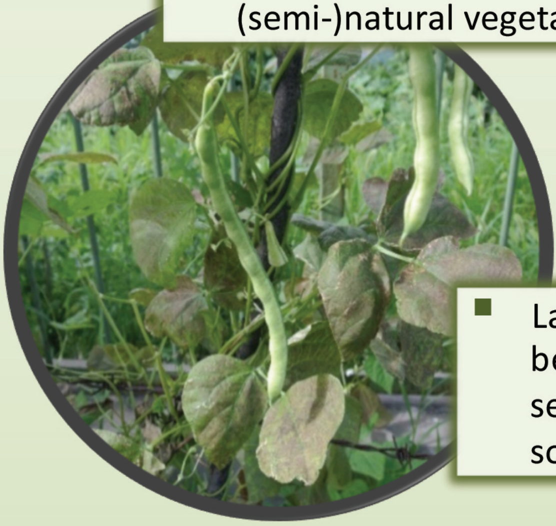
Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

LRTAP
Long-range Transboundary Air Pollution

Field evidence of ozone impacts on vegetation in ambient air (2007-2015)

- Widespread impacts of ambient ozone have been demonstrated on a wide variety of crop, tree and (semi-)natural vegetation species.



- Large reductions in yield have been attributed to ozone for several crops including wheat, soybean, rice, and other legumes.

- Detected impacts on natural vegetation species are diverse and include visible leaf injury and reductions in biomass.

http://icpvegetation.ceh.ac.uk

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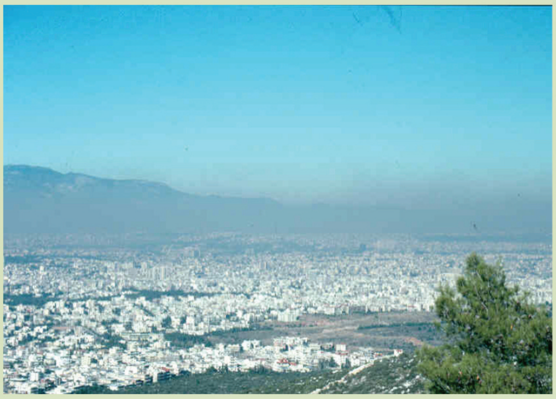
Working Group on Effects
of the
Convention on Long-range Transboundary Air Pollution

Introduction

Sources of the precursors of ozone pollution include vehicles and industry



Ozone is present in smog above cities such as Beijing (top) and Athens (bottom)

Ground level tropospheric ozone is formed from reactions in sunlight involving oxides of nitrogen, carbon monoxide and non-methane volatile organic compounds released mainly from vehicle and industrial sources. These pre-cursor molecules can travel on the wind for thousands of miles, so that increased ozone formation can occur far away from where the pre-cursors were released. Ozone concentrations tend to be highest in rural and upland areas.

Effects of ozone on vegetation have been demonstrated in scientific experiments and include reduced plant growth, reduced yield of crops and visible injury symptoms on leaves. Many factors such as sunlight, temperature, humidity and soil moisture can influence the uptake of ozone into the leaves of the plants, and it has been shown that ozone effects are better related to ozone uptake rather than ozone concentration (Mills et al., 2011. Atmospheric Environment 45: 5064-5068). It is important to demonstrate where impacts of ambient ozone have been detected in field conditions to verify predictions from concentration and flux-based models.

Here we show an overview of the evidence of ozone impacts on vegetation in Europe and the rest of the world for the period 2007-2015. This gives new information to add to that previously collated for Europe for the period 1990 to 2006 (Mills et al., 2011. Global Change Biology 17: 592-613; Hayes et al., 2007; http://icpvegetation.ceh.ac.uk).

Evidence from filtered-air experiments

Experimental facilities, usually open-top chambers, can be used to investigate effects of reducing ambient ozone concentrations by charcoal filtration. Comparisons of responses between unfiltered and filtered air provide valuable indications of the effects of ambient ozone. Many species have been studied and a wide range of effects of ambient ozone have been reported, including physiological effects such as reduced photosynthesis, growth or yield.

Ozone exposure experiments using open-top chambers in Spain and Italy

Reductions in crop yield have been detected on a range of crops including wheat, soybean and rice in several countries in Europe and Asia. Grain size and quality has also been affected for some crops including wheat.

Crop	No. of datapoints	% yield reduction
Soybean[1,2]	3	22.5
Rice[1,2,4]	11	13.7
Wheat[1,2]	10	7.4
Durum wheat[2]	2	14.2
Peas / beans[3]	2	3.2

Crop yield reductions, using data from [1]China, [2]India, [3]Japan and [4]Pakistan

Reduced biomass of (semi-) natural vegetation has been found in seven studies on species covering a range of (semi-)natural vegetation types. Other responses reported include reductions in greenness of leaves and seed quality.

Country	Ozone (24h mean, ppb)	Species	Biomass reduction	Reference
Spain	28	Mediterranean pasture	8%	Calvete-Sogo et al., 2014, Atmospheric Environment 95:197-206.
Italy	37	*Quercus ilex*	17%	Gerosa et al., 2015, Atmospheric Environment 113: 41-49.
Spain	35	*Quercus ilex*	1%	Alonso et al., 2014, Plant Biology 16: 375-384.
Spain	32	*Briza maxima*	3%	Sanz et al., 2011, Environmental Pollution 159: 423-430.
Japan	19	*Betula ermanii*	4%	Hoshika et al., 2013, Environmental and Experimental Botany 90: 12-16.

Examples of responses to ozone shown in non-filtered compared to filtered air experiments

Biomonitoring for visible injury

The ICP Vegetation Biomonitoring Programme has used ozone-sensitive and ozone-resistant dwarf French bean (*Phaseolus vulgaris)* since 2008. Reductions in biomass and yield of >20% for the ozone-sensitive compared to ozone-resistant genotypes were shown in Austria, Belgium, China, France, Germany, Greece, Hungary, Italy, Latvia, Slovenia, Spain and USA. Members of the ICP Vegetation and volunteers have been recording the presence of ozone visible injury symptoms on leaves of plants within the biomonitoring programme, by use of ozone-sensitive plant species in 'ozone gardens' and in field and natural habitats using a smart-phone app (available from http://icpvegetation.ceh.ac.uk/record/index).

China

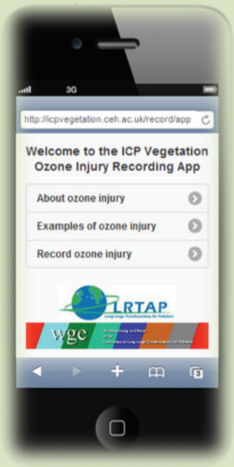
Pakistan

Ukraine

Biomonitoring ambient ozone impacts by ICP Vegetation participants at sites including China-Changping, Pakistan-Rawalpindi and Ukraine-Kiev. In each photo ozone-resistant Phaseolus vulgaris *are shown on the left, and ozone-sensitive* Phaseolus vulgaris *on the right.*

Visible leaf injury symptoms attributed to ozone have been observed on over 60 species of crops, wild flowers, shrubs and trees over the period 2007-2015. In many cases these symptoms have been verified by comparison with symptoms present in experimental ozone exposure studies. Visible leaf injury has been observed in 19 countries from Europe, Asia, and North and South America.

China



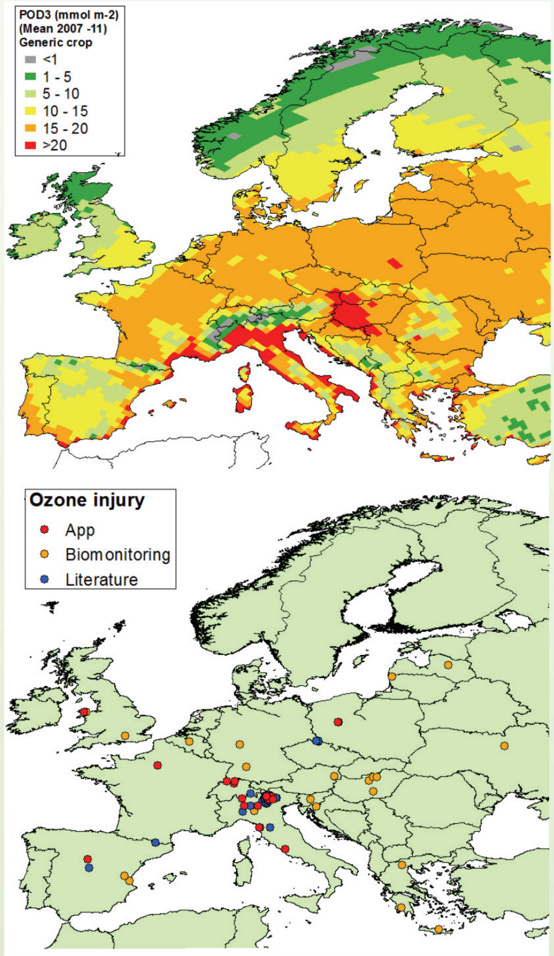
Switzerland

Ozone visible leaf injury has been observed in field conditions on many species including beans in China-Beijing and ash in Switzerland. A smart-phone app has been used to report symptoms.

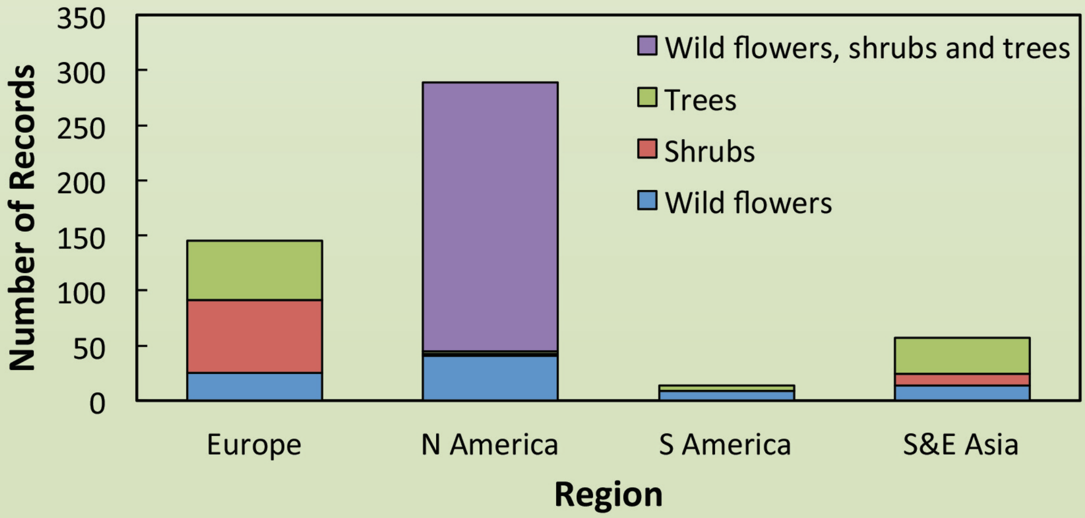
Observations of visible leaf injury symptoms

Visible leaf injury has been observed in many parts of the world. Maps of the occurrence of ozone-induced visible leaf injury made using data from the literature, surveys, the ICP Vegetation biomonitoring programme and the smart-phone app reflect the intensity of effort in surveying for symptoms. Lack of observations in a region may not mean a lack of symptoms on vegetation. There is a fairly equal distribution of the numbers of records of injury on wild flowers, shrubs and trees.

Observations of leaf injury and the regions with the highest ozone flux generally show good agreement for Europe. However, injury symptoms can still be found in regions where fluxes tend to be lower. Additional data showing observations of ozone visible leaf injury across central and eastern Europe are available from the ICP Forests network (http://icp-forests.net/).



For Europe there is good agreement between regions with the highest ozone flux (top map) and observations of ozone-induced leaf injury (bottom map).



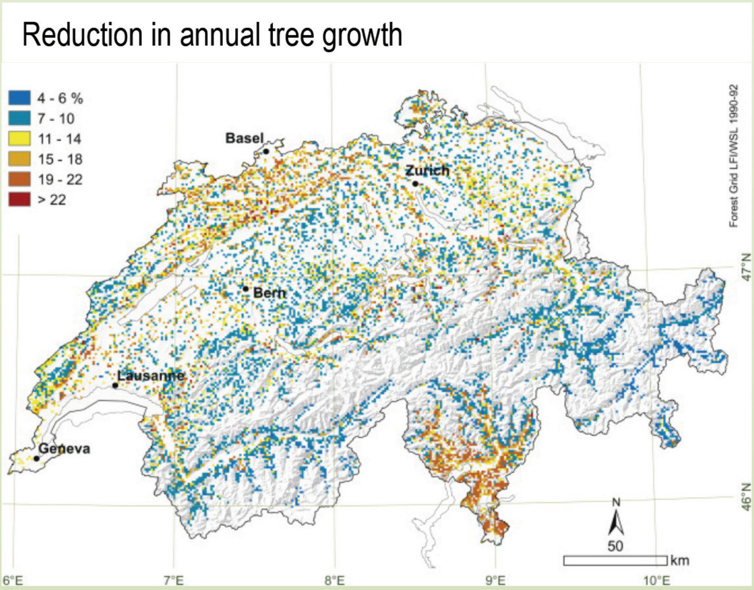
Observations of visible leaf-injury symptoms have been recorded using the smart-phone app, during the course of biomonitoring experiments, from the literature, and from surveys including the USDA Forest Service: http://www.nrs.fs.fed.us/fia/topics/ozone/; Smith 2012, Environmental Monitoring and Assessment 184: 4049-4065). Many occurrences have been recorded in Europe and North America, where there is more effort from scientists to detect injury. However, visible leaf injury has also been detected in many other areas of the world.

Evidence from epidemiology studies of trees

Ozone impacts on mature trees in the field have been demonstrated using epidemiological analysis. The approach can disentangle and quantify the contributions of many predictor variables by utilising naturally occurring gradients of these predictors and relating these to impacts such as visible leaf injury and growth. Repeated measurements over several years are used so that location and tree-specific variations can be accounted for.

Examples of this approach include Switzerland, where basal area increment of forest trees was related to ozone and climatic variables. Based on measurements on approximately 4800 trees it was estimated that the **reduction in annual growth rate** due to ozone pollution was 19.5% for deciduous and 6.6% for coniferous forests during the period 1991–2011 (Braun et al., 2014. Environmental Pollution 192: 129-138). This agreed well with European estimates of growth reductions based on the calculated ozone uptake (POD; Harmens and Mills, 2012. Ozone pollution: impacts on carbon sequestration in Europe. http://icpvegetation.ceh.ac.uk/).

In northern Italy and southern France epidemiological analysis has been used to show that **ozone injury symptoms** on forest trees were better explained by ozone uptake (POD) rather than ozone concentrations (Sicard et al., 2016. Science of the Total Environment 541: 729-741).



Epidemiological analysis of forest trees in Switzerland has been used to estimate reductions in annual growth rate due to ozone pollution.

Reprinted from Environmental Pollution, Braun et al., 2014. Growth losses in Swiss forests caused by ozone: Epidemiological data analysis of stem increment of Fagus sylvatica L. *and* Picea abies Karst. *Environmental Pollution 192: 129–138. (Copyright 2014, with permission from Elsevier).*

Conclusions

- Ad hoc field observations, epidemiological studies, biomonitoring and ambient air filtration studies provide field-based evidence for widespread damage to vegetation from current ozone levels present in ambient air.
- Impacts have been shown on over 60 vegetation species and include visible leaf injury symptoms, and reduced vegetation biomass and crop yield.
- For Europe there is good agreement between observations of leaf injury and the regions with highest ozone flux.

Ozone injury can be recorded in parks, gardens and dedicated 'ozone gardens' containing ozone sensitive species

Recommendations and future challenges

- Although effects of ambient ozone have been frequently recorded in many European countries and parts of the USA, there is a need to broaden coverage worldwide.
- Planting ozone-sensitive species ('ozone gardens') is a useful tool for demonstrating the occurrence of visible leaf injury in ambient conditions (e.g. the NASA ozone gardens, http://science-edu.larc.nasa.gov/ozonegarden/pdf/Bio-guide-final-3_15_11.pdf). The ICP Vegetation is also establishing a network of ozone gardens where ozone-sensitive species are planted.
- Much current evidence of ozone impacts on vegetation is from records of visible injury, which occur following episodic peaks of ozone. Models predict that over the coming decades the pattern of ozone exposure will continue to change in Europe and the USA, with peaks reducing and background concentrations increasing. This pattern is less likely to cause visible leaf injury, but is still expected to impact on vegetation growth and crop yield. These impacts, although biologically and economically important, are more difficult to observe under field conditions and therefore there is an increasing need to establish fast and reliable methods to quantify them.

Field evidence of ozone impacts on vegetation in ambient air (2007-2015)

Using a combination of scientific experiments, mathematical models and predictions of pollutant emissions it has been predicted that ambient ozone concentrations are sufficient to cause impacts on vegetation. In this brochure we show evidence to verify these predictions using a combination of recording of visible leaf injury symptoms, biomonitoring studies using ozone-sensitive and ozone-resistant plants, experiments using filtered air compared to ambient air, and epidemiological studies. Impacts of ozone have been found on a wide variety of species. Responses include reductions in crop yield in addition to visible leaf injury and biomass reductions in native species, including trees. Effects of ambient ozone have been shown worldwide, but more field-based data is needed, especially in Africa, Asia and South America.

This brochure was produced by the Programme Coordination Centre of the ICP Vegetation. The ICP Vegetation is an International Cooperative Programme reporting on effects of air pollution on vegetation to the Working Group on Effects of the UNECE Convention on Long-range Transboundary Air Pollution.

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This brochure and other publications are also available at http://icpvegetation.ceh.ac.uk

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