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Metrics of ozone risk assessment for Southern European forests: Canopy moisture content as a potential plant response indicator

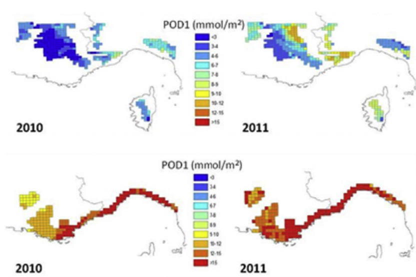
A. De Marco [a], P. Sicard [b], M. Vitale [c], G. Carriero [d], C. Renou [b], E. Paoletti [d,*]

[a] ENEA, Via Anguillarese 301, 00123 Rome, Italy
[b] ACRI-ST, 260 route du Pin Montard, BP 234, 06904 Sophia Antipolis Cedex, France
[c] UNIROMA1, Piazzale Aldo Moro, 00196 Rome, Italy
[d] IPSP-CNR, Via Madonna del Piano 10, 50019, Sesto Fiorentino, Florence, Italy

HIGHLIGHTS

- Stomatal ozone flux (POD) is a better metric than AOT40 for the protection of forests.
- We recommend POD0 rather than POD1.
- We cannot recommend CMC as a plant-response indicator.

GRAPHICAL ABSTRACT



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ABSTRACT

Present standards for protecting ecosystems from ozone (O_3), such as AOT40, use atmospheric concentrations. A stomatal flux-based approach (Phytotoxic O_3 Dose, PODY) has been suggested. We compared the spatial and temporal distribution of AOT40 and PODY – with and without a hourly threshold of uptake (POD1 and POD0) – for *Pinus halepensis* and *Fagus sylvatica* in South-eastern France and North-western Italy. Ozone uptake was simulated by including limitation due to soil water content, as this is an important parameter in water-limited environments. Both AOT40 and POD1 exceeded the critical levels suggested for forests. AOT40 suggested a larger O_3 risk relative to PODY. No significant spatial and temporal difference occurred between POD1 and POD0. The use of POD0 in the assessment of ambient O_3 risk for vegetation is thus recommended, because it is more biologically-meaningful than AOT40 and easier to be calculated than POD1. Canopy Moisture Content (CMC), a proxy of foliar water content, was modelled and tested as a potential plant O_3 response indicator. CMC response to O_3 was species-specific, and thus cannot be recommended in the epidemiology of O_3 injury to forests.

1. Introduction

Tropospheric ozone (O_3) is a secondary pollutant generated from volatile organic compounds (VOCs), carbon monoxide (CO) and nitrogen oxides (NO_x) in photochemical reactions. Ozone is an important air quality issue, causes serious health problems, damages materials and ecosystems, and contributes to climate change

* Corresponding author.
E-mail addresses: alessandra.demarco@enea.it (A. De Marco), Pierre.Sicard@acri-st.fr (P. Sicard), marcello.vitale@uniroma1.it (M. Vitale), carriero@ipp.cnr.it (G. Carriero), elena.paoletti@cnr.it (E. Paoletti).

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(Kampa and Castanas, 2008; Screpanti and De Marco, 2009; Sicard et al. 2011a). Background O_3 concentrations have doubled since pre-industrial times and have increased by 1–2% per year at northern mid-latitudes since about 1950 (Vingarzan, 2004). Sicard et al. (2013) showed an increase at suburban (0.46% per year) and urban (0.64% per year) background sites around the Western Mediterranean basin over 2000–2010. Compared to 2000, the relative changes in mean tropospheric O_3 burden in 2030 (2100) vary from −4% to +7% (−16% to +18%) (Young et al., 2013). Global surface temperature change for the end of the 21st century is likely to exceed 1.5 °C relative to 1850–1900 (IPCC, 2013). Formation of O_3 depends on temperature (The Royal Society, 2008). The risk of drought in summer will increase in southern Europe (IPCC, 2013). As O_3 exposure is expected to unbalance the water control of vegetation (Paoletti and Grulke, 2010; Hoshika et al., 2012a), such climate changes emphasize the importance of a proper assessment of O_3 risk to vegetation, in particular in Mediterranean climates. The Mediterranean region shows the highest O_3 concentrations in Europe as atmospheric stability over the summer and high temperature and solar radiation promote O_3 formation (Sicard et al., 2013). The increase of background O_3 levels may have large negative impacts on vegetation in this region (Paoletti, 2007; Fares et al., 2013).

Current European standards use the O_3 exposure index AOT40 to protect vegetation, although it does not give information about the environmental constraints to O_3 uptake into leaves, such as water stress (Paoletti and Manning, 2007). As a consequence, the AOT40 index may be inadequate for the quantification of O_3 impacts on vegetation, particularly in water-limited regions (Paoletti, 2006). For this reason, a stomatal flux-based approach was suggested (Emberson et al., 2000) for estimating the amount of O_3 that is absorbed into the leaf through stomata and integrating the effects of climatic factors and vegetation characteristics. The stomatal flux-based model, or DO3SE model, incorporates the seminal Jarvis' (1976) algorithm and describes species-specific effects of soil water availability, vapour pressure deficit, air temperature, irradiation, plant phenology and O_3 concentration on stomatal functioning. The flux-based approach uses the maximum stomatal conductance to describe the upper limit of stomatal response to environmental stimuli, as represented by the 95th–98th percentile of a cohort of conductance measurements (Hoshika et al., 2012b). Stomatal conductance modelled by DO3SE has been validated against direct measurements carried out by many previous studies (e.g. Altimir et al., 2004; Tuovinen et al., 2004; Nunn et al., 2005; Fares et al., 2014). The flux is then accumulated over a species-specific phenological time window and expressed as PODY (Phytotoxic Ozone Dose), where Y represents a detoxification threshold below which it is assumed that any O_3 molecule absorbed by the plant will be detoxified (Mills et al., 2011a). A threshold of 1 is at present recommended for all forest trees (UNECE, 2010), although insufficient evidence is available in order to validate this threshold. The dose–response relationships have been derived mostly from field-based open-top chamber experiments (Hayes et al., 2007; Mills et al., 2007; Pleijel et al., 2007; UNECE, 2010). Although climatic conditions are naturally fluctuating inside such chambers, there is a constant windspeed which may affect ozone flux and thus a broad-scale application in risk assessment is to be verified (Paoletti, 2007).

Because of the many factors contributing to effects, epidemiological studies are better suited to validation of standards/thresholds than controlled-condition experiments. The epidemiology of O_3 injury may be very helpful when real-world forests are investigated, as large trees require expensive experimental facilities for realistic O_3 simulation and usually only a few individuals can be investigated. The epidemiology of injury due to stomatal O_3 flux, however, is still in its infancy. Assessing large-scale stomatal O_3 fluxes is challenging as it requires access to data from different sources, complex long-term field measurements or modelling. This is why the majority of previous epidemiological assessments used ambient O_3 exposure as a metric of injury (e.g., Braun et al., 2007; McLaughlin et al., 2007; Baumgarten et al., 2009; Sun et al., 2012; Kefauver et al., 2013; De Marco et al., 2013). A few epidemiological studies used stomatal O_3 flux. De Marco et al. (2010) used geostatistics for combining the observation networks of O_3, meteorology and durum wheat yield in central Italy, and found that stomatal O_3 flux was the best O_3 predictor for yield decline when compared to the exposure-based metrics used as legislative standards in Europe and North America. Mills et al. (2011b) superimposed visible foliar O_3 injury and metrics across Europe and found a better fitting with PODY than with AOT40. Fares et al. (2013) compared long-term eddy-covariance measurements of carbon and O_3 fluxes in three Mediterranean-type plant ecosystems and concluded that the observed reduction in carbon assimilation was better related to stomatal O_3 flux than to O_3 concentration. Similar conclusions were reached in a two-month micrometeorological assessment in a Norway spruce forest (Zapletal et al., 2011). By a sap-flow approach, Braun et al. (2014) estimated radial growth losses in *Fagus sylvatica* (19.5%) and *Picea abies* (6.6%) in Switzerland, based on annual O_3 stomatal uptake during the period 1991–2011.

Canopy Moisture Content (CMC) is a functioning index of forest ecosystems given that biogeochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water content (Sellers et al., 1992). Quantification of vegetation water content has important implications in agriculture and forestry (Gao and Goetz, 1995), e.g. drought assessment of natural vegetation (Zhang et al., 2013), and prediction of forest susceptibility to fires (Ustin et al., 1998). CMC can be assessed by remote sensing (Goetz, 1990, 1995; Gao, 1996; Dawson et al., 1999) and carefully simulated by modelling (Ceccato et al., 2001; Chen and Dudhia, 2001; Strachan et al., 2002; Colombo et al., 2008). Ozone has been reported to induce both stomatal closure (Wittig et al. 2007) and slower or less efficient stomatal control (Paoletti, 2005; Paoletti and Grulke, 2010; Hoshika et al., 2012a, 2013, 2014). Such O_3-induced stomatal sluggishness has the potential to affect leaf water losses and explain why O_3-exposed leaves usually show lower water content than control leaves (Nali et al., 2004; Paoletti et al., 2007). We thus tested CMC as a plant-response indicator in the assessment of stomatal O_3 flux effects on forest health.

The aim of this study was to evaluate the performance of O_3 risk indicators, namely POD0, POD1 and AOT40, in South-eastern France and North-western Italy forests in 2010–2011. Data were generated by the WRF-CHIMERE modelling system (9 × 9 km grid). In addition, modelled CMC was used as potential plant-response indicator for assessing impacts in *F. sylvatica* and *Pinus halepensis*. Exposure to simulated O_3 enrichment suggests that these species are among the most O_3 sensitive forest species (Gerant et al., 1996; Nunn et al., 2005; Karlsson et al., 2007; Löw et al. 2006). However, they show very contrasting ecology. *F. sylvatica*, or European beech, is a deciduous broadleaf tree, whose natural range extends from southern Sweden to Sicily in Italy, and from France and northern Portugal to northwest Turkey. *F. sylvatica* is an oceanic-climate species, requires a humid atmosphere and well-drained soil, tolerates rigorous winter cold and is sensitive to spring frost. Typically, it extends from 1000 to 1650 m a.s.l. in the investigation area and its growing season is from April to September (Jump et al., 2007). *P. halepensis*, or Aleppo pine, is a *circum*-Mediterranean conifer, mostly distributed along the coastline and at low altitudes, from sea level to 200 m a.s.l., except up to 1000 m a.s.l. in Southern Spain. *P. halepensis* is very drought-resistant and thermophilic, and its