, we assumed that g_c closely approximates stomatal conductance (Oren et al., 1999). Therefore, canopy O_3 uptake per m^2 ground surface area (F_{O3c}) was calculated according the flux equation:

$$F_{O3c} = [O_3] g_c 0.613$$

where $[O_3]$ is the ambient air ozone concentration, g_c is the canopy conductance for water vapour scaled to ground surface area, and 0.613 is the

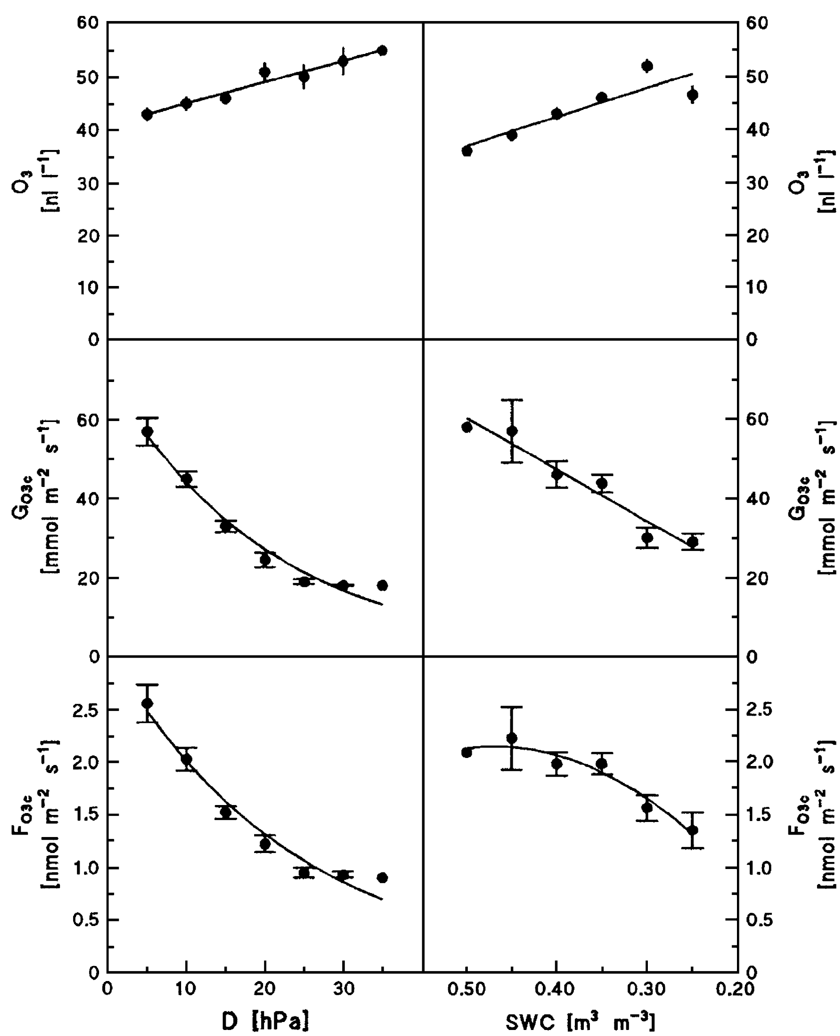

Fig. 2. Means of ambient air ozone concentration (O_3), canopy conductance for ozone (G_{O3c}), and canopy ozone flux (F_{O3c}) in relation to relation to (left) vapour pressure deficit (D) and (right) soil water content (SWC). Points were fit by regression analysis. D: O_3: $y = 0.4x + 41$, $r^2 = 0.95$; G_{O3c}: $y = 71.4\exp(-0.04x)$, $r^2 = 0.97$; F_{O3c}: $y = 3.08\exp(-0.04x)$, $r^2 = 0.97$. SWC: O_3: $y = -54x + 64$, $r^2 = 0.78$; G_{O3c}: $y = 130.4x - 49$, $r^2 = 0.94$; F_{O3c}: $y = (-17.4x + 16.3)x - 1.7$, $r^2 = 0.94$.

Table 1
Average canopy conductance for O_3 (g_c), canopy O_3 flux (F_{O3c}), cumulative O_3 uptake rate (CU), average daily mean ambient air O_3 concentration, and AOT40 values estimated during the wet cold and during the dry and warm season

	Wet and cold season (October–April)	Dry and warm season (May–September)
Duration (days)	212	153
g_c (mmol m^{-2} s^{-1})	44.8	29.2
F_{O3c} (nmol m^{-2} s^{-1})	1.88	1.49
CU (mol m^{-2})	34.5	19.7
Ambient O_3 (nl l^{-1})	42	51
AOT40 (ppm-h)[a]	16.5	29.2

[a] AOT40: accumulated exposure to ozone above a threshold of 40 nl l^{-1} during daylight hours.

conservation factor accounting for the lower diffusivity of O_3 relative to water vapour in air (cf. Wieser, 2002).

3. Results and discussion

Seasonal variations in of ambient O_3 concentration, g_c, and F_{O3c} are shown in Fig. 1. Ambient air O_3 concentration exhibited a seasonal cycle with maxima during the dry and warm period and minima during the wet and cold season (Fig. 1). Daily means of O_3 concentration, however, corresponded only weakly F_{O3c} (Fig. 1). A further analysis of daily means showed that g_c declined significantly with increasing vapour pressure deficit and decreasing soil water availability (Fig. 2), because the primary response of *P. canariensis* to water limitation and increasing evaporative demand is stomatal closure (Peters et al., 2003). At high humidities however, g_c was high and thus allowed a high F_{O3c} flux even at low O_3 concentrations (Fig. 2).

The average g_c, F_{O3c}, and cumulative O_3 uptake rates (CU) obtained for the wet and cold season and the warm and dry period are summarised in Table 1 and compared to the corresponding mean ambient O_3 concentrations and AOT40 values. The estimation of F_{O3c} and CU by the sap flow technique clearly reflects the influence of the water limitation and high evaporative demand, even though mean ambient O_3 concentrations and AOT40 were significantly enhanced during the warm and dry as compared to the wet and cold season.

Thus, we conclude that in contrast to exposure-based O_3 indices the O_3 flux-based concept allows the integration on external factors determining the possible risk of O_3 injury in forest stands; especially in the Mediterranean region where stomatal narrowing significantly limits O_3 uptake during periods of high evaporative demand and low soil water availability as the highest O_3 levels coincide with the time when trees suffer from water stress and stomata are closed. In addition, the sap flow based method offers an inexpensive, spatially and temporally approach for estimating ozone uptake at the whole tree (Wieser et al., 2003) and stand level, and such data sets can also be used for the parameterisation and the validation of O_3 uptake models.

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