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Current surface ozone concentrations significantly decrease wheat growth, yield and quality

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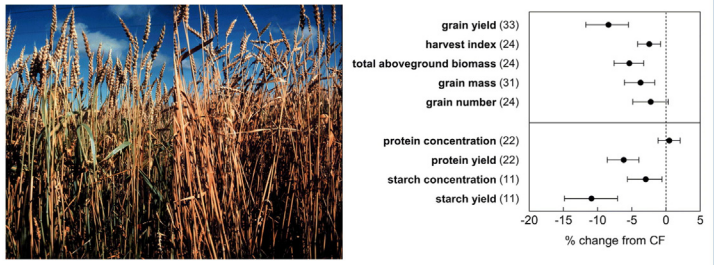
HIGHLIGHTS

- The effects of current vs. preindustrial ozone on wheat were investigated.
- Compared to preindustrial levels, current ozone negatively affected wheat growth, yield and quality.
- The effect on yield was related to the amount of ozone removed by filtration.
- The effect on yield was not related to the age of the cultivar.

GRAPHICAL ABSTRACT



Wheat grown in filtered air (CF, photo left) senesces more slowly than in non-filtered (NF, photo right). A range of yield and growth variables responded negatively to NF vs CF in meta-analysis.

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ABSTRACT

Tropospheric ozone is known to adversely affect crops and other vegetation. Most studies have focussed on the effects of elevated ozone levels vs. present ambient. We investigated the effect of present ambient surface ozone (O_3) concentrations vs. preindustrial on a range of agronomically important response variables in field-grown wheat, using results from 33 experiments (representing 9 countries, 3 continents, 17 cultivars plus one set of 4 cultivars) having both charcoal filtered (CF) and non-filtered (NF) air treatments. Average filtration efficiency was 62%, reducing the O_3 concentration from 35.6 ± 10.6 SD ppb in NF to 13.7 ± 8.8 SD ppb in CF. Average CF concentrations were in the range of levels believed to represent pre-industrial conditions, while NF concentrations were 7% lower than in the ambient air at plant height on the experimental sites. NF had significant ($p < 0.05$) negative effects compared to CF on grain yield (−8.4%), grain mass (−3.7%), harvest index (−2.4%), total above-ground biomass (−5.4%), starch concentration (−3.0%), starch yield (−10.9%), and protein yield (−6.2%). No significant effect was found for grain number and protein concentration. There was a significant relationship between the effect of filtration on grain yield and the difference in O_3 concentration between NF and CF treatments. The average yield loss per ppb O_3 removed was 0.38% and did not systematically vary with year of experiment (ranging from 1982 to 2010) or with the average O_3 level in the experiments. Although there are many differences among the field experiments included in this meta-analysis (e.g. genotype, degree of O_3 pollution of the site and year, nutrient and soil condition, filtration efficiency), our study clearly shows that there is a consistent and significant effect of present ambient O_3 exposure on a range of important response variables in wheat, the most strongly affected being starch yield.

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1. Introduction

Elevated ozone (O_3) concentrations have been shown to strongly affect several crops including wheat (Mills et al., 2007; Royal Society, 2008). Responses include reduced biomass, harvest index and seed yield; in many cases also an increased protein concentration was observed while protein yield was reduced (Feng and Kobayashi, 2009; Feng et al., 2008; Grünhage et al., 2012). Very few studies have focussed on the evidence of agronomic effects of current surface ozone levels compared to preindustrial. Pleijel (2011) investigated the effect on wheat grain yield of charcoal filtration (CF) compared to non-filtered (NF) air in open-top chamber (OTC) experiments. The effect of CF vs. NF on wheat grain yield turned out to be significantly positive. Evidence of effects from current O_3 levels is important from a policy perspective, since they highlight the gains from reducing present ambient air pollution levels, rather than the potential effects of further increases in O_3 concentration. In this paper we substantially extend the study by Pleijel (2011) by adding new datasets, performing meta-analysis for a range of agronomically important yield and quality traits, quantifying the relationship between yield effects and the amount of O_3 removed by air filtration, and testing for a possible trend in the response of wheat with respect to the release year of the cultivar and the year that the different experiments were performed.

In many individual experiments the difference in O_3 exposure between CF and NF treatments was small and did not always result in statistically significant effects on wheat. The general observation was, however, that reduction in ozone concentration by air filtration tends to improve wheat grain yield. Effects are easier to detect using treatments with substantially increased O_3 concentrations since they become large in relation to the random variation in the experiments. However, the response to elevated O_3 in OTC and other chamber experiments, or FACE (Free Air Concentration Elevation of O_3), cannot be used to directly assess the effects of the increase in O_3 from preindustrial times to present. The current effects of O_3 can be assessed by the combined analysis of data from all existing field experiments for which a comparison of NF and CF treatments is possible.

Ozone is the most important air pollutant influencing crop yield in most parts of the world (Ashmore, 2005), although concentrations of other pollutants, such as SO_2 and NO_2, may be significant in certain areas, in particular in rapidly developing countries where air pollution emissions are high and in some areas increasing (Rao et al., 2017). In developed countries, emissions of SO_2 have been cut very significantly, and also emissions of NO_2 have declined but to a lesser extent (Rafaj et al., 2014). However, background O_3 concentrations, which have increased substantially since preindustrial times (Volz and Kley, 1988; Vingarzan, 2004), remain high. In many parts of the world the increase in surface O_3 concentrations continues (Royal Society, 2008; Cooper et al., 2014) and tropospheric ozone is increasingly influenced by global precursor emissions including methane and substantial hemispheric transport (Cooper et al., 2014).

CF treatments have been used to reduce air pollution levels in many, but far from all, chamber based ozone experiments with wheat and other crops. Charcoal filters are known to efficiently remove O_3, but only slightly less efficiently reduce other potentially phytotoxic compounds such as SO_2 and NO_2 (Fowler et al., 1988; Pleijel, 2011). Pleijel (2011) found that, when reported, especially SO_2, but also NO_2 concentrations, were much lower than O_3 concentrations in almost all the sites where OTC experiments have been performed. Thus, O_3 effects are likely to dominate responses of crops to air filtration in OTC experiments. It should also be kept in mind that O_3 concentrations in NF are lower by ~10% than ambient due to loss by deposition in the fan and chamber system (Pleijel, 2011).

O_3 concentrations in both NF and CF treatments differed considerably among different experiments. This depends on several factors such as the geographical and year-to-year variation in O_3 concentration among experiments and sites. Further, the filtration efficiency varies depending on properties of the filters used, but also on the variable incursion of air at the top of the OTC (Unsworth et al., 1984; Pleijel et al., 1994), which is sensitive both to chamber design and wind speed. All in all, these factors result in a considerable variation in the reduction of the O_3 concentration in the different experiments. Based on this variation a response function between the effect on grain yield and the difference in O_3 concentration between NF and CF treatments can be derived for the population of relevant experiments.

Several experiments have shown that old cultivars of wheat are less sensitive to O_3 than modern ones. Based on studies with ten Greek genotypes of wheat, introduced between 1932 and 1980, Barnes et al. (1990) and Velissariou et al. (1992) found that O_3 sensitivity had been increasing during the 50-year study period, and that inadvertent selection by breeders may be responsible for this development. A limitation of the studies by Barnes et al. (1990) and Velissariou et al. (1992) was that plants were cultivated in controlled environment chambers and only long enough to develop ears, not to produce mature seeds. Consequently, studies of O_3 effects on grain yield were not made, which was also the case in the study of Biswas et al. (2008) showing similar results for Chinese wheat cultivars of different age. However, Pleijel et al. (2006) also found a higher sensitivity to O_3 when comparing a modern cultivar with an old one in experiments where the wheat plants were grown until maturity. These earlier studies to a large extent contrasted genotypes which had not been subject to modern plant breeding with highly bred genotypes of the late 20th century. It remains unexplored whether there has also been a temporal trend with successively increasing O_3 sensitivity in wheat cultivars released during the last few decades, the period during which most OTC experiments have been undertaken.

The specific aims of this investigation were:

- to perform meta-analysis on available data where field-grown wheat was exposed to CF and NF air in OTCs to quantify the effect of current O_3 pollution on a range of agronomically important response variables (grain yield, grain mass, grain number, total above-ground biomass, harvest index, grain starch concentration, grain protein concentration, starch yield, protein yield);
- to test if the effect of NF vs. CF on wheat grain yield is quantitatively related to the amount of ozone removed by air filtration;
- to investigate if the effect of air filtration depends on the year of release (1965–2001) of the different wheat cultivars or on the year that different experiments were performed (1982–2010).

2. Methods

2.1. Data

Web of Science was used to survey the peer-reviewed literature published between 1980 and 2016 containing experiments with wheat grown in CF and NF in OTC treatments. In order to avoid confounding influences from artificial rooting environments, only experiments using field soil grown crops were included in the quantitative analysis, but results from pot experiments are also discussed. To be included in the study one of the following response variables had to be reported: grain yield, grain mass or the equivalent "1000-grain weight", grain number per unit area, total above-ground biomass, harvest index (the fraction of the above-ground biomass found in grains at harvest), starch concentration of grains or protein concentration of grains. In addition, daytime average O_3 concentration in the CF and NF treatments had to be reported for an experiment to become part of the study. Protein yield (mass of grain protein per unit area) and starch yield (mass of grain starch per unit area) were calculated from grain yield and, respectively, grain starch concentration and grain protein concentration. Daytime O_3 concentrations were used to avoid any influence of the more variable but toxicologically less important night-time exposure (Pleijel, 2011). If the daytime O_3 concentration was reported