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New flux based dose–response relationships for ozone for European forest tree species

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ABSTRACT

To derive O_3 dose–response relationships (DRR) for five European forest trees species and broadleaf deciduous and needleleaf tree plant functional types (PFTs), phytotoxic O_3 doses (POD*y*) were related to biomass reductions. POD*y* was calculated using a stomatal flux model with a range of cut-off thresholds (*y*) indicative of varying detoxification capacities. Linear regression analysis showed that DRR for PFT and individual tree species differed in their robustness. A simplified parameterisation of the flux model was tested and showed that for most non-Mediterranean tree species, this simplified model led to similarly robust DRR as compared to a species- and climate region-specific parameterisation. Experimentally induced soil water stress was not found to substantially reduce POD*y*, mainly due to the short duration of soil water stress periods. This study validates the stomatal O_3 flux concept and represents a step forward in predicting O_3 damage to forests in a spatially and temporally varying climate.

1. Introduction

A large body of evidence has shown that ozone (O_3) causes damage to trees (Wittig et al., 2009; Matyssek et al., 2010). These O_3 effects range from impacts such as visible injury on foliage (Schaub, 2005), decreasing leaf chlorophyll content and photosynthesis (Wittig et al., 2009), changes in carbon allocation (Paoletti et al., 2009) and biomass production (Wittig et al., 2009), premature leaf senescence (Pell et al., 1999), and altered tree water use (Sun et al., 2012). By synthesising information expressed as O_3 flux based dose–response relationships (DRR) derived from field-experiments, critical levels (CLs) have been identified above which O_3 damage would be expected to occur (LRTAP Convention, 2010; Mills et al., 2011). The United Nations Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) has used such CLs as a policy tool to identify areas of CL exceedance across Europe and subsequently to formulate European emission reduction strategies to improve air quality.

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This study presents the next stage in the derivation of DRR for forest trees, which use the accumulated stomatal O_3 flux above a threshold '*y*' as the dose metric (Emberson et al., 2007), often referred to as POD*y* (Phytotoxic Ozone Dose above a threshold '*y*'), and the relative change in annual whole tree biomass production as the response metric (Karlsson et al., 2007). Current CLs for forest trees are based on an analysis performed by Karlsson et al. (2007) on Norway spruce (27 data points from 3 countries and 8 experiments) and beech/birch (38 data points from 3 countries and 14 different experiments) and were set to values for which there was a >95% confidence of finding a significant effect at the percentage loss chosen (LRTAP Convention, 2010; Mills et al., 2011). Since the publication of Karlsson et al. (2007), additional experimental data have become available that extend the species under investigation and increase the range of environmental conditions under which the fumigation or filtration experiments were performed. In addition, new methods to assess the influence of soil moisture on stomatal O_3 flux have been developed (Büker et al., 2012).

In performing this re-analysis including all currently available forest tree data, we addressed the following sources of uncertainty in flux-effect modelling for forest tree species: i. the parameterisation of the stomatal flux model; ii. the choice of the '*y*' threshold (which is considered to statistically represent the plants' ability to detoxify a certain level of O_3 dose (Pleijel et al., 2007)); iii. the influence of reduced water-availability on stomatal O_3 flux and; iv. whether particular groupings of species, e.g. according to plant functional types (PFTs), with similar O_3 sensitivities can be identified. We also compared regression functions based on the same updated dataset using the updated flux methodology with those using the formerly accepted concentration-based approach (AOT40[1]).

To investigate the parameterisation of the flux model, this study applied two different methods to estimate stomatal O_3 fluxes. The first method was that used previously by Karlsson et al. (2007), but with updates to include new parameterisations defined in the 2010 revision of the UNECE Mapping manual (LRTAP Convention, 2010). These 'real species' parameterisations incorporate new data to define parameter values and also identify climate specific parameterisations to account for different species ecotypes. A second method tested the suitability of a simplified parameterisation, i.e. standard functions that describe the effect of light, vapour pressure deficit and temperature on stomatal conductance (g_s) irrespective of species, called simplified parameterisation or simple model from hereon. Application of this method was used to test the hypothesis that a simplified parameterisation of the multiplicative g_s model leads to a similarly robust DRR as compared to the 'real species' parameterisation. As such it examined whether there is a need for a rigorous species-specific parameterisation of the model, which often complicates large-scale application of the flux based method both for flux-effect as well as total O_3 deposition estimation.

This study also presented the opportunity to compile new dose–response functions and datasets for two species (i.e. Holm oak and poplar) not considered in Karlsson et al. (2007). This allowed a more thorough investigation of the uncertainty in the current CLs related to the selection of the '*y*' threshold. Karlsson et al. (2007) used a single '*y*' value of 1.6 nmol O_3 m^{-2} s^{-1} based on a previous analysis (Karlsson et al., 2004), which found that this value gave higher R^2 values for flux–effect relationships when compared with thresholds of 0.0, 3.2 and 4.8 nmol O_3 m^{-2} s^{-1}. Since it is more statistically robust to test a number of '*y*' thresholds (Feng et al., 2012), the analysis presented here set out to trial a far wider and incrementally refined number of '*y*' threshold values than has been performed previously for forest tree species.

Another key area of uncertainty investigated here is the influence of reduced water availability on POD*y* and hence O_3 sensitivity. Some of the new datasets are derived from experimental O_3 fumigations or filtrations conducted under varying levels of water supply. This allows the effect of reduced water availability on POD*y* to be investigated using a new soil water balance method described in Büker et al. (2012). This is particularly important as the exclusion of data representing non-optimal water supply, which is known to reduce g_s (Büker et al., 2012) and therefore stomatal O_3 flux, has been cited as reason why the stomatal flux approach sometimes does not provide a substantial improvement of DRR developed using the concentration based AOT40 index (e.g. Karlsson et al., 2007).

Finally, this study also investigated whether species groupings of O_3 sensitivity can be defined. Past studies have been rather inconclusive in defining DRR that are able to represent different tree PFTs. For example, Karlsson et al. (2004, 2007) found Norway spruce, Scots pine and birch/beech to be more sensitive than Aleppo pine and oak such that no obvious distinction could be made between broadleaf and needleleaf trees. In contrast, a meta-analysis performed for forest trees by Wittig et al. (2009) found evidence for gymnosperms being less sensitive than angiosperms when related to O_3 concentrations. Also, broadleaf evergreen species have been reported to be more resistant to O_3 than broadleaf deciduous species (Calatayud et al., 2010, 2011; Zhang et al., 2012). However, a study by Reich (1987) suggested that when taking into account O_3 uptake (or flux) per leaf life span, conifers and hardwoods have similar sensitivity in terms of declines in photosynthesis and growth. This analysis provided an opportunity to investigate these issues in further detail using more advanced methods for estimating stomatal O_3 flux.

The overall aim of this study was to evaluate the performance of POD*y* and AOT40 metrics in predicting biomass reductions for forest trees. This was achieved through analysis of the statistical performance of linear regressions of DRR constructed using data collected from fumigation and filtration studies. This work was conducted with a view to developing new DRR that could be used in the derivation of critical levels within the LRTAP Convention.

2. Materials and methods

2.1. Estimating stomatal conductance gs

The stomatal conductance (g_s) algorithm of the DO_3SE (Deposition of O_3 for stomatal exchange) model was used as the basis for estimates of g_s for all model runs. The model employs a multiplicative algorithm, based on that first developed by Jarvis (Jarvis, 1976), modified for O_3 flux estimates (Emberson et al., 2000a, 2000b, 2001, 2007; Büker et al., 2012) to estimate leaf/needle g_s (the inverse of r_s (stomatal resistance)) as:

$$g_s = g_{max} * f_{phen} * f_{PPFD} * \max\{f_{min}, f_T * f_D * f_{SW}\} \quad (1)$$

where the species-specific maximum g_s (g_{max}) is modified by relative response functions (scaled from 0 to 1) to account for g_s variation with leaf/needle age over the course of the growing season (f_{phen}) and the functions f_{PPFD}, f_T, f_D and f_{SW} relating g_s to irradiance (described as photosynthetic photon flux density, *PPFD*, μmol/m^2/s), temperature (*T*, degrees Celcius), vapour pressure deficit of the air (*D*, kPa) and soil water, respectively. f_{SW} can either be related to soil water potential (*SWP* in MPa) or plant available soil water expressed in volumetric terms (*PAW* in % vol/vol). f_{min} is the minimum daylight g_s under field conditions, expressed as a fraction of g_{max}.

[1] AOT40 = Ozone concentrations accumulated over a threshold of 40 ppb.