Developing ozone critical levels for multi-species canopies of Mediterranean annual pastures


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ABSTRACT

Ozone (O₃) critical levels (CLe) are still poorly developed for herbaceous vegetation. They are currently based on single species responses which do not reflect the multi-species nature of semi-natural vegetation communities. Also, the potential effects of other factors like the nitrogen (N) input are not considered in their derivation, making their use uncertain under natural conditions.

Exposure- and dose-response relationships were derived from two open-top chamber experiments exposing a mixture of 6 representative annual Mediterranean pasture species growing in natural soil to 4 O₃ fumigation levels and 3 N inputs. The Deposition of O₃ and Stomatal Exchange model (DO3SE) was modified to account for the multi-species nature of the canopy following a big-leaf approach. This new approach was used for estimating a multi-species phytotoxic O₃ dose (PODᵧ-MS). Response relationships were derived based on O₃ exposure (AOT₄₀) and flux (PODᵧ-MS) indices.

The treatment effects were similar in the two seasons: O₃ reduced the aboveground biomass growth and N modulated this response. Gas exchange rates presented a high inter-specific variability and important inter-annual fluctuations as a result of varying growing conditions during the two years. The AOT₄₀-based relationships were not statistically significant except when the highest N input was considered alone. In contrast, PODᵧ-MS relationships were all significant but for the lowest N input level.

The influence of the N input on the exposure- and dose-response relationships implies that N can modify the O₃ CLe. However, this is an aspect that has not been considered so far in the methodologies for establishing O₃ CLe. Averaging across N input levels, a multi-species O₃ CLe (CLₑf-MS) is proposed: PODᵧ-MS = 7.9 mmol m⁻², accumulated over 1.5 month with a 95% confidence interval of (5.9, 9.8). Further efforts will be needed for comparing the CLₑf-MS with current O₃ CLₑ based on single species responses.

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1. Introduction

Tropospheric Ozone (O₃) is an important greenhouse gas that is also considered the most phytotoxic air pollutant, inducing negative effects on growth, productivity and yield quality of forests, crops and pastures (Ainsworth et al., 2012; Fuhrer, 2009).

Background O₃ concentrations have been raising since the Industrial Revolution in many parts of the Northern Hemisphere (Stevenson et al., 2006). Although the implementation of environmental policies in the last two decades has decreased peak O₃ concentrations (Klingberg et al., 2014), the air quality in Europe is still not acceptable for protecting the human health and the environment (EEA, 2014).

The Convention of Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNEP) is leading the process of setting O₃ critical levels (CLe) as policy target values for the protection of vegetation. Initially, O₃ CLe made use of exposure indices based on the atmospheric O₃ concentration (CLₑ) (Karenlampi and Skarby, 1996). More recently, O₃ stomatal uptake or flux-based CLe (CLₑf) have been developed in recognition that effects are more related with the amount of O₃ being absorbed by the leaves (Emberson et al., 2000a; Mills et al., 2011). CLₑf are used within the CLRTAP for performing O₃ risk assessment.
assessments where the O$_3$ stomatal fluxes, also known as Phyto-toxic O$_3$ Doses (POD$_y$), are computed by the Deposition of Ozone and Stomatal Exchange model (DO$_3$SE).

The current DO$_3$SE model configuration computes POD$_y$ values for a big-leaf of a single species (Emberger et al., 2000a; CLRTAP, 2010). However, this represents a limitation when the model is used to assess the risk of O$_3$ effects on plant communities composed by different species like pastures. The community-level response to O$_3$ is the aggregated response of the component species and the existing interactions between them (Bassin et al., 2007; Gonzalez-Fernandez et al., 2008; Calvete-Sogo et al., 2016). Besides, pasture species often present a great range of stomatal conductance ($g_{sto}$) values (e.g. Gonzalez-Fernandez et al., 2010). Thus, the O$_3$ risk assessment methodology for pastures could be improved by using POD$_y$ estimates that integrate the species composition of the pasture.

Mediterranean annual pastures are one of the most valuable eco-systems in Southern Europe. In the Iberian Peninsula, annual pastures constitute the understorey of Dehesas, a traditional agroforestry system (Montado in Portugal) covering nearly 20,000 km$^2$ (Diaz et al., 2007). Dehesas present a high vascular plant richness estimated at 230 species (Garcia del Barrio et al., 2014). This diversity is comparatively higher than other forest and agroforestry ecosystems from temperate climates (Diaz et al., 1999; Ojeda et al., 2000). Dehesas are located in areas frequently exceeding current European air quality limit values (EU Air Quality Directive, 2008/50/EC) for the protection of ecosystems. The particular climatic conditions of the Mediterranean area with high temperature and solar radiation and stable atmospheric conditions favour photochemical reactions that produce O$_3$ (Millan et al., 2000; Cristofanelli and Bonasoni, 2009). This results in some of the highest surface O$_3$ concentrations in Europe (EEA, 2014).

Ozone has been recognized as an important negative factor affecting the yield, reproductive capacity and species composition of annual pasture species (Bermejo et al., 2003; Gimeno et al., 2004a, b; Calvete-Sogo et al., 2014, 2016). These studies also showed how atmospheric nitrogen (N) deposition interacts with O$_3$, where N can mitigate the O$_3$-induced effects and O$_3$ reduces the efficiency of the N fertilization. Nonetheless, there is still the need to expand the experimental basis for evaluating the effect of O$_3$ and its interaction with N under close to field conditions and to increase the information available about the ecophysiology and gas exchange behavior of annual species for developing more robust CLE$_y$.

In this study, a new O$_3$ and N experiment with annual Mediterranean pastures following the same methodology than in Calvete-Sogo et al. (2014) is presented. The combined experimental results from the two seasons are analyzed through an improved O$_3$ flux model considering a multi-species approach and the influence of N on the response of the pasture to O$_3$. The inclusion of the specific O$_3$-sensitivity and gas exchange rates of the component species in this new approach will allow to propose more realistic CLE for Mediterranean annual pasture communities. The hypotheses were that higher CLE will be obtained with multiple species compared with individual sensitive species due the introduction of O$_3$-resistant species in the model and that nitrogen availability will modify the response to O$_3$. The main objectives of this work are: (1) to present a new experiment on the response of an annual community to O$_3$ and N; (2) to set a parametrization of the multiplicative algorithm of DO$_3$SE for $g_{sto}$ modelling combining the six assayed species; (3) to estimate the POD$_y$ for a multi-species canopy (POD$_{y,M}$); (4) to develop exposure- and dose-response functions for yield considering the multi-species approach and the influence of N availability, and suggesting CLE$_y$ and CLE$_f$ for annual pastures based on this method.

2. Material and methods

2.1. Experimental design

In February 2011 and 2012 seeds were sown on the ground of 12 open-top chambers (OTC) located in central Spain (450 m.a.s.l.; 40°3’N, 4°26’W). Plants were exposed to four O$_3$ treatments from 7:00 to 15:00 GMT, seven days a week (3 OTC per O$_3$ treatment): charcoal filtered air (FA), non-filtered air (NFA) reproducing ambient levels, non-filtered air supplemented with 20 nl l$^{-1}$ O$_3$ (NFA+) and non-filtered air supplemented with 40 nl l$^{-1}$ O$_3$ (NFA++). Three ambient plots (AA) were also considered. Ozone was supplemented by a generator (Model 16, A2Z Ozone Systems Inc., USA) system fed with pure oxygen. A time sharing system registered the pollutants levels inside the OTCs and AA plots (O$_3$, SO$_2$ and NO$_x$) above the canopy (50 cm above the soil). All plots were divided in three sectors (1.4 m$^2$ each) following a split-plot design with three N treatments: N-low (soil N background), N-medium (N addition equivalent to 20 kg N ha$^{-1}$) and N-high (40 kg N ha$^{-1}$). To reach these integrated doses, N supplementation was applied every 2-weeks using a NH$_4$NO$_3$ solution.

Micro-meteorological conditions were continuously monitored inside the different chambers: air RH and temperature, photosynthetic active radiation (PAR), PAW (Plant Available Water, difference in water content between field capacity and permanent wilting point) and temperature at 10−15 cm depth. More details of the experimental design can be found in Calvete-Sogo et al. (2014).

2.2. Plant material and harvests

The simplified pasture community was composed of six representative species from Dehesa acidic annual grasslands. Three legumes (Trifolium striatum, Trifolium cherleri, Oniphtus compressus), two grasses (Briza maxima, Cynosurus echinatus) and one forb (in 2011 Silene gallica; in 2012 Petroshagia nanteuilii) were sown by hand using a mixture of seeds on 11th and 27th February 2011 and 2012 respectively until the community reached its seed maturation, which happened in late May and early June in 2011 and 2012 respectively.

Aboveground biomass was harvested three times throughout the life span of the pasture in both years. The first harvest was done just before the start of O$_3$ treatments and N applications. The homogeneity of the species distribution between the sub-plots was tested at this harvest. The second harvest was collected after 39 (2011) and 38 (2012) days of O$_3$ exposure, at 84 DaE in both years, when the pasture reached its maximum development and productivity. Then the O$_3$ exposure system was switched off allowing plants to dry up and complete seed maturation, which happened in late May and early June in 2011 and 2012 respectively.
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