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Short communication

Wheat yield responses to stomatal uptake of ozone: Peak vs rising background ozone conditions

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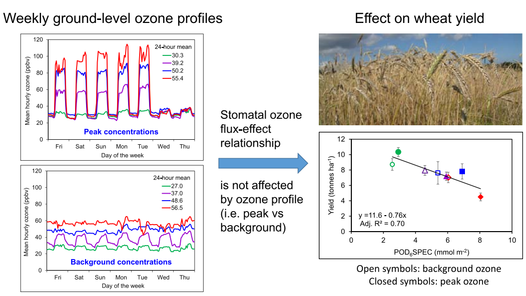
GRAPHICAL ABSTRACT



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ABSTRACT

Recent decades have seen a changing temporal profile of ground-level ozone (O_3) in Europe. While peaks in O_3 concentrations during summer months have been declining in amplitude, the background concentration has gradually increased as a result of the hemispheric transport of O_3 precursors from other world regions. Ground-level O_3 is known to adversely affect O_3-sensitive vegetation, including reducing the yield of O_3-sensitive crops such as common wheat (*Triticum aestivum* L.). The reduction in wheat yield has been shown to be linearly related to the phytotoxic O_3 dose above a flux threshold of Y (POD_Y) accumulated over a specific period. In the current study, we tested whether the flux-effect relationships for wheat yield and 1,000-grain weight were affected by the temporal profile of O_3 exposure. A modern wheat cultivar (Skyfall) was exposed to eight different realistic O_3 profiles repeated weekly: four profiles with increasing background O_3 concentrations (ca. 30–60 ppb) including small peaks and four profiles with increasing O_3 peak concentrations (ca. 35–110 ppb). Both wheat yield and 1,000-grain weight declined linearly with increasingPOD_Y. The slope of the flux-effect relationships was not affected significantly by the profile of O_3 exposure. Hence, flux-effect relationships developed for wheat based on exposure to enhanced peak O_3 concentrations are also valid for the changing European O_3 profile with higher background and lower peak concentrations. The current study also shows that the modern wheat cultivar Skyfall is more sensitive to O_3 than European wheat varieties tested for O_3 sensitivity in the 1980s and 1990s.

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1. Introduction

Tropospheric or ground-level ozone (O_3) is a secondary pollutant formed in the atmosphere by solar radiation-driven chemical reactions between O_3 precursor gases, i.e. carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4) and non-methane volatile organic compounds (nmVOCs; Monks et al., 2015; Royal-Society, 2008). Annual variation in O_3 concentrations depends on geographical location, proximity to sources of O_3 precursors and prevailing meteorological conditions. This variation in concentration is determined by both photochemical and physical processes, including photochemical production and destruction of O_3, hemispheric transport, and removal by deposition at the Earth's surface (Monks et al., 2015). Usually a distinction is made between peak/episodic, hemispheric background and baseline O_3 (Royal-Society, 2008). Peak concentrations of O_3 (also known as episodes) occur when high levels of O_3 precursor emissions coincide with meteorological conditions that promote O_3 formation, for example stable, high pressure systems. Hemispheric background O_3 is the remaining concentration when the emissions of anthropogenic O_3 precursors from within a region are excluded. It is the sum of O_3 produced from natural sources of precursors within a region and O_3 imported into the region (derived from all sources). Baseline O_3 is the average measured concentration within a region and is made up of both the anthropogenic emissions produced within the region and the background concentration of O_3.

Ground-level O_3 pollution increased significantly between the end of the 19th and 20th century (Cooper et al., 2014; Marenco et al., 1994). Parrish et al. (2012) reported an approximate doubling of baseline O_3 concentrations between 1950 and 2000 at northern mid-latitudes. Since 2000, however, the rate of increase has slowed, particularly at European sites, to the extent that at present O_3 baseline concentrations are decreasing at some sites in some seasons, especially in the summer (EMEP, 2016). Although measurements at rural O_3 monitoring stations in Europe showed a decline in peak concentrations of O_3 at some (but not all) European sites, there has been a concurrent rise in concentrations in the lower range up to 40 ppb (Simpson et al., 2014; Tørseth et al., 2012). The largest decline in amplitude of peak O_3 episodes has been observed at stations which saw the highest levels of peak O_3 in the early 1990s (Derwent and Hjellbrekke, 2013). Since 1990, a clear downward trend in high summertime O_3 episodes has been confirmed for many EMEP (European Monitoring and Evaluation Programme) rural monitoring stations, whilst the annual mean (baseline) O_3 increased between 1990 and 2001 and began to level off between 2002 and 2012 (EMEP, 2016). The decline in peak O_3 concentrations in Europe in recent decades is the result of the implementation of air pollution abatement policies and the use of cleaner energy in Europe, which has resulted in a decline in emission of O_3 precursors compounds such as NO_x and nmVOCs (EMEP, 2016).

O_3 is known to be toxic for vegetation (Ainsworth et al., 2012; Mills et al., 2011a; Wittig et al., 2009). O_3 enters the leaf through the stomata and triggers a reaction chain involving reactive oxygen species (ROS). Plants have the capacity to detoxify O_3 and ROS but the detoxification capacity is species-specific, with damage occurring when this detoxification capacity is exceeded (Burkey et al., 2006). Recently, it has been shown that impacts of O_3 on vegetation are best correlated with the accumulative stomatal O_3 flux, calculated over a species-specific time period, using a threshold for the stomatal O_3 flux as a surrogate for the O_3 detoxification capacity (Mills et al., 2011a). The accumulative stomatal O_3 flux above an hourly threshold Y has been defined as the Phytotoxic Ozone Dose (POD_Y; Mills et al., 2011b; LRTAP Convention, 2017). A flux-effect relationship has been derived for the crop species common wheat (*Triticum aestivum* L.) based on experimental O_3 exposure studies conducted with five cultivars in four countries. The function uses a wheat-specific parameterisation of the stomatal O_3 flux model DO_3SE (Deposition of O_3 for Stomatal Exchange - http://sei-international.org/do3se; Emberson et al., 2000, 2001) for the flag leaf. For wheat, previous work has shown that the flux threshold Y of 6 nmol m^{-2} projected leaf area s^{-1} (Grünhage et al., 2012) produces the best statistical fit between yield and stomatal flux (Pleijel et al., 2006); the accumulative stomatal O_3 flux is defined as POD_6SPEC (LRTAP Convention, 2017 – Section III.3.5.2). Plant species vary in their sensitivity to O_3, with wheat being an O_3-sensitive crop (Mills et al., 2016). Flux-based critical levels have been defined for a limited number of crop species (LRTAP Convention, 2017). Data for wheat were also used to develop a generic flux-effect relationship for crops for application in large scale modelling, including integrated assessment modelling (IAM), based on a lower O_3 flux threshold Y of 3 nmol m^{-2} projected leaf area s^{-1}, defined as POD_3IAM (LRTAP Convention, 2017 – Section III.3.6). POD_YIAM-based flux models have a simpler form and parameterisation than POD_YSPEC based ones.

Flux-effect relationships for wheat are based on studies conducted between 1987 and 1999 in which the crop was exposed to high O_3 episodes, representing peak O_3 concentrations during the growing season (Grünhage et al., 2012). With the current O_3 temporal profile changing in Europe, we investigated whether O_3 flux-effect relationships based on exposure of vegetation to peak O_3 concentrations are also valid for vegetation exposed to rising background concentrations. We hypothesise that effects on wheat yield are determined by the accumulated stomatal O_3 flux, independent of the temporal profile of O_3 exposure, i.e. background O_3 concentrations or peak O_3 episodes.

2. Material and methods

2.1. Plant material, experimental site and treatments

The experiment was conducted in 2015 at the Centre for Ecology & Hydrology (CEH) air pollution facility at Abergwyngregyn, North Wales (53.2°N, 4.0°W). On 13th March, wheat (*Triticum aestivum* L., cv. Skyfall) seeds were sown outdoors in containers (0.3 m × 0.3 m x 0.3 m) filled to 25 L with John Innes No. 3 compost (J. Arthur Bowers). Skyfall is a new, high yielding, bread-making winter wheat variety in the UK and was launched in 2014. Seeds were sown in four rows 7 cm apart with 40 seeds per container, resulting in a seedling density of approximately 260 seedlings per m^2, similar to the recommended field seedling density (AHDB, 2015). Containers were inoculated with soil microbial communities from a nearby wheat field using a soil slurry applied shortly after sowing. Seedlings emerged on 5th April. On 7th May, the containers were randomly distributed between eight hemispherical glasshouses (solardomes; 3 m diameter, 2.1 m height); each dome contained four containers. After an acclimation period in the solardomes, O_3 treatments were started on 15th May. Plants were exposed to O_3 until harvest (11th – 13th August) and each solardome had a different weekly O_3 regime (Fig. 1). The O_3 regimes were assigned randomly to the solardomes to minimise the impacts of any potential environmental gradients at the research site. In four solardomes, plants were exposed to varying background O_3 concentrations (low, medium, high, very high) and in the other four solardomes, plants were exposed to varying peak O_3 concentrations (low, medium, high, very high), representing a 5-day O_3 episode per week. The weekly temporal profiles were applied such that pairs of background and peak O_3 treatments represented a similar mean O_3 concentration, e.g. low background and low peak O_3 exposure represented a seasonal 24 h mean O_3 of 27.0 and 30.3 ppb respectively (Fig. 1). The lack of treatment replication in this experiment was due to the limited number of solardomes. However, a previous assessment found that climatic conditions do not vary significantly between the solardomes used in this experiment (Hewitt et al., 2014).

The solardomes were ventilated at a rate of two air changes per minute and charcoal-filtered air was injected with controlled amounts of O_3. O_3 was provided by a G11 O_3 generator (Ozone Industries, UK) equipped with a Sequal 10 oxygen concentrator, (Pure O2, UK). Concentrations were determined by a computer-controlled O_3 injection