Ozone & Agriculture: A hidden Threat

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CEH Bangor,
Why is ozone a particular threat to agriculture?

‘Seasonal’ distribution and ‘geographical’ location of ozone concentrations
Ground level ozone pollution - Seasonal distribution

Rural location in the UK

Regional / local emissions contribute to peak ozone concentrations
Can reach 200 ppb and over

Global emissions contribute to global background - Frank Dentner
~30 to 40 ppb and rising

The photochemical formation and secondary nature of O₃ makes it an important summertime and rural air pollutant...
Current day $O_3$ concentrations are now high in many agriculturally important regions ....
How does ozone affect agricultural productivity?

VI areas ‘Key Concerns’ of ozone impact on agriculture - these often interact with existing threats to agriculture
Key concerns for agriculture I. Leaf damage by ozone

Wheat, Europe

Spinach, Europe

Especially relevant for horticulture e.g. salad leaf crops

Incidences of $O_3$ injury in the field, 1990 - 2006

(Mills et al., 2011, Global Change Biology)
Field evidence: New ICP Vegetation Smart Phone App

For recording incidences of leaf ozone injury

Submit photos of ozone

Report location on interactive map

Download this App at:
http://icpvegetation.ceh.ac.uk
Key concerns for agriculture II. Growth reductions

Plants grown in ambient air with high levels of O₃ pollution
Plants grown in filtered air (pollutant free), Lahore, Pakistan
Key concerns for agriculture III. Yield quantity and quality reductions

Ozone exposure experiments in Sweden

Threshold for significant yield effects

The fraction of N (P & K) added that ends up in grain is negatively affected by ozone - leading to additional environmental problems.

Adding more N fertilizer is not a good solution to the ozone problem!
Key concerns for agriculture

V. Drought tolerance reduced

- Ozone reduces drought tolerance in agricultural species by interfering with hormonal control.
- Increase in stomatal conductance
- Also affects C allocation - decrease in root biomass further limiting access to soil water

\[ R^2 = 0.31, \quad p = 0.15 \]
\[ R^2 = 0.75, \quad p = 0.005 \]

\[ \text{AFst0 (mmol m}^{-2}\text{)} \]

Biomass Allocation

\[ \text{Shoot} \]
\[ \text{Root} \]

1 Mills et al., 2009;
2, 3 Wilkinson and Davies (2009, 2010)
Ozone within ambient ranges also reduces N fixation in many legume species (bean, soybean, clover)

Accelerated reproductive rate may allow mites to adapt quickly to resist pesticides
How can we collate this information?

ICP Vegetation

- Reports to UN LRTAP Convention on impacts of air pollutants on crops & natural vegetation
- 35 European countries and USA, over 60 Institutes and 200 scientists participate
- Outreach to eastern Europe, Asia (including India), South Africa and the Caribbean

Examples of ICP Vegetation Thematic Reports

http://icpvegetation.ceh.ac.uk/
How are ozone concentrations likely to change in the future?

Problem across the World, especially in the mid West US, Europe and Asia; with the situation in Asia in particular likely to worsen in the coming 20 to 30 years.
O$_3$ concentrations already high in Europe though it is likely these concentrations will decline in the future...

...essentially O$_3$ concentrations will depend on whether O$_3$ precursor control options are implemented

...Markus Amann

HTAP, 2010
How will changing ozone concentrations affect wheat yield across Europe?

Gothenburg Protocol Scenarios
2005  Current legislation, 2030

10.7% loss  8.2% loss

Percentage yield loss (POD$_3$IAM)

http://icpvegetation.ceh.ac.uk/
O$_3$ concentrations likely to continue to increase in the future across Asia?

....essentially O$_3$ concentrations will depend on whether O$_3$ precursor control options are implemented

...Markus Amann

HTAP, 2010
How will ozone affect wheat yield across Asia?

• Based on modelled ozone uptake ($POD_{12}$), ozone pollution is predicted to reduce wheat yield by 10.3% in China and 9.7% in India in 2000.

• Losses predicted to increase by a further 8.9 and 6.4% respectively in 2020.

Tang et al., 2013
Crop yield commonly improved by around 5-30% by filtration of air pollution from plant micro-climate

**Varanasi, India**
- Winter wheat (Nov to April) RY = 90-75%
- Rice RY = 86-84%
- Indian mustard RY = 92-86%
- Palak RY = 78%
- Soybean (?) RY = 89%

**Allahabad, India**
- Mung bean (Dec to March) RY = 70%

**Lahore, Pakistan**
- Winter wheat (Nov to May) RY = 69-53%
- Spring wheat (Nov to April) RY = 82 to 52%
- Rice (May to Nov) RY = 71 to 53%
- Mung bean RY = 50%
- Soybean (Aug to Oct) RY = 68 to 26%

**Tokyo, Japan**
- Rice (April to Sept) RY = 80%

**Yangtze River Delta, China**
- Rice (July to Oct) RY = 92%

**Thailand**
- Rice (?) RY = 94 to 70%

**Klang Valley, Malaysia**
- Rice (Oct to Jan) RY = 97 to 94%

**Legend**
- Field chambers
- O₃ monitors
- O₃ generators
- Face

*Emberson et al., 2009; ICP Vegetation reports (2011, 2014)*
What can we do to minimise ozone effects on agricultural sustainability?

Mitigation or adaptation
Mitigation options: **Emission reductions**

International efforts to reduce ozone pollution:

**ICP Vegetation**

UNECE Convention on Long-range Transboundary Air Pollution

...Brings together scientific evidence to establish air quality guidelines (AQGs)

**UNEP/WMO Black Carbon and Ozone Assessment**

Identifies 16 measures to reduce emissions that would benefit human health, agriculture and near-term climate change
Mitigation options: Emission reductions

Climate Smart Agriculture (CSA)

- CSA - agricultural management practices that reduce GHG emissions and enhance productivity & livelihoods

- CSA could focus on CO\textsubscript{2}, CH\textsubscript{4}, N\textsubscript{2}O but also aerosols and ozone

- Aerosols have a local/regional influence on climate (meteorology) e.g. effect of aerosol on precipitation patterns and solar radiation (dimming)

- Ozone has a direct toxic effect on seasonal productivity
Adaptation options: Raised awareness in crop breeding

Selection of higher yielding varieties tend to have higher gas exchange and hence greater ozone uptake.

Similar results found that modern wheat cultivars are more ozone-sensitive (Barnes et al., 1990; Biswas et al., 2008; Pleijel et al., 2006; Velissariou et al., 1992).
Adaptation options: Early warning systems

Early warning system of ozone episodes in place in Cuba since 1992:

- Farmers get 5 day warning of high ozone
- Watering withheld
- Damage to garlic reduced from 73% to 2%

Source: Jésus Ramirez
Summary

- Ozone pollution is a ‘hidden threat’ to agricultural sustainability often causing 5 to 30% yield losses in ‘hot-spot’ regions

- Many of our most important food crops are ozone sensitive including rice, wheat and pulses

- Ozone affects Nitrogen use efficiency, drought tolerance, resistance to pests & diseases, forage quality….as well as reducing yields

- Ozone concentrations look likely to continue to increase in Asia over the coming decades

- Solutions to the problem include:
  
  ✓ mitigation (emission reduction) and require international efforts to coordinate reductions to optimise benefits for agriculture but also human health and climate
  
  ✓ Adaptation (agricultural management) e.g. crop breeding for varieties that are not sensitive to ozone, seasonal forecasting of ozone episodes
Deleted slides
Based on modelled ozone uptake (POD$_{12}$), ozone pollution is predicted to reduce wheat yield by 10.3% in China and 9.7% in India in 2000.

Losses predicted to increase by a further 8.9 and 6.4% respectively in 2020.

Tang et al., 2013, Global Change Biology, 19, 2739 - 2752
What can we do to minimise ozone effects on sustainability?

1. International effort to reduce ozone pollution
   - ICP Vegetation
   - UN Convention on Long-range Transboundary Air Pollution

2. Developing ozone tolerant varieties
   - But: Selection of higher yielding varieties tend to have higher gas exchange and hence greater ozone uptake

3. Exploring chemical protectants against ozone damage
   - E.g. Ethylene diurea, 1-MCP, ABA

Similar results found that modern wheat cultivars are more ozone-sensitive (Barnes et al., 1990; Biswas et al., 2008; Pleijel et al., 2006; Velissariou et al., 1992).
(1) International effort to reduce ozone pollution
  *ICP Vegetation*
  *UN Convention on Long-range Transboundary Air Pollution*

(2) Developing ozone tolerant varieties
  *But: newer varieties are often more sensitive than older ones*

(3) Exploring chemical protectants against ozone damage
  *E.g. Ethylene diurea, 1-MCP, ABA*

Yield benefit of applying EDU in ambient air

Feng et al.(2010), *Env. Poll.* , 158, 3236
Could these ozone effects be contributing to ‘yield gaps’?

Yield gap fraction values on a 5’ grid with an equirectangular projection for wheat


Sustainable Agriculture and Air Pollution
10 July 2015; EXPO, Milan, Italy
Concentration-response relationships have been used to perform risk assessments to estimate yield losses...

Year 2000 global economic losses estimated to cost $14-26 billion

For economies largely based on agriculture, O$_3$ induced damage is estimated to offset a significant portion (20 - 80%) of the year 2000 GDP growth rate.
Many studies have estimated similar magnitudes of yield losses...

<table>
<thead>
<tr>
<th>Reference</th>
<th>O₃ index</th>
<th>Geographical Region</th>
<th>Crops</th>
<th>Yield / economic crop losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe &amp; US</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adams et al. (1988)</td>
<td>7- &amp; 12- hr seasonal means</td>
<td>US</td>
<td>9 crops arable</td>
<td>US $ 3 x 10⁹</td>
</tr>
<tr>
<td>Holland et al. (2002)</td>
<td>AOT40</td>
<td>Europe</td>
<td>&gt; 20 arable crops</td>
<td>US $ 8 x 10⁹</td>
</tr>
<tr>
<td>Asia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang &amp; Mauzerall (2004)</td>
<td>7- &amp; 12- hr seasonal means</td>
<td>East Asia</td>
<td>wheat, rice, corn, soybean</td>
<td>US $ 5 x 10⁹</td>
</tr>
<tr>
<td>Jamir et al (pers comm)</td>
<td>AOT40</td>
<td>South Asia</td>
<td>Wheat, rice, soybean and potato</td>
<td>US $ 3.9 x 10⁹</td>
</tr>
<tr>
<td>The globe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Dingenen et al (2009)</td>
<td>7- &amp; 12- hr seasonal means and AOT40</td>
<td>World</td>
<td>wheat, rice, corn, soybean</td>
<td>3 to 10 % US $ 14 to 26 x 10⁹</td>
</tr>
</tbody>
</table>
Ozone flux response relationship

\[ y = -0.0013x^2 + 0.0177x + 0.9547 \]

\[ R^2 = 0.8548 \]

...O₃ also causes shifts in species composition of grasslands... with implications for forage quality

Ozone within ambient ranges also reduces N fixation in many legume species (bean, soybean, clover)
Where does ozone pollution come from and why is it a particular threat to agriculture? 

I think this may be too complex for this audience.

The photochemical formation and secondary nature of $O_3$ makes it an important summertime and rural air pollutant...
How do we assess the risks posed to arable agriculture by ozone?

**Fumigation / Filtration studies**
National Crop Loss Assessment Network (NCLAN) - 1980s in North America
European Open Top Chamber (EOTC) - 1990s in Europe
Key sustainability concerns for agriculture: I Water stress

Ozone induces loss of sensitivity to ABA through the production of ethylene which prevents stomatal closure and reduces drought tolerance

(Wilkinson et al., 2009)
What biophysical factors are responsible for this ‘yield gap’?

Soil water availability (rain-fed, irrigation)
Soil nutrient status (soil fertility, fertilizer)
Heat stress
Pests & diseases (agro-ecosystem resilience, chemicals)
Ozone ??

Stomatal Ozone flux plays a substantial role in determining ozone damage...and is related to

- Ozone concentration
- Atmospheric mixing (delivering ozone concentrations to the plant canopy)

As well as yield related parameters.....

- Growing season (determined by effective temperature sum)
- Stomatal conductance (determined by photosynthesis)
- Photosynthesis dependant upon water availability, soil nutrient status
South Asia has a number of different stresses affecting agriculture

Aerosol optical depth (AOD)

Ozone concentrations ppm.hrs

Water scarcity index

Heat stress

Biotic Stress (pests, pathogens and diseases)

Engardt, 2008

Null & Diamond, 2012

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Wheat yield progress in India and in Punjab State 1992-2012 (irrigated low latitude)

- Punjab progress not unlike Yaqui Valley but all yields lower
- Yield gap larger than Yaqui Valley: many small constraints

PY = Potential yield
FY = Farm Yield

Source
FAOSTAT, Singh et al 2011, I. Sharma pers.comm.
Key sustainability concerns for agriculture: III Heat stress

The importance of phenology in determining crop exposure to ozone

Crop breeding developing heat stress tolerant varieties that grain fill earlier to avoid exposure to high temperature at end of growing season

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## Adaptation Options for Ozone

### Identification and registration of trait specific genetic stocks

<table>
<thead>
<tr>
<th>Trait</th>
<th>Genetic strains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotic stress (rust, loose smut, powdery mildew, Karnal bunt, hill bunt and foliar blight)</td>
<td>82</td>
</tr>
<tr>
<td>Abiotic stress (drought, heat and salt tolerance)</td>
<td>15</td>
</tr>
<tr>
<td>Primary yield components (grain size, grain number per spike, fertile tillers)</td>
<td>10</td>
</tr>
<tr>
<td>Grain quality (protein, lysine, beta carotene, sedimentation value, bread quality, Chapati quality, spread factor, loaf volume, glutenin)</td>
<td>25</td>
</tr>
<tr>
<td>CMS lines with maintainers and fertility restorers</td>
<td>8</td>
</tr>
<tr>
<td>Others</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>160</td>
</tr>
</tbody>
</table>

*All India Coordinated Wheat Improvement Project (AICWIP)*

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*‘Sustainable Agriculture and Air Pollution’ 10 July 2015; EXPO, Milan, Italy*
Crop breeding

Large variation in O$_3$ sensitivity within cultivars of the same species
Substitute with varieties resistant to O$_3$....but need screening to identify cultivar sensitivity
Crop breeding

Selection of higher yielding varieties tend to have higher gas exchange and hence greater ozone uptake.

Similar results found that modern wheat cultivars are more ozone-sensitive (Barnes et al., 1990; Biswas et al., 2008; Pleijel et al., 2006; Velissariou et al., 1992).
Mitigation: reduce $O_3$ levels and limit climate change.
One option may be to tackle short-term climate forcers.

- Review scientific literature on BC and $O_3$
- Focus on small number of carefully identified measures
- Assess the extent of near-term global and regional climate protection
- Estimate co-benefits on health and $O_3$ induced crop yield loss
- Examine how the measures can be widely implemented

Two groups of measures - $CH_4$ and BC measures
UNEP Integrated Assessment of Black Carbon (BC) and Ozone (O₃)

Millions of tonnes/year

Food security
CH₄ measures
CH₄ + BC measures

Millions of tonnes/year

Annually avoided crop yield losses (total maize, rice, soybean and wheat, million tonnes)
‘Food security’ assessment only focussed on ozone induced crop yield losses of four key crops - wheat, rice, maize and soybean. It ignores influence of regional climate change and other impacts associated with air pollutants on crops (and ecosystems).
Incoming solar radiation

- Aerosol can reduce the quantity of incoming radiation (‘dimming’)

- Aerosol can change the quality of surface dimming (increase diffuse radiation)

- Higher diffuse fractions can increase all leaf area photosynthetic and increase leaf photosynthesis

- Aerosols can also cause warming (or cooling) of the atmosphere depending on BC/OC fraction

...and such regional climate change (altered T°C, Precipitation etc... can also affect plant growth)

- Black Carbon (BC)
- e.g. Organic Carbon (OC) and sulphates, nitrates