Ozone pollution and wheat: Quantifying future impacts and scope for increasing tolerance

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Wheat – global importance

- 215 million hectares planted annually
- Most important protein source and provides around 20% of global calories for human consumption
- More than 60% of wheat is produced in emerging and developing countries: China and India together produce nearly twice as much wheat as the USA and Russia combined.
- In North Africa and West and Central Asia, wheat is the dominant staple crop and provides 40 – 50% of all calories.

Wheat is also one of the most ozone-sensitive crops

* source: www.wheatinitiative.org
Figure 1. Rank of wheat as a food crop worldwide in terms of proportion of daily calories supplied to the diet.
Ozone exposure experiments in Sweden

Functions in Mills et al., 2007 were updated where possible

Threshold for significant yield effects

<table>
<thead>
<tr>
<th>Crop</th>
<th>Threshold ozone conc (ppb)</th>
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<td>Lettuce</td>
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<td>Barley</td>
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<td>Sugar beet</td>
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<tr>
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<tr>
<td>Maize</td>
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<td>Peas and beans</td>
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<tr>
<td>Rice</td>
<td>3</td>
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<tr>
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<td>2</td>
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<td>Soybean</td>
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7h mean ozone conc. required for a significant effect on yield
Ozone and wheat yield

Quantifying potential impacts under current and future scenarios

- EU27+CH+NO
- Eastern Europe
- India and China

Options for mitigation

- Reductions in precursor emissions
- Understanding the physiology of responses
- Crop management
- Scope for ozone-resistant cultivars
Ozone effects on Food Security

- ICP Vegetation
- Coordinated by CEH Bangor
- Quantifying impacts for the UN Convention on Long-Range Transboundary Air Pollution

Palais des Nations, Geneva
European projections: Surface maximum O3 conc.
(annual mean)

2005 Max surface ozone, annual mean, ppb

2030CLE Max surface ozone, annual mean, ppb
Wheat yield loss – Revised GP scenarios

Percentage yield loss – calculated using a new response relationship for the generic crop flux model (POD$_3$IAM)$^1$

$^1$ assumes soil water is not limiting
Wheat yield loss – Revised GP scenarios

See informal document no. 4 (‘Guidance document’)

Mean % yield loss* for EU27: 12.4% for GP2005 10.3% for GP CLE2020

*assumes soil water is not limiting; one flux model used for all of Europe
Air Pollution: Deposition to and impacts on vegetation in (South-)East Europe, Caucasus, Central Asia (EECCA/SEE) and South-East Asia.

* Includes ozone effects on wheat in Eastern Europe and SE Asia
Potential effects on wheat yield in E Europe

Potential “large” ozone effects on wheat yield expected in eastern Europe, especially the Ukraine, Belarus and eastern Russia

Note: The flux model used to generate the data in this figure provides an estimation of the worst case for damage with adequate water supply (either rain-fed or irrigated).

From: Harmens, H. and Mills, G. (Eds.) (2014). Air Pollution: Deposition to and impacts on vegetation in (South-)East Europe, Caucasus, Central Asia (EECCA/SEE) and South-East Asia.
Predictions for India and China

14.9% wheat yield loss for China and 22.3% yield loss for India in 2000 (POD6)

Losses predicted to increase by 8.1% for China and 5.4% for India by 2020

From: Tang et al., 2013, Global Change Biology (2013) 19, 2739–2752
Summary - sustained effects of ozone on crop yields in EU, increasing effects in Eastern Europe and in Asia

- Mechanistic basis of the effects of ozone on plants
- Interactions between ozone effects and drought (and heat)
- Impacts on Food Security and beyond
70 ppb ozone prevents stomatal closure in drying soil. As soil dries, ozonated plants lose more water (within 24h).

More open *Trifolium* stomata with 70ppb ozone under drought but substantial genetic variation. Effects are persistent!
ABA doesn’t close stomata at higher ozone concentration -

Serious problem under drought

Fig. 7 Effect of abscisic acid (ABA) on the transpiration rate of excised nonsenescing inner canopy leaves of Leontodon hispidus. Data is presented as the percentage change in the rate of transpiration of the +ABA treatment relative to the distilled water control treatment. N = 8, bars represent ± SE. Differences

Ozone stimulates ethylene accumulation

Effect of 9 days exposure +/- 80ppb 24h ozone on ethylene generation by Leontodon leaves sprayed +/- 3x10^{-6}M ABA once daily over the preceding 3 days.

Inhibit ethylene binding and stomata regain capacity to close in response to drought/ABA

Effect of ACC and ABA (2x10^{-6}M) sprayed onto lettuce plants, on increase in leaf length over following 36h.

ACC restricts leaf growth but ABA over-rides this effect

Single population of plants.

What is the impact of variation in background concentration of Ethylene?
1. Stomata open, water loss increases and above-ground biomass increases.

2. Plant and soil water potentials decrease, particularly under drought.

3. Plant injury, reduced productivity (direct and indirect)

4. Catchment effects (soil and water)

- Decreased soil and plant water potential
- Reduced leaf growth
- Reduced biomass and grain production
- Reduced grain number and size
- Decreased CO₂ assimilation
- Increased ozone
- Stomatal opening, growth promotion, increase S/R ratio
- Increased ethylene plus ABA
- Soil drying, flooding, high VPD
- Decreased water infiltration into soils
- Increased overland flow
- Increased soil erosion
- Increased diffuse pollution
- Reduced stream flow

Wilkinson and Davies 2010 Plant Cell and Environment 33, 510-525
Rhizobacterium (Variovorax C52) restores stomatal functioning under ozone stress

11 days +/- ozone
4 days since rhizobacterial addition
3rd day of ABA spraying

Stomatal conductance (mmol m\(^{-2}\) s\(^{-1}\))

- Control
- + R

+/- rhizobacteria
ABA applied to all plants

- ozone
+70ppb ozone

Treatment

The Lancaster Environment Centre
Conceptual models of stress-adaptive Physiological trait combinations

ABA

CK

ABA + ETH +…..

ABA + AUX

HEAT

ETH + CK

YIELD = LI x RUE x HI

ETH

DROUGHT

ABA

WUE

YIELD = WU x WUE x HI

Access to water

Under drought to increase total water availability to the crop (WUE).

Under hot, irrigated conditions to permit transpiration rates that match a high evaporative demand (RUE).
The stress hormone ABA regulates plant functioning (stomatal functioning as a model)

Note - when ethylene is not a complicating issue?

Hu, Wilkinson and Davies, 2013
Hormone ratios provide plasticity in response (______)

![Graph showing stomatal conductance in relation to Log₁₀ (ABA / Ethylene) with R² values 0.3580 and 0.4971.](Image)

Hu, Wilkinson and Davies, 2013
Hormone ratios integrating environmental impacts on plant functioning and development?
Stomatal conductance (mmol m\(^{-2}\) s\(^{-1}\)) vs. Log\(_{10}\) (ABA/Ethylene)

- Ashby
- No.4
- No.6
- No.10

Log\(_{10}\) (ABA/Ethylene)

Hu et al. 2014 Unpublished
Real-time measurement of ethylene using Sensorsense laser technology
Hormone profiling in wheat with lcms  (Thiry et al Unpublished)

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<th>ZR</th>
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Measured and modelled late-season streamflow (baseflow) of the Walker Branch Watershed, southern Appalachian forest catchment, USA, over 23 years. Reduced ozone levels gave rise to increases in streamflow, and the authors concluded that ozone-induced increases in whole-tree canopy conductance and consequent depletions in soil water content were responsible. (Mclaughlin et al 2007)
Crop management to reduce water use
Because there is little water in the irrigation canals, farmers have dug wells to access ground water. As a result the water table has fallen dramatically.
Techniques used over an area of approximately 120,000ha in the Wuwei district alone. “maize, water saving 50% with yield reduction at 11%; apple and wine grape, water saving 10-18% and 35-40% respectively with no yield reduction for both crops; cotton, water saving 30% with seed cotton yield reduction only at 5%, but with much higher quality of lint cotton yield”
New 111 project funded by Ministry of Education China
“Improving water use efficiency in agriculture from molecular level to regional scales”
Assuming water use efficiencies of 1.5 and 2.7 kg t⁻¹ for wheat and maize, production of the required wheat and maize output in the region for 2030 (91.7 and 96.8 MT) would need 96.9 billion tons of water, which is more than the current estimates of groundwater reserve in the region (75.4 billion tons; Ministry of Water Resource of China 2012).

WITH OZONE, WUEs MAY BE EVEN LOWER
Phenotyping for high grain yield

Selection under: IRRIGATED, HEAT and DROUGHT

Adapted from: Cossani et al., 2012
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