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Original article

Stomatal conductance models for ozone risk assessment at canopy level in two Mediterranean evergreen forests

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ABSTRACT

Forests in Mediterranean Europe are located in a hot spot for tropospheric ozone formation. We applied two canopy-level stomatal conductance models (Jarvis-type and Ball-Woodrow-Berry models) to two Mediterranean evergreen forests (Umbrella pine at San Rossore, and Holm oak at Castelporziano, in central Italy), which is essential for assessing ozone impact on forests via the stomatal flux-based approach. Parameterizations of the models was carried out by the Eddy Covariance technique. Both Jarvis-type and Ball-Woodrow-Berry models well explained the observed stomatal conductance and stomatal ozone flux in both forests. Maximum stomatal conductance was 72% higher in Umbrella pine than in Holm oak, leading to higher stomatal ozone flux. Inclusion of a soil water function improved the performance of the Jarvis-type model for the estimation of stomatal ozone flux. We found contrasting results concerning the coefficient *m* (the slope of the photosynthesis-stomatal conductance relationship) in the Ball-Woodrow-Berry model between the two forests: while *m* was constant for varying soil water status in the Holm oak forest, it declined with soil drying in the Umbrella pine forest. This may result from higher stomatal sensitivity to drought in Umbrella pine as a response to avoid drought stress. Overall, these results advance our understanding of ozone risk assessment in Mediterranean forests.

1. Introduction

Concentrations of tropospheric ozone (O_3) have now doubled in the northern hemisphere since the pre-industrial period (Hartmann et al., 2013). In the Mediterranean countries, current surface O_3 levels are high enough to damage forest trees (Sicard et al., 2013). Ozone induces damages to plants, e.g., visible leaf injury, premature leaf senescence, decreased photosynthesis, reduced growth rates and altered allocation of carbon (Paoletti, 2007; Mills et al., 2011; Matyssek et al., 2013; Fares et al., 2013a; Sicard et al., 2016).

Recent O_3 risk assessment for forest trees has focused on a stomatal O_3 flux basis (Hoshika et al., 2012a; CLRTAP, 2015), because O_3 enters the plant tissues through the stomata and directly damages cell proteins and membranes by oxidation (Omasa et al., 2002; Contran and Paoletti, 2007; Leisner and Ainsworth, 2012; Tiwari et al., 2016). To better understand O_3 flux partitioning in stomatal and non-stomatal sinks over forest canopies, direct measurements of O_3 fluxes were carried out using the Eddy Covariance technique (Cieslik, 2004; Mikkelsen et al., 2004; Fares et al., 2013a). Thanks to techniques such as the Evaporative/Resistance method, bulk-canopy stomatal conductance can be estimated from the energy balance of a forest canopy (Monteith and Unsworth, 1990; Cieslik, 2004; Fares et al., 2013b). In the last decade, it was intensively discussed in which way O_3 damage to plants can best be estimated (CLRTAP, 2015). Eddy covariance provides an opportunity to parameterize canopy-level stomatal conductance for forests, where leaves may not respond to their environment equally throughout the canopy (Baldocchi, 1989). An accurate parameterization is

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essential for a stomatal flux-based approach to assess O_3 impact on forest trees (Zhang et al., 2003; Emberson et al., 2007).

Traditionally, two main empirical approaches are used for estimating stomatal conductance (Damour et al., 2010): the empirical Jarvis-type model (Jarvis, 1976; Emberson et al., 2007) and the semi-empirical approach, called Ball-Woodrow-Berry (BWB) model (Ball et al., 1987). The former approach is based on a multiplicative algorithm that adjusts a reference value of stomatal conductance (i.e., maximum stomatal conductance, G_{max}) according to changes in phenology and environmental variables such as light intensity, air temperature, vapor pressure deficit and soil moisture. This model is recommended by UNECE-CLRTAP (United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution) to calculate stomatal O_3 fluxes and estimate a metric for O_3 risk assessment of forest trees in Europe (CLRTAP, 2015). The BWB method assumes that stomatal conductance is tightly coupled to photosynthetic rate because stomata open and close to keep a nearly constant ratio between intercellular and ambient CO_2 concentration. This ratio may vary with atmospheric humidity. Therefore, Ball et al. (1987) elaborated a model that links stomatal conductance to leaf photosynthesis, humidity deficit and CO_2 concentration at the leaf surface.

The Mediterranean climate is characterized by a hot summer with low precipitation, which results in a limitation of stomatal O_3 flux by stomatal closure due to drought stress (Paoletti, 2006). Southern Europe is representative of water-limited environments (dry and semi-dry habitats) that cover about 41% of Earth's land surface (Reynolds et al., 2007). Soil moisture deficit represents a major limiting factor for stomatal conductance in the Mediterranean region (Chaves et al., 2002; Alonso et al., 2008). Several studies have tried to include a soil moisture function into the Jarvis-type model because it is critical for water-limited environments (Stewart, 1988; Alonso et al., 2008; Büker et al., 2012; González-Fernández et al., 2013; De Marco et al., 2016). Also for the BWB model, recent studies have included the drought impact by using the modification of *m* (the slope of the photosynthesis-stomatal conductance relationship of the BWB model) with soil drying (van Wijk et al., 2000, 2002; He et al., 2014; Knauer et al., 2015). However, it is still under discussion whether drought stress may change the coefficient *m* (Sala and Tenhunen, 1996; Xu and Baldocchi, 2003; Baldocchi and Xu, 2005; Keenan et al., 2009; Fares et al., 2013b).

In Mediterranean Europe, previous modeling studies for O_3 risk assessment have mainly targeted the evergreen broadleaf Holm oak (*Quercus ilex*) representing the most typical climax forest (Emberson et al., 2007; Fares et al., 2013b). However, Mediterranean forests are also dominated by pioneer tree species such as pines (*Pinus pinea, P. pinaster* and *P. halepensis*). The crown condition of Mediterranean lowland pines is characterized by an increase in mean defoliation since 1991 (Fischer and Lorenz, 2011; Sicard and Dalstein-Richier, 2015). Stomatal conductance models may need different parameters for Mediterranean pine forests. For example, under water limitation, pine trees may avoid drought stress by earlier stomatal closure relative to oak species (Picon et al., 1996).

The aims of this study were i) to characterize the difference in the stomatal conductance parameters of both Jarvis-type and BWB models in two representative Mediterranean forests (*Q. ilex* and *P. pinea*), ii) to examine whether the slope of the photosynthesis-stomatal conductance relationship (i.e., the coefficient *m*) in the BWB parameterization changes under drought stress, and iii) to test the performance of both Jarvis-type and BWB models for the estimation of canopy-level stomatal O_3 flux in both forests.

Table 1
Daily mean temperature (T, in °C), daily mean volumetric soil water content (*SWC*, in $m^3\ m^{-3}$) and daily mean ozone concentration (in ppb) in a Holm oak forest (Castelporziano) and an Umbrella pine forest (San Rossore) and associated standard deviations (±SE).

Sites and seasons	T (°C)	*SWC* ($m^3\ m^{-3}$)	O_3 (ppb)
Castelporziano			
Spring	18.3 (±0.2)	0.187 (±0.004)	38.7 (±0.7)
Summer	26.7 (±0.2)	0.100 (±0.002)	40.2 (±0.9)
Autumn	23.2 (±0.2)	0.126 (±0.005)	29.9 (±0.8)
Winter	13.1 (±0.3)	0.194 (±0.006)	23.2 (±1.0)
San Rossore			
Spring	17.0 (±0.4)	0.085 (±0.002)	36.1 (±1.5)
Summer	24.4 (±0.2)	0.051 (±0.001)	50.8 (±1.6)
Autumn	19.5 (±0.3)	0.032 (±0.002)	34.2 (±2.3)
Winter	7.8 (±0.6)	0.174 (±0.011)	23.8 (±1.2)

At Castelporziano (in 2013–2014), spring: March to May, summer: June to August, autumn: September to November, winter: January, February and December. At San Rossore (in 2013), spring: 22 April-12 May, summer: 8–27 July, autumn: 9–29 September, winter: 20 January-10 February.

2. Materials and methods

2.1. Site descriptions

The first site is a Holm oak forest at Castelporziano (41°70′42″N, 12°35′72″E), 15 m a.s.l., 1.5 km from the seashore of the Thyrrenian sea, and 25 km SW from the center of Rome (Italy). The soil has a sandy texture (sand content above 60%) and low water-holding capacity according to a detailed study carried out by Pinzari et al. (1999). The dominant tree species is *Q. ilex* with an average height of 14.9 m and a Leaf Area Index of 3.7 $m^2{}_{leaf}\ m^{-2}{}_{ground}$. The forest stand is uneven-aged with the oldest trees planted more than 80 years ago. Further details are described in Fares et al. (2014).

The second site is a *Pinus pinea* (Umbrella pine) forest at San Rossore (43°43′55″N, 10°17′27″E), 12 m a.s.l., approximatively 1200 m from the seashore of the Thyrrenian sea and 8 km from Pisa (Italy). The soil is a sandy calcaric regosol. Soil texture was as follows (% on weight): clay 3%, silt 2% and sand 95% (Gruening, person. comm.). It is an almost pure, even-aged about 93 years old forest. The average canopy height is 19 m, with a Leaf Area Index of 3.3 $m^2{}_{leaf}\ m^{-2}{}_{ground}$. Further information on the general area of the measurement site is given in Matteucci et al. (2015).

At both sites, the climate is Thermo-Mediterranean, characterized by prolonged stress aridity during the summer, and a moderate cold stress during the winter. The meteorological data during the measurement campaign were shown in Table 1.

2.2. Measurements of environmental parameters and fluxes

At Castelporziano, values of air temperature, precipitation (Davis vantage pro meteorological station, Davis Instruments Corp. CA, USA) and volumetric soil moisture content in the soil profile (10, 50, 100 cm depth, CS 650, Campbell scientifics, Shepshed, UK) were measured at 1-min resolution, averaged at half-hour intervals and recorded by a data logger (CR3000, Campbell scientifics, Shepshed, UK). Flux measurements above canopy started on 1st January, 2013 and ended on 31st December, 2014. Instantaneous wind speed and temperature fluctuation were measured by a three-dimensional sonic anemometer (Gill Windmaster, Gill Instruments, Lymington, UK). Closed-path analytical equipment was installed in an air conditioned cabin, below a 19-m tall tower. Fast response measurements of O_3 were made by chemiluminescence using coumarin dye with an instrument custom developed by the National Oceanic and Atmospheric Administration (NOAA, Silver Spring, MD). Air was sampled continuously at one inlet at the top of the tower through Teflon tubes with 4 mm internal diameter and a Teflon filter (PFA